EFFECT OF SUPERABSORBENT POLYMER AND SALICYLIC ACID ALONG WITH DIFFERENT SOURCES OF SULPHUR ON GROWTH, YIELD, AND QUALITY OF GOBHI SARSON (*Brassica napus* L.) UNDER CONTROLLED IRRIGATION

Thesis Submitted for the Award of the Degree of

DOCTOR OF PHILOSOPHY

in

Agronomy

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DECLARATION

I, hereby declared that the presented work in the thesis entitled **"Effect of Superabsorbent polymer and Salicylic acid along with different Sources of sulphur on growth, yield, and quality of Gobhi Sarson (*Brassica napus* L.) under controlled irrigation"** in fulfilment of degree of **Doctor of Philosophy (Ph.D.)** is outcome of research work carried out by me under the supervision of **Dr. Sarvjeet Kukreja** and co-supervision of **Dr. Rajeev Kumar Gupta,** working as Professor, in the Department of Agronomy, School of Agriculture of Lovely Professional University, Punjab, India. In keeping with the general practice of reporting scientific observations, due acknowledgments have been made whenever work described here has been based on findings of other investigators. This work has not been submitted in part or in full to any other University or Institute for the award of any degree.

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CERTIFICATE

This is to certify that the work reported in the Ph.D. thesis entitled **"Effect of Superabsorbent polymer and Salicylic acid along with different Sources of sulphur on growth, yield, and quality of Gobhi Sarson (*Brassica napus* L.) under controlled irrigation"** submitted in fulfillment of the requirement for the award of degree of **Doctor of Philosophy (Ph.D.)** in Department of Agronomy, School of Agriculture is a research work carried out by **Palvi Dogra (12020441)** is Bonafide record of her original work carried out under my supervision and that no part of thesis has been submitted for any other degree, diploma or equivalent course.

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Palvi Dogra

Date:

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LIST OF ABBREVIATIONS

Abbreviation	Full Form
DAS	Days After Sowing
GSC-7	Gobhi Sarson Cultivar 7
LAI	Leaf Area Index
SPAD	Soil Plant Analysis Development (chlorophyll meter reading)
SSP	Single Superphosphate
B. napus L	*Brassica napus* Linné
SA	Salicylic Acid
SAP	Superabsorbent Polymer
A0–A7	Agrochemical Treatment Codes
S1	Gypsum (Sulphur source)
S2	Bentonite Sulphur (Sulphur source)
S3	Elemental Sulphur (Sulphur source)
N	Nitrogen
P	Phosphorus
K	Potassium
S	Sulphur
ANOVA	Analysis of Variance
LSD	Least Significant Difference
CD	Critical Difference
CV	Coefficient of Variation
cm	Centimeter

cm^3	Cubic centimeter
m^2	Square Meter
ml	Milliliter
kg/ha	Kilograms per Hectare
q/ha	Quintals per Hectare
t/ha	Tones per Hectare
ppm	Parts Per Million
dS/m	Deci Siemens per Meter
Rs/ha	Indian Rupees per Hectare
wt.	Weight
%	Percent
LPU	Lovely Professional University
PAU	Punjab Agricultural University
IARI	Indian Agricultural Research Institute
PV	Peroxide Value
SV	Saponification Value
B: C	Benefit-Cost Ratio

Abstract

Water is essential to agriculture, although its availability is rapidly declining. The continuing depletion of groundwater supplies is an ongoing worry, especially in water-intensive crops such as Gobhi Sarson (*Brassica napus* L.). Restricted water availability affects crop development, production, and quality, necessitating the investigation of solutions that improve water-use efficiency and nutrient absorption. Superabsorbent polymers, including hydrogel, used together with salicylic acid (SA), have come to light as effective treatments for enhancing moisture retention and plant resistance in water-scarce environments. Moreover, sulphur is crucial for oilseed crops, significantly contributing to seed yield, oil content, and protein synthesis. The efficacy of various sulphur sources under regulated irrigation remains a significant research inquiry. During the rabi seasons of 2021–22 and 2022–23, a field experiment was conducted at Lovely Professional University's Agronomy Farm using a split-plot design to address this challenge. The research assessed the synergistic impacts of hydrogel, salicylic acid (SA), and various sulphur sources on the growth, yield, quality, and nutrient absorption in Gobhi Sarson. The variety used during the experiment was GSC 7, a high-yielding variety developed by Punjab Agricultural University (PAU), Ludhiana, recognized for its exceptional adaptability, oil content, and disease tolerance. The treatments were carried out at two crucial growth phases—flowering and pod formation—to evaluate their effects on essential metrics. Data was collected on growth parameters (plant height, leaf count, dry matter accumulation, root characteristics, and leaf area index), yield parameters (siliquae per plant, siliqua length, seed weight, biological yield, and seed yield), and nutrient uptake (nitrogen, phosphorus, potassium, and sulphur). Furthermore, quality indicators like oil content, protein content, and oil recovery were examined. The findings indicated that the utilization of gypsum as a sulphur source, along with hydrogel and salicylic acid throughout the flowering and pod formation stages, markedly enhanced plant performance. This treatment resulted in enhanced plant height, increased dry matter accumulation, improved root development, and a greater leaf area index. Yield traits, such as the number of siliquae per plant, siliqua length, 1000-seed weight, and total seed output, were markedly improved. The absorption of nutrients, especially sulphur, demonstrated a positive correlation with enhanced growth and productivity. Additionally, under the most suitable treatment, oilseed quality was improved, showing higher oil content, better protein recovery, and increased oil production. This work underscores the essential function of gypsum as an excellent sulphur source, in conjunction with hydrogel and salicylic acid treatment during crucial growth phases, in augmenting water-use efficiency, increasing nutrient absorption, and enhancing crop yield. The results indicate that the combined effect of various treatments can substantially enhance yield and quality characteristics, providing a sustainable and water-efficient method for oilseed crop production. Considering the ongoing challenges of water scarcity in agricultural systems, incorporating these measures will be crucial for enhancing production and maintaining long-term sustainability in rapeseed cultivation.

Keywords: Bentonite sulphur, Controlled irrigation, Drought tolerance, Elemental sulphur, Gypsum, Hydrogel, Salicylic acid,

CHAPTER-I

INTRODUCTION

Oilseed crops have a significant role in the current energy crisis, considerably contributing to India's agricultural sector and export trade. Recent years have seen a significant change in the oilseed scenario, with oilseeds now becoming a net foreign exchange earner and triggering the "Yellow Revolution". Edible oils and oil meals have significantly contributed to alleviating malnutrition and providing nutritional nourishment for both human and animal populations. Oilseed crops are vital to India's agricultural economy, serving as a principal source of edible oils and industrial products (Usman *et al.,* 2023). India is a significant global oilseed producer, contributing roughly 7-8% of total oilseed output. The predominant oilseeds cultivated in the country are peanut, soybean, sunflower, and several types of mustard and rapeseed, which are crucial for meeting domestic edible oil requirements and producing export revenue (Narayan, 2017).

Indian mustard (*Brassica juncea* L.) is an essential rabi oilseed crop in India, important to the nation's agricultural industry. It ranks third in area and production, following soybean and groundnut, accounting for around 80% of the entire rapeseed-mustard area in India. It belongs to the family *Brassicaceae* and has a chromosome number. 2n=36 (Meena *et al.,* 2014; Singh *et al.,* 2022). Rapeseed, *i.e., Brassica napus,* and mustard, *i.e., Brassica juncea,* are closely related oilseed crops that exhibit differences in growing needs, oil quality, and adaptability. Rapeseed generally possesses a greater oil content (40-45%) and yields oil with low erucic acid levels, such as canola, which is characterized by a moderate flavor and enhanced health benefits due to its abundance of unsaturated fatty acids. Conversely, mustard oil possesses a unique, acrid smell, elevated erucic acid levels, and is esteemed for its antibacterial characteristics and traditional culinary applications in India. Mustard and Rapeseed oil, extensively utilized for frying and seasoning in northern India owing to their unique taste and nutritional advantages, are a crucial element of Indian culinary traditions, rendering Indian mustard a vital crop for both subsistence and commercial agriculture (Singh *et al.,* 2023). Mustard seeds comprise 37-49% oil, employed as a cooking medium and for the creation of pickles and assorted sauces. The oil is employed for its medicinal properties, rich in omega-3 fatty acids and low in saturated fats, therefore offering a healthier alternative to traditional cooking oils (Das *et al.,* 2022). After oil extraction, the residual oil cake functions as a high-protein animal feed and organic fertilizer, due to its significant concentrations of crude protein (25-30%), nitrogen, phosphate, and potassium (Singh *et al.,* 2022). Young mustard leaves are employed as a green leafy vegetable, commonly known as "sarson ka saag" in Indian cuisine. India imports a significant quantity of edible oils, and mustard is one of the few indigenous oilseed crops that mitigates this import burden. Mustard is a crucial crop for India's food security, representing 31.3% of the nation's total edible oilseed production. Its oil is favored for its culinary attributes and nutritional benefits, making it widely used in both urban and rural environments. The cultivation of mustard greatly influences rural economies, increasing farmers' livelihoods through funds earned from the sale of oil and oilseed cake, which is further utilized as cow feed and manure. The oil cake contains 25-30 % crude protein, 5% nitrogen, 1.8 - 2.0% phosphorus, and 1.0 - 1.2% potassium (Dubey *et al.,* 2022). The need for healthy cooking oils is increasing, leading to the growing popularity of mustard oil globally (Pathak *et al.,* 2022). Traditionally used as a treatment for skin conditions, hair care, and massages, mustard oil has become known for its antibacterial and antifungal qualities. Because of its great concentration of helpful fatty acids, it also helps digestion and is thought to enhance cardiovascular condition (Kaur *et al.,* 2019; Yadav and Kumari, 2013).

Particularly in semi-arid areas like Rajasthan, Haryana, Madhya Pradesh, Uttar Pradesh, and Gujarat, Indian mustard is a significant cash crop. Its production, distribution, and processing help small and medium-sized businesses, increasing rural income and employment (Hosamani, 2016; Srivastava & Kumar Verma, 2023). Furthermore, mustard oil is being utilized more and more to produce biodiesel, which is a sustainable substitute for fossil fuels. Mustard's contribution to the production of biofuel is anticipated to increase as India and other nations move toward renewable energy, hence boosting its economic significance (Alam & Rahman, 2013; Monika *et al.,* 2023). In 2024, India is projected to be the fourth-largest global producer of rapeseed and mustard, with a production of approximately 11 million metric tons (MMT). This placed it between China, Canada, and the European Union in world rankings (USDA, 2024). Rapeseed and mustard are grown in many temperate and subtropical regions of the world, especially in arid and semi-arid environments (Ashraf and McNeilly, 2004; Mahto *et al.,* 2023). Indian mustard is mostly grown in Rajasthan, Uttar Pradesh, Haryana, Madhya Pradesh, Gujarat, Punjab, and Bihar. This crop accounts for nearly one-third of the oil produced in India, making it the country's key edible oilseed crop. Between 2020 and 2023, the area planted with mustard and rapeseed has increased by 29%, from 68.56 lakh ha to 88.58 lakh ha (Ministry of Agriculture and Farmers Welfare, 2023).

India increased its mustard production to 93 lakh hectares during the 2023–2024 season, yielding a record 12.09 million metric tons a 7% increase over the previous year. Indian mustard (*Brassica juncea* Cosson & Czern L.) is the major oilseed, spanning 80% of rapeseed-mustard lands and producing 31.3% of the country's edible oilseed production (Singh *et al.,* 2022). India has 66.90 lakh hectares of mustard land, with an average yield of 1511 kg/ha and an annual production of 101.10 lakh tonnes (Anonymous, 2023). Although rapeseed and mustard are significant oilseeds in Punjab, their yield and planted area are inferior to those of Rajasthan. Punjab increased its production from 0.070 million tons in 2022 to 0.090 million tons in 2023; nonetheless, the average productivity is still lower than the national average, suggesting room for yield improvement. Due to competition with other vital crops, the limited potential for expanding agriculture in Punjab requires the implementation of innovative crop production technology and enhanced agronomic techniques to improve production and productivity (Sharma *et al.,* 2022). Executing these techniques can help close the production gap and fulfill the state's oilseed requirements.

Mustard growth and output are frequently restricted by environmental factors such temperature swings, wind, and pest infestations (Bindhani *et al.,* 2020; Singh *et al.,* 2019). Because mustard is very sensitive to temperature changes and irrigation, ignoring these factors can lower its yield. Thus, efficient agronomic management is crucial, encompassing techniques for stress reduction and moisture conservation (Pillai & Walia, 2024; Sakpal *et al.,* 2023). The lack of stored soil moisture on sandy soils in semi-arid areas like Rajasthan results in water stress, which, in conjunction with other biotic and abiotic variables, continues to be a significant barrier to mustard output in India. India's production is lower than the global average due to moisture stress, late rainfall, and moisture of soil reserves (Jat *et al.,* 2018; Rathore *et al.,* 2020a). Because of fluctuating rainfall patterns and diminishing groundwater levels, water stress presents significant obstacles to mustard farming in Punjab. Groundwater is depleted by excessive irrigation of water-intensive crops like rice, which restricts the amount of moisture available for mustard during crucial growth stages. Due to their limited water retention, sandy loam soils make the issue worse by creating quick drainage and extended moisture stress (Datta *et al.,* 2022). Water availability is further diminished throughout the Rabi season by climate unpredictability, which includes erratic rainfall and rising temperatures. To address these issues, farmers are now thinking about variable double cropping with beans and mustard (Asefa Bogale, 2023; Karri & Nalluri, 2024). Therefore, to sustain mustard productivity in this water-limited environment, sustainable water conservation and effective irrigation techniques are essential.

Mustard productivity can be increased by adopting better scientific methods and agrochemicals to lessen water stress (Kumar *et al.,* 2022; Patra *et al.,* 2022; Prakash *et al.,* 2021). Regarding this, hydrogel, a semi-synthetic superabsorbent polymer, exhibits potential for increasing yield in water-limited environments. When paired with accurate irrigation and fertigation, hydrogels' high water-holding capacity, biocompatibility, and flexibility improve sandy soils' water use efficiency (WUE) (Seliktar, 2012). They prolong irrigation intervals by holding onto soil moisture and rainfall and releasing it gradually in accordance with crop requirements (Dar *et al.,* 2017; Palanivelu *et al.,* 2022). It has been demonstrated that applying hydrogel greatly increases agricultural production and WUE for a variety of crops (Kumawat *et al.,* 2024).

Hydrogel is an insoluble, cross-linked three-dimensional polymer that holds water over 400 times its weight and gradually releases it, enhancing soil hydro-physical qualities such as porosity, aggregate stability, and hydraulic conductivity (Abdelghafar *et al.,* 2024). Without changing its structure, the hydrogel's swelling ratio rises with temperature up to 50°C, improving water conservation and lessening plant stress during drought or excessive wetness. It reduces evaporation, keeps water and nutrients close to roots, and increases fertilizer efficiency by lessening leaching. Moreover, hydrogel increases soil water-holding capacity and infiltration, enabling a 55–80% decrease in irrigation frequency and volume, which raises crop production (Malik *et al.,* 2023; Saini and Malve, 2023). The use of such types of conditioners as a super absorbent polymer (hydrogel) has the highest potential to exploit the existing water in the soil for crops by increasing their production. It is mixed with the soil on which the seeds are sown. Due to the use of hydrogel, there is a 40 to 70% saving of water (Zheng *et al.,* 2023). Hydrogel application and salicylic acid treatment can help preserve moisture, reduce environmental stress, and improve soil water retention.

Salicylic acid (SA), a phytohormone, regulates plant growth, development, and defence against environmental stresses by increasing plant response to biotic and abiotic stress conditions and System Acquired Resistance (Arif *et al.,* 2020; Vishnu *et al.,* 2021). It acts as an important signaling molecule that adds to tolerance against abiotic stresses by activating the antioxidative defense mechanism via downplaying ethylene production, along with increased production of osmolytes such as proline and glycine betaine. A growing number of studies have proven that SA is crucial in modulating plant responses to a range of environmental stressors, such as metal toxicity (Guo *et al.,* 2019), osmotic stress (Ilyas *et al.,* 2024), chilling and drought (Mohi-Ud-din *et al.,* 2021), and thermogenesis (Wassie *et al.,* 2020). The use of hydrogel improved overall stress tolerance by modulating redox balance and augmenting photosynthesis and stomatal conductance (Nazar *et al.,* 2015). Salicylic acid, a naturally occurring phenolic phytohormone, serves as an essential signaling molecule to enhance tolerance to abiotic stresses. It is essential for plant growth, development, photosynthesis, transpiration, ion absorption, and transport (Liu *et al.,* 2022; H. Yang *et al.,* 2023; W. Yang *et al.,* 2023). Additional factors contributing to the low productivity of Indian mustard in northern locations include low soil fertility and poor physical condition, as well as inadequate and imbalanced nutrient availability, resulting in numerous nutrient deficits (Das *et al.,* 2022). Punjab's sandy loam soils are problematic for growing mustard because of their high nutrient leaching and poor water-holding ability. Rapid drainage frequently results in moisture stress, which lowers agricultural productivity. Deficits result from the root zone's easy loss of mobile nutrients like sulphur and nitrogen. Although mustard requires a lot of sulphur, effective management of moisture and nutrients is essential to maximizing its yield (Chaudhari *et al.,* 2022). Sulphur, an essential component for protein synthesis and oil production, is typically insufficient in sandy loamy soils, with available sulphur levels typically below the ideal range. This shortage can significantly affect mustard oil content and overall production, prompting the application of sulphur-containing fertilizers to improve soil fertility and crop performance (Narayan *et al.,* 2023; Varényiová *et al.,* 2017). The amount of available sulphur (5–10 ppm) in Punjab's light-textured soils is not enough to meet crop requirements. This limitation restricts mustard's capacity to produce proteins and oils, which lowers yield. According to studies, sulphur fertilization can greatly increase oil content; for every unit of sulphur, oil output increases by roughly 3.5 units. Therefore, addressing the sulphur deficiency is essential to raising Punjab's mustard yield (Kumar Pachauri and Trivedi, 2012). Reports show that the average sulphur absorption per tonne of grain produced is 3-4 kg in cereals, 8 kg in pulses, and 12 kg in oilseeds. (Ghosh and Sarkar, 1999a; Kumar Udayana *et al.,* 2021). This suggests that economic crop production cannot be expected from fertilizers devoid of sulphur.

A vital component of the amino acids methionine (21% S), cystine (27% S), and cysteine (26% S), sulphur is the fourth major nutrient for plants. It is absorbed as SO_4^{2-} and is essential for the synthesis of proteins and oils, oxidation-reduction processes, the production of chlorophyll, and other metabolic processes (Chaudhary *et al.,* 2023; Narayan *et al.,* 2023b). Through disulfide bonds, sulphur improves root growth, cold and drought tolerance, disease resistance, and residue breakdown. Research conducted throughout India has demonstrated that applying sulphur significantly increases crop yields (Maurya *et al.,* 2023). It primarily resides in organic forms in soils and is gradually released through microbial degradation.

Sulphur deficits in soil are becoming more common due to intense cropping techniques, poor recycling of crop residues, excessive leaching, soil erosion, inadequate application of sulphur-based fertilizers, and increased sulphur absorption by high-yielding crop types. Soil poor in sulphur cannot supply sufficient sulphur to satisfy crop requirements, leading to sulphur-deficient crops and unsatisfactory yields. (McNeill *et al.,* 2005; R. K. Sharma *et al.,* 2024). The two main categories of sulphur fertilizers are elemental sulphur-based and sulphate-based. While elemental sulphur and pyrites release sulphur gradually after oxidizing to sulphate, providing longer availability and lower losses, sulphate fertilizers such as gypsum supply sulphur easily but are prone to leaching (Bouranis *et al.,* 2018; Degryse *et al.,* 2020). Mustard reacts favorably to sulphur, although the source determines how effective it is. The sulphur content and availability of common sulphur fertilizers vary, and they include elemental sulphur, ammonium sulphate, superphosphate, pyrite, and gypsum (Ghosh & Sarkar, 1999b; Kumar *et al.,* 2018). Alkali soil reclamation makes extensive use of gypsum ($CaSO_4 \cdot 2H_2O$), which Benjamin Franklin initially identified as a soil additive in 1768. It lowers soil pH and increases nutrient uptake by replacing sodium with calcium, improving soil structure, and supplying sulphur, calcium, and magnesium (Bello *et* *al.,* 2021a; Chen *et al.,* 2011).

Gypsum is an affordable source of sulphur and efficiently enhances the physicochemical characteristics of sodic soils. By swapping calcium for sodium, its application improves nutrient availability and reduces soil pH. However, elemental sulphur (up to 85% S) frequently works better in fine-textured calcareous soils, releasing sulphur gradually through microbial decomposition. Its application rates are higher than those usually employed for seasonal crops like mustard, although they are more advantageous in some soils. Another major source of sulphur is pyrite (FeS_2), which contains 15–30% sulphur (Tozsin *et al.,* 2015). Despite its minimal commercial worth, pyrite has proven beneficial in the reclamation of sodic or saline-sodic soils by the successive biochemical oxidation of FeS_2, resulting in the production of sulphuric acid. This process solubilizes calcium carbonate ($CaCO_3$) in the soil and displaces salt, enhancing soil structure (Ahmed *et al.,* 2017; Bello *et al.,* 2021b). Recent research has shown that the low productivity of Indian mustard is due to the coefficient of effectiveness and inadequate partitioning of photosynthates between the reproductive and vegetative components under moisture-stress conditions (Kumari *et al.,* 2019; Rathore *et al.,* 2020b; Shahid *et al.,* 2020). Research indicates that plant growth agents, such as agrochemicals and growth regulators, may significantly boost crop production, particularly in situations where water stress is present. They maximize assimilate distribution between vegetative and reproductive portions while improving root development, nitrogen uptake, and water-use efficiency.

Taking all of these factors into account, the current study titled **"Effect of Superabsorbent polymer and Salicylic acid along with different Sources of sulphur on growth, yield, and quality of Gobhi Sarson (*Brassica napus* L.) under controlled irrigation"** was prepared and carried out in the *rabi* seasons of 2021-22 as well as 2022-23 with the following objectives:

1. To study the effect of Hydrogel and Salicylic acid, along with various Sources of sulphur, on the growth, yield, and quality.
2. To find the impact of Hydrogel and Salicylic acid, along with different Sources of sulphur, on nutrient uptake.
3. To work out the economic feasibility of various treatments.

CHAPTER-II

REVIEW OF LITERATURE

This chapter presents a comprehensive synopsis of research regarding the influence of various forms of sulphur, superabsorbent polymers, and salicylic acid on the growth, yield, and quality of Gobhi Sarson with controlled watering. We also looked at studies on similar crops when needed to get a wider view. This review aims to combine results from research done in various parts of India and other countries, focusing on important information that helps us understand the topic being studied.

2.1 Effect of different sources of sulphur

2.1.1 Effect on growth

Rani *et al.,* (2009) carried out a field experiment at Hyderabad's Central Research Institute for Dryland Agriculture's Hayathnagar Research Farm. This experiment compared the effectiveness of sunflowers grown with two different types of sulphur: elemental sulphur and gypsum. Compared to elemental sulphur, they observed a substantial increase in growth parameters in sunflowers with the administration of gypsum.

Kumar *et al.,* (2011) carried out a field experiment on Allahabad's sandy loam soil to assess the growth of spring sunflower (Helianthus annus L.) utilizing two different sources of sulphur: gypsum and elemental sulphur. Using gypsum instead of elemental sulphur, they found that increasing sulphur levels from 0 to 45 kg ha-1 significantly enhanced growth and growth characteristics.

A field study conducted by Chandra Banik and Rakesh (2016) in West Bengal revealed showed, similar to the benefits of 30 kg S ha-1 as Bentonite-S, 25 kg S ha-1 applied as SSP improved plant height, leaf count, as well as branch count per mustard plant.

Singh *et al.,* (2017) performed a research study on green gram and revealed that various levels and sources of sulphur significantly affected most growth and yield indices. The maximum plant height, number of branches per plant, number of nodules per plant, and the experiment weight were recorded when 40 kg S ha-1 of gypsum was applied.

Singh *et al.,* (2018) noted demonstrated the number of leaves, plant height, and dry matter output per plant were significantly impacted by the application of 60 kg/ha sulphur. Greater plant height and more initial branches per plant are characteristics of the mustard crop when cultivated with sulphur compared to those planted without it.

Kumar *et al.,* (2018) found that the source and dosage of sulphur significantly influenced the dry matter output per plant of mustard in Bihar, attributable to the varying sulphur sources and treatment dosages. The maximum dry matter yield (85.0 g per plant) was obtained with bentonite sulphur at a rate of 60 kg ha-1, which was significantly superior to all other treatments.

Kumar *et al.,* (2018) executed conducted a field experiment in Pantnagar that found that the plants' height, the number of branches per plant, and the dry weight of mustard were all greatly affected by the sources of sulphur. Zypmite applied 60 kg S ha- 1 significantly boosted plant height branch count per plant, and dry weight of mustard compared to the control.

Kumar *et al.,* (2018) conducted a field experiment in Varanasi to assess the impact of varying quantities and sources of sulphur on the growth, yield, nutrient removal of nitrogen, phosphorus, and sulphur, as well as the relative economic viability of cultivating Indian mustard. Elemental sulphur applied at 60 kg ha-1 produced the best mustard plants in terms of plant height, leaf area index, branch density, dry matter accumulation, and number of green leaves per plant.

Parmar *et al.,* (2018) conducted a field experiment in Navsari, Gujarat, during the summer season of 2015-16, revealing that the application of several sources of sulphur greatly enhanced the growth parameters of sesame. The maximum plant height and branch count of sesame were observed in plots treated with ammonium sulphate, which was comparable to gypsum treatment and superior to elemental sulphur. The utilization of sulphur via SSP combined with gypsum was identified as the most efficacious method for improving plant height and dry matter in sesame cultivation.

Yadav *et al.,* (2019) accomplished that our results showed that different sources of sulphur significantly affected sesame growth characteristics in a field experiment conducted at SKRAU, Bikaner. According to the study's results, sulphur applied through SSP and gypsum greatly improved dry matter buildup at 30- and 60-day post-sowing, as well as during harvest. There were significant gains in dry matter accumulation, plant height at harvest, and biological yield when this combination was applied at a rate of 60 kg S per hectare compared to the control group.

The results demonstrate that the performance at 60 kg S ha is statistically similar to that at 75 kg S ha, indicating that higher sulphur levels beyond 60 kg S ha may not provide additional agronomic benefits.

Singh *et al.,* (2021) conducted a field experiment in Faizabad (U.P.) during the Rabi season of 2015-16, revealing that varying quantities and sources of sulphur significantly influenced the growth parameters of mustard. The maximum height of mustard plants and the number of branches were considerably recorded at the 100% recommended dose of fertilizers (RDF) combined with 40 kg of sulphur via SSP, which was superior to the lower levels of sulphur from bentonite and phosphogypsum sources.

Nayee *et al.,* (2022) indicated that the application of sulphur had a significant impact on the development of mustard in comparison to a control, independent of the sulphur sources employed. The tallest groundnut plants ever measured were those that had sulphur applied to them using gypsum at a rate of 45 kg/ha. But it was no different from applying 30 or 45 kg ha-1 of elemental or bentonite sulphur, the standard rates for sulphur applications.

An Under the auspices of Acharya Narendra Deva University of Agriculture & Technology's Agronomy Research Farm in Kumarganj, Ayodhya, Dubey *et al.,* (2022) studied mustard throughout the rabi seasons of 2018–19 and 2019–20. According to the results, different sulphur sources had a substantial impact on mustard's dry matter accumulation and leaf area index. The phosphogypsum sulphur source resulted in the greatest amounts of dry matter accumulation as well as leaf area index which was comparable to single super phosphate and significantly better than the elemental sulphur source.

A field experiment by Kumar Singh *et al.,* (2022) at Veer Bahadur Singh Purvanchal University in Jaunpur, Uttar Pradesh, tested how sulphur and zinc together affected mustard growth. The study used four amounts of sulphur: 0, 20, 40, and 60 kg per hectare, with Single Super Phosphate (SSP) as the source of sulphur. The results showed that the application of 40 kg S ha^{-1} significantly enhanced plant height and the number of branches per plant. The study found that higher amounts of sulphur helped increase dry matter and leaf area.

Devatwal *et al.,* (2023) studied how different amounts and types of sulphur affected the production and costs of growing Indian mustard. The experiment used three types of sulphur: Gypsum, SSP, and Bentonite Sulphur, applied in various amounts. The findings showed that applying 45 kg S ha^{1} through SSP significantly improved mustard seedling emergence, growth rate, and total biomass.

Pandey *et al.,* (2024) investigated the synergistic impact of sulphur sources and nitrogen on mustard growth, concluding that the combination of SSP and gypsum yielded optimal outcomes in terms of plant vigor, chlorophyll concentration, and growth rate.

A field experiment carried in the N.D. University of Agriculture & Technology's Agronomy Research Farm at Kumar Ganj, Faizabad, Uttar Pradesh, studied the impact of sulphur and phosphorus on Indian mustard. Research demonstrated that increasing the soil fertility by 45 kg S ha^{-1} resulted in a significant uptick in primary branch density, siliquae density, seed density per siliqua, and 1,000-seed weight. Different quantities of sulphur also had a substantial impact on seed and stover yields, with 45 kg S ha^{-1} producing the highest yields. Seed yields were enhanced by applying 15, 30, and 45 kg S ha^{-1} production of 20.5%, 42.3%, and 48.0%, respectively, relative to the control (Sharma *et al.,* 2024).

2.1.2 Impact on yield attributes and yield

Fernandez Martinez (2005) investigated the impact Utilizing three different sources of sulphur applied to sesame at rates of 15, 30, and 45 kg ha-1: gypsum, elemental sulphur, and single super phosphate. The goal was to increase seed production and oil content. Applying 15 kg ha-1 resulted in the maximum seed production of 645 kg/ha of sulphur via single super phosphate compared to the control.

Singh and Singh (2007a) observed found, in comparison to other sources of sulphur, gypsum greatly boosted the seed and stover yields of linseed. The rapid availability of SO42- S in gypsum, in contrast to pyrite's sulphide form, which basically requires oxidation to be, is responsible for the increase in yield transformed into SO42- S before its absorption by the crop.

Sharma and Arora (2008) conducted experiments over two consecutive years and determined that the control group did not achieve the maximum mean seed yields of 20.30 q ha-1 and 18.01 q ha-1, respectively, in the first and second years, when 50 kg S ha-1 of ground gypsum was applied. This represents increases of 30% and 29.8%, respectively. The experiment revealed that in rainfed circumstances, mustard crops thrived with an adequate dosage of 25 kg S ha-1, especially when applied as ground gypsum.

Pati *et al.,* (2011a) performed conducted a study in Sriniketan, West Bengal, to evaluate the effect of different sulphur sources (phosphogypsum as well as magnesium sulphate) and amounts (0, 15, 30, 45, 60, 75, and 90 kg ha-1) on sesame production and sulphur absorption. Phosphogypsum was followed by magnesium sulphate, which, when applied at 60 kg ha1, had the highest grain yield at the identical rate. The maximum stover output was achieved using magnesium sulphate at 90 kg S ha^{1}.

Chattopaddhyay and Ghosh (2012) indicated that sources such as solitary superphosphate, phosphogypsum, pyrites, and elemental sulphur significantly affect grain yield and overall biological yield. The highest grain yield was observed with SSP, succeeded by phosphogypsum and pyrite of the numerous sulphur sources evaluated, single superphosphate yielded the highest grain output, followed by phosphogypsum, pyrites, and elemental sulphur.

Kumar and Trivedi (2012) revealed showed ammonium sulphate obtained the highest seed and straw yields in mustard, which was superior than other sources. The highest seed and straw yields were seen with the application of ammonium sulphate, succeeded by gypsum, single super phosphate, and pyrite.

Rao *et al.,* (2013) indicated that sulphur spraying markedly affected the yield-related traits and yield of groundnut compared to the control group. The application of sulphur at 45 kg ha-1 via gypsum resulted in the largest number of filled pods per plant, 100-pod weight, 100-kernel weight, pod yield, and haulm yield of groundnut.

Rakesh and Chandra Banik (2016) compared the effects of applying 25 kg S ha- 1 as SSP to those of applying 30 kg S ha-1 as Bentonite-S in terms of plant yield, stover yield, number of seeds per siliqua, length of siliqua, weight of 1000 seeds, seed yield, along with stover yield of mustard. The results showed that the former treatment was more effective.

Ravikumar *et al.,* (2016) undertook an experiment to investigate the reaction of sunflower (*Helianthus annuus* L.) variety K-1 to various sources and concentrations of sulphur (elemental sulphur, gypsum, and pyrite). Positive effects on sunflower development, production, and nutrient absorption were seen when 45 kg ha-1 of Elemental Sulphur was applied in combination with 40:20:20 kg ha-1 of RDF. In terms of growth, yield characteristics, along with yield, the lowest results were observed at 0 kg S ha-1 in conjunction with RDF.

Kumar *et al.,* (2018) experimented on the black gram, reported that the gypsum was a superior sulphur source, which was evident from the yield increase due to gypsum application. Elemental sulphur and pyrite were at par in their effect. The highest benefit cost ratio was also realized from gypsum source and at levels 30 and 40 kg S ha^{-1}.

Singh *et al.,* (2018) noted that the 30 kg S ha-1 was applied to mustard, which greatly enhanced the yield characteristics, seed yields, and stover yields.

Kumar *et al.,* (2018a) shown in Bihar that the source and dosage varying sulphur sources and treatment doses accounted for the substantial impact of sulphur on mustard yield characteristics and yield. At 60 kg ha-1, bentonite sulphur had the best results compared to the other treatments for mustard, including the greatest siliqua per plant, siliqua length, seeds per siliqua, test weight, seed yield, and overall stover yield.

Deo Singh *et al.,* (2019) carried out a field experiment at the Research Farm of Narendra Deva University of Agriculture & Technology in Ayodhya during the rabi season of 2015-16 to investigate the effects of different quantities and sources of sulphur on soil properties and mustard yield. The experiment employed a Randomized Block Design with seven treatments, incorporating RDF (NPK: 120:60:60 kg ha^{1}) and several sulphur sources (SSP, Sulphur Bentonite, Phosphogypsum) administered at 20 as well as 40 kg S ha^{1}. The findings demonstrated that RDF, when combined with 40 kg S ha^{1} from SSP, significantly improved grain yield 19.36 q ha^{1} and stover production (58.50 q ha^{1}), while the harvest index remained constant.

At the Research Farm of Bihar Agricultural College, Sabour, Bhagalpur, Kumar *et al.,* (2018) tested different sources and doses of sulphur-on-sulphur absorption and mustard yield in a field experiment that ran from 2013 to 2014. Bentonite sulphur demonstrated a markedly superior production of mustard in comparison to the other two sources of sulphur, namely gypsum and iron pyrite.

Kumar *et al.,* (2018) performed a field experiment in Varanasi to evaluate the relative economic feasibility of growing Indian mustard, the effects of different amounts and sources of sulphur on growth, yield, and nutrient removal of nitrogen, phosphorus, as well as sulphur. Mustard seed yield, stover yield, test weight, siliqua length, and siliquae count were all best achieved with an application of 60 kg ha-1 of elemental sulphur.

Parmar *et al.,* (2018b) executed conducted a field trial in Navsari, Gujarat, and discovered that using different sulphur sources significantly enhanced the sesame yield, yield characteristics, and use. Ammonium sulphate, which was better than elemental sulphur and on par with gypsum, increased the maximum capsule number per plant, capsule length, seed yield per capsule, seed yield, as well as stalk yield of sesame.

Kumar *et al.,* (2019) did a field experiment in Bihar to assess the impact of various sulphur sources (Phosphogypsum, Bentonite, and Control) on the yield and economics of mustard. They discovered that the application of bentonite as a sulphur source, in conjunction with the recommended NPK dosage, resulted in the largest number of seeds per siliqua, seed yield, and stover yield of mustard.

Dwivedi *et al.,* (2021) conducted an experiment in Azamgarh, (U.P.), during the 2014–15 and 2015–16 Rabi seasons. Various sources of sulphur were shown to boost mustard production and most yield characteristics. The following data were recorded for mustard: maximum number of siliqua plants per unit area, maximum length of seeds per unit area, test weight, seed yield, stover yield, & harvest index with gypsum source of sulphur.

Prashant Deo Singh (2021) carried out an experiment in the field at Faizabad (U.P.) and they found showed the highest number of siliquae and length of siliquae of mustard were achieved by applying 100% of the required dose of fertilizers (RDF) together with 40 kg of sulphur by SSP.

Dubey *et al.,* (2022) executed a field experiment in Kumarganj, Ayodhya, revealing that various sources of sulphur considerably influenced the yield characteristics of and mustard crop. Using phosphogypsum as a source of sulphur increased mustard's siliqua count, siliqua length, seed density per siliqua, 1000 grain weight, seed yield, stover yield, while harvest index; these results were on par with those of single super phosphate and much better than those of elemental sulphur.

Research undertaken by Kumar *et al.,* (2023) in the rabi season of 2022 at SHUATS, Prayagraj, examined the impact of varying sulphur concentrations on many mustard cultivars. The results demonstrated that elevated sulphur concentrations significantly affected growth metrics and yield among various types, indicating the importance of sufficient sulphur fertilizer for effective mustard cultivation.

A field experiment carried out by Gautam (2024) in the rabi season of 2023-24 at Vivekananda Global University, Jaipur, found the synergistic effects of sources of sulphur and biofertilizers on mustard cultivation. The research demonstrated that the utilization of sulphur, in conjunction with seed treatment with liquid biofertilizers, markedly enhanced yield characteristics, including the number of siliquae per plant. This indicates a synergistic effect in sulphur fertilization and biofertilizer treatment on improving mustard productivity.

2.1.3 Effect on nutrient composition, uptake, and quality

Singh and Singh (2007b) executed an experiment conducted in the field in Bichpuri, Agra, to determine the effect of different sulphur sources and concentrations on linseed's productivity, sulphur content, and nutrient absorption (NPS). The oil output was significantly improved with each incremental increase in sulphur up to 60 kg ha-1 and sulphur content, in addition to the overall absorption of nitrogen, phosphorus, and sulphur by the crop. Gypsum demonstrated substantial superiority over alternative sulphur sources in terms of seed and oil yields, as well as nutrient uptake.

A field experiment was performed in Sriniketan, West Bengal, throughout the summer to assess the impact of several sources (phosphogypsum and magnesium sulphate) on sulphur uptake by sesame in red and lateritic soils. The maximum total sulphur uptake was recorded at all sulphur levels when magnesium sulphate was utilized as the source, succeeded by phosphogypsum. An elevation in the concentration of sulphur in the soil compared to the control was noted across all levels and sources of sulphur (Pati *et al.,* 2011b).

The 2012 Kharif season saw the conduct of a field experiment with sesame at the Agronomy Instructional Farm, College of Agriculture, SDAU, Sardarkrushinagar. Applying gypsum as a sulphur source resulted in the maximum nitrogen, phosphorus, potassium, and sulphur content in seed yield and stalk of sesame. Additionally, both the seed and stalk absorbed these nutrients to the greatest extent (Verma *et al.,* 2013).

Yashwant Kumar Singh *et al.,* (2014) tested mustard and found that different amounts of sulphur significantly improved nutrient absorption, yield, and nutritional content. Using gypsum to apply sulphur at a rate of 40 kg ha-1 demonstrated remarkable superiority compared to alternative sulphur sources.

Rakesh and Chandra Banik (2016) executed an experiment in the field of West Bengal and reported that the application of 25 kg S ha^{1} as SSP gave maximum oil content in seeds of mustard. However, S the greatest absorption was seen at 30 kg S ha-1 as Bentonite, but when the dosage increased from 25 to 30 kg ha-1 as SSP, the uptake reduced.

Field experiments were conducted in Faizabad (U.P.) in the Rabi season of 2015-16, revealing that the highest uptake of Using 40 kg of nitrogen, phosphorous, potassium, and sulphur in mustard at 100% of the required dose of fertilizers (RDF) sulphur via SSP, outperforming lower sulphur levels sourced from bentonite and phosphogypsum (Singh *et al.,* 2021b).

Adkine *et al.,* (2017) executed a field experiment at the Agriculture College research farm in Nagpur, revealing that the use of 54 using gypsum to apply kg of sulphur per acre produced the greatest oil content (40.65%) and protein content (19.93%).

The growth, production, quality, and economic viability of mustard were all evaluated according to the results of a field experiment that was carried out to determine the influence of the source and dose of sulphur. Bentonite sulphur at a rate of sixty kilograms per hectare was shown to be much more effective than the other treatments in terms of achieving the highest possible oil content in mustard seeds, according to the data (Banik & Chandra Banik, 2018).

A field experiment shown that the administration of 60 kg S ha-1 via Zypmite and gypsum resulted in elevated nitrogen and sulphur content in both seed and stover, as well as their uptake by mustard seed and stover, in comparison to the control (Chauhan *et al.,* 2020).

Kumar *et al.,* (2018) conducted a field experiment from 2013 to determine the effect that different sources and doses of sulphur have on mustard production and sulphur absorption. The research was conducted from 2013 to 2014 at the Research Farm of the Bihar Agricultural College at Sabour, Bhagalpur. It was disclosed that throughout all growth stages, the sulphur content and its uptake were maximized with bentonite sulphur, greatly surpassing the other two sources of sulphur (gypsum along with iron pyrite).

Parmar *et al.,* (2018b) executed a field experiment in Navsari, Gujarat, during the Rabi season of 2015-16. The highest protein content, oil content, protein yield, and oil yield of sesame were achieved with ammonium sulphate application, which was comparable to gypsum application and superior to elemental sulphur.

Sahoo *et al.,* (2019) performed an experiment on mustard and the findings indicated that the absorption of sulphur with the treatment of 45.0 kg and 60.0 kg S ha- 1 as SSP, 45 kg and 60.5 kg S ha-1 as gypsum, 45 kg, and 60 kg S ha-1 as elemental sulphur were 101.0, 107.7, 90.9, 97.0, 65.10 and 79.01percent greater above control respectively.

Kumar *et al.,* (2018b) a field experiment was carried out in Varanasi with the purpose of determining the effects of different quantities and sources of sulphur on the growth, yield, nitrogen, phosphorus, including sulphur removal, as well as the relative economic viability of farming Indian mustard. The findings of the study demonstrated that the levels of nitrogen, phosphorus, potassium, as well as sulphur in seeds and stalks, as well as their consumption, protein content, and oil content, were much greater when gypsum was present application compared to iron pyrite and elemental sulphur.

R. Singh *et al.,* (2020) examined the impact of sulphur and boron fertilizers on the yield and quality of rapeseed in subtropical acidic soil conditions. The results indicated that sulphur application significantly improved seed production, oil content, and nutrient uptake efficiency. The concurrent administration of sulphur and boron enhanced these parameters, demonstrating a synergistic effect on rapeseed quality and yield.

A field experiment was carried out during rabi 2020 at an investigation was conducted at the Rajasthan College of Agriculture in Udaipur to investigate the impact of different sources and quantities of sulphur on the nutritional content and absorption of Indian mustard, scientifically known as Brassica juncea (L.) Czern and Coss. According to the findings of the experiment, the sources of sulphur have a considerable impact on the amount of nitrogen, phosphorus, potassium, and sulphur that plants take in. Mustard was shown to have a much higher absorption of nitrogen, phosphorus, potassium, and sulphur when it was treated with bentonite sulphur, which was superior to the control (Tiwari *et al.,*2021).

Singh *et al.,* (2023) evaluated the effects of varying amounts of sulphur and zinc on mustard, a plant closely related to rapeseed. The study demonstrated indicated the use of sixty kg of sulphur per hectare considerably enhanced output and quality parameters, including oil content and nutrient uptake. The research focused on mustard, yet the results are relevant to rapeseed because of the similarities between the two crops. Thakur *et al.,* (2024) a field experiment was carried out in the highlands of Himachal Pradesh with the purpose of determined the impact that the application of nitrogen and sulphur had on the yield of rapeseed and its ability to absorb nutrients. The findings of the study demonstrated that the simultaneous application of nitrogen and sulphur resulted in a considerable increase in seed production, oil content, and the uptake of nitrogen, phosphorus, and sulphur by the crop. Optimal outcomes were achieved with the application of 80 kg N ha^{1} and 40 kg S ha^{1}, leading to improved nutritional composition and overall quality of the rapeseed.

2.1.4 Effect on soil fertility

Kaya *et al.,* (2009) conducted experiments and reported that the application of elemental sulphur and sulphur-containing trash led to a reduction in soil pH, while generally increasing nutrient concentrations for plants and enhancing the residual accessible nutrient concentration in the experimental soils.

The findings of Makoi and Verplancke (2010) indicated that Na (exchangeable sodium), EC (electrical conductivity of the saturated paste), SAR (sodium absorption ratio), ESP (exchangeable sodium percentage), and AWC (available water capacity) were significantly enhanced ($P \leq 0.05$). Despite the application of gypsum resulting in a gradual reduction of Ks (hydraulic conductivity), it did not entirely reverse the drop, perhaps due to intense storms causing compaction and/or an equilibrium between Ca2+ and Mg2+ ions in the soil matrix.

Jhansy *et al.,* (2013) conducted a pot culture experiment at the Saline Water Scheme farms in Bapatla, utilizing gypsum, pyrite, farmyard manure, press mud cake, and aluminium sulphate to mitigate the adverse impacts of RSC fluids on the soil's physicochemical qualities. The results demonstrated a decrease in soil pH, electrical conductivity (ECe), and exchangeable sodium percentage (ESP), alongside an increase in available nitrogen (N), phosphorus pentoxide (P2O5), and potassium oxide (K2O) following the application of various soil amendments. Gypsum was determined to be more effective than pyrites, farmyard manure, press mud cake, and aluminium sulphate in mitigating the detrimental impact of sodic fluids on soil characteristics.

Singh and Singh (2014) experimented to investigate the enhancement of micronutrients and chemical characteristics in gypsum-amended soils. The use of gypsum markedly enhanced the soil's chemical characteristics by decreasing the electrical conductivity and pH levels.

Saini *et al.,* (2015) conducted a field experiment at the Agronomy Instructional Farm, College of Agriculture, SDAU, Sardarkrushi Nagar during Kharif 2012 on sesame. The results indicated that the application of gypsum as a source of sulphur at 60 kg ha-1 enhanced the available sulphur status in the soil post-harvest. The nitrogen and phosphorus levels in the soil post-harvest remained constant despite varying sources of sulphur.

Abhiram (2016) investigated the impact of various sulphur sources (elemental sulphur, ammonium sulphate, and gypsum) and application rates (10, 20, and 30 kg ha- 1) on alterations in soil properties and the status of primary and secondary nutrients in maize cultivation, finding no significant changes in soil pH and electrical conductivity values.

Deekshitha *et al.,* (2017) documented that the concentrations of available sulphur, zinc, iron, manganese, and copper in soil significantly elevated following the application of higher doses of these nutrients, and the incorporation of gypsum at 4 t ha-1 enhanced iron availability and augmented manganese levels in the soil.

The research was undertaken by Meena, *et al.,* (2017a) at the Agriculture Research Farm, BHU, Varanasi, during the rabi season of 2015-16. The research offers significant insights into the impact of land layout and sulphur application on soil characteristics in mustard farming. The results demonstrate that various field layouts affected soil moisture retention and aeration, with furrow sowing being the most successful method for sustaining optimal soil conditions for plant growth. The enhanced soil structure in furrow-sown plots likely facilitated superior root development, nutrient absorption, and overall crop efficacy. The application of sulphur significantly influenced soil characteristics. The application of 40 kg S ha^1 increases soil fertility by increasing sulphur availability, crucial for protein synthesis and oil production in mustard. Elevated sulphur concentrations enhanced microbial activity and optimized nutrient cycling, hence augmenting soil health and promoting plant development. Nonetheless, the study lacks long-term data on soil sulphur balance, which may be essential for sustainable nutrient management.

Singh *et al.,* (2017b) executed an experiment at Meerut on green gram, and the results revealed that the pH of the soil had a tendency to decline as the amount of sulphur in the soil increased, and gypsum was more efficient than elemental sulphur in lowering the pH of the soil. There was not a major impact on the available nutrients in the soil (nitrogen, phosphorus, potassium, and sulphur) after the crop was harvested because of the presence of sources of sulphur. On the other hand, a larger accumulation of these nutrients in the soil was seen when sulphur levels were as high as gypsum.

Rashmi *et al.,* (2018) indicated that gypsum is the most economical and readily accessible solution for addressing sulphur shortage and enhancing the physico- chemical properties of soil. Gypsum is a fairly soluble source of vital plant minerals, calcium, and sulphur, which can enhance overall plant growth. Gypsum enhances the physical and chemical characteristics of soils and mitigates soil erosion and nutrient loss, particularly phosphorus, in surface water runoff.

Kumar *et al.,* (2019) a field experiment was carried out in the state of Bihar with the purpose of determining the effect that different sources of sulphur, such as phosphogypsum and control, have on the yield of mustard as well as its economics. They made the discovery that the application of bentonite as a source of sulphur, in conjunction with the proper dose of nitrogen, phosphorus, and potassium, led to the maximum level of accessible sulphur in the soil after mustard was harvested.

2.1.5 Effect on economics

Kumar *et al.,* (2017) a field experiment was carried out in order to investigate the influence that the source of sulphur and the dose of sulphur have on the growth, production, quality, and economics of mustard. Based on the data, it was determined that the highest net yields for mustard were obtained by applying bentonite sulphur at a rate of sixty kilograms per hectare. This was significantly higher than the other treatments.

Kumar *et al.,* (2018) conducted field trials in Varanasi. Experimental findings indicated that the optimal gross return, net returns, and benefit-to-cost ratio for mustard were achieved with the application of elemental sulphur at 60 kg ha-1. A field experiment done by Parmar *et al.,* (2018) in Navsari, Gujarat, revealed that the highest net returns and benefit-to-cost ratio for sesame were observed in plots treated with ammonium sulphate.

Kumar *et al.,* (2019) a field experiment was carried out in the state of Bihar with the purpose of determining the influence that different sources of sulphur (Phosphogypsum, Bentonite, and Control) had on the yield of mustard and its economic feasibility. The researchers came to the conclusion that the utilization of bentonite as a source of sulphur, in conjunction with the necessary dose of nitrogen, phosphorus, and potassium, led to the highest net returns as well as benefit-to-cost ratio for mustard.

2.2 Effect of hydrogel:

2.2.1 Effect on Growth Attributes

Rehman (2011) observed in Pakistan that the hydrogel application in practice increased levels of soil moisture across all three planting strategies (flat, ridge, as well as bed) in contrast to soil that did not include hydrogel. Hydrogel-amended soil facilitated superior germination and enhanced stand establishment of rice across all planting tactics compared to soil without hydrogel.

Dar *et al.,* (2017) executed a field experiment in Ludhiana and noted a considerably increased tillering per plant in wheat resulting from hydrogel application at a rate of 2.5 kg/ha.

Singh *et al.,* (2017) conducted a field experiment at the G.B. Pant University of Agriculture and Technology in Pantnagar, which revealed that the application of hydrogel affected the height of the plant, the accumulation of dry matter, and the number of primary as well as secondary branches of Indian mustard. The application of five kilograms of hydrogel per acre resulted in a considerable increase in plant height as well as the buildup of dry matter in the absence of hydrogel application.

The findings of a field A study conducted at the Agricultural Research Farm of Banaras Hindu University in Varanasi, Uttar Pradesh, revealed that the crop with the highest growth rate, relative to the other crops, was the one that growth rate, and leaf area index of wheat were achieved with the application of 7.5 kg hydrogel per hectare (Singh and Singh, *et al.,* 2017c).

Saini *et al.,* (2018) determined that the highest in comparison to the control, the application of hydrogel at a rate of 5 kg/ha resulted in an increase in plant height along with dry matter production during the following development stages of the pearl millet group. Chaithra and Sridhara (2018) documented that the soil application of Pusa hydrogel at 5.0 kg/ha in Hiriyur (Karnataka) considerably enhanced growth parameters such as Leaf Area Index (LAI), average Absolute Growth Rate (AGR), and average Crop Growth Rate (CGR) of maize compared to the suggested package of measures.

The results of a field experiment conducted by Jat *et al.,* (2018a) at Sardarkrushinagar, Gujarat, demonstrated that increased levels of hydrogel exhibited a positive impact on the growth properties of mustard. Both the highest plant height and the greatest number of main branches per mustard plant were seen in plots that were treated with 5.0 kg of hydrogel per hectare, in comparison to the control group.

Ram *et al.,* (2018a) studied at the Agricultural Research Station in Kota, which is located in the state of Rajasthan. According to the findings of the experiments, the application of hydrogel at a rate of 5.0 kg/ha prior to sowing resulted in the maximum plant height and number of branches per plant in lentil. This was superior to both the control and the application of hydrogel at a rate of 2.5 kg/ha.

Kumar *et al.,* (2019a) a field experiment was carried out at Rari Durgapura (Jaipur), and the results showed that the application of 2.5 kilogrammes per hectare of

Pusa hydrogel resulted in a considerable increase in plant height (89.16 centimeters at harvest) as well as dry matter accumulation (261.77, 671.30, as well as 1134.61 g/m2 at 60, 90 days after sowing, and at harvest, respectively) of wheat.

Trisha Roy (2019) conducted a study in Dehradun on the effects of hydrogel treatment on rain-fed wheat, noting a substantial enhancement in yield characteristics and overall yield in fields treated with hydrogel compared to those without it.

A field experiment conducted by R. S. Meena *et al.,* (2020a) in Varanasi revealed that the application of hydrogel at 5.0 kg/ha significantly enhanced plant height, branch count, leaf area index, and dry matter accumulation in Indian mustard compared to the control group.

B. S. Meena *et al.,* (2020) conducted a field experiment at ARS, Kota, and found that the application of hydrogel at 5.0 kg/ha, combined with two sprays of salicylic acid at 200 ppm during the flowering and siliqua formation stages, resulted in significantly greater Indian mustard is characterized by its height, the number of branches it has, and the buildup of dry substance.

Naik *et al.,* (2020a) conducted a study in Hiriyur, Karnataka, which demonstrated that the treatment utilizing a soil application of 100% of the recommended hydrogel dosage resulted in significantly greater plant height (106 cm) and branch count (3.4) in castor compared to other treatments.

A field experiment that was carried out at the Research Farm of Central Agricultural University in Imphal demonstrated that the treatment that consisted of a basal application of 2.5 kg/ha of hydrogel, in conjunction with a foliar application of thiourea at a concentration of 0.05% twice during the 50% flowering and 50% pod formation stages, led to plants that were taller, accumulated more dry matter, as well as had a higher leaf area index (LAI) thereby exhibiting marked superiority over the other treatments. (Singh & Singh, 2020)

Yadav *et al.,* (2020a) indicated that the soil application of Pusa hydrogel markedly enhanced the height of the plant and the amount of dry matter that accumulates in pearl millet at different phases of its growth attributable to improved moisture retention and prolonged availability to the crop.

Choudhary (2021) performed a field experiment at ICAR-Directorate of Rapeseed-Mustard Research, Bharatpur, to assess the effectiveness of the superabsorbent polymer (Pusa hydrogel) in the field and the application rates at which it is used under both moisture stress and normal moisture circumstances on mustard. The findings indicated that the application of Pusa hydrogel at 5.0 kg/ha yielded the greatest plant height at harvest, as well as a superior number of primary and secondary branches of mustard, greatly surpassing the control group.

Priyanka Kumawat (2021) from Jobner stated that the application of hydrogel at an application of 5.0 kg/ha, in conjunction with two sprays of salicylic acid at a concentration of 100 ppm, was carried out during the blossoming and siliqua development stages significantly greater plant height and an increased number of primary and secondary branches in taramira.

The function of SAP in drought-stressed peas (Pisum sativum L.) was examined by Fatima et al., in 2021. The application of 0.2% SAP improved soil moisture and decreased evapotranspiration losses while increasing shoot biomass, pod number, and seed weight. According to the study's findings, SAP improves production characteristics and water retention by acting as a soil conditioner, which helps water-limited systems remain economically viable.

Hydrogel and salicylic acid were assessed for their impact on the growth and yield of rainfed Indian mustard (*Brassica juncea* L.) in Varanasi during the Rabi season of 2017-18. Hydrogel at 5 kg/ha and salicylic acid at 200 ppm improved plant growth, yield, and productivity compared to the control group. This intervention improved plant height, branch count, and dry biomass. The quantity of siliquae per plant and seed output was positively affected. The research demonstrated that hydrogel and salicylic acid improved the growth and yield of rainfed Indian mustard. Mahto *et al.,* (2023).

The impact of SAP on green beans (*Phaseolus vulgaris* L.) at two irrigation levels—50% and 75% of crop water requirement—was assessed by Alharbi *et al.,* in 2024. When SAP was applied, proline buildup and oxidative stress markers decreased while shoot and root dry matter, chlorophyll content, and leaf water status rose. To achieve higher yields under drought stress, the study verified that SAP enhanced growth, hydration status, and physiological performance.

2.2.2 Effect on yield attributes and yield

Singh (2012) conducted a field experiment at the Agricultural Research Station, Fatehpur-Shekhawati (Rajasthan). They observed that the largest increase in the number of effective tillers per plant, ear length, grain weight per ear per head, and test weight was recorded with seed coating by 20 g of hydrogel. This was done in order to explore the influence of hydrogel on yield and water usage efficiency in pearl millet. Thiourea + Dimethyl Sulphoxide were found significantly superior over the control.

Dass *et al.,* (2013), an experiment was carried out in New Delhi using sandy-loamy soil, and the results showed that the application of Pusa hydrogel at a rate of 5 kilograms per hectare increased the production of sorghum fodder by 14.5% in comparison to the control setting.

Tyagi *et al.,* (2015a) carried out a field experiment at BHU, Varanasi and experimental results showed that maximum number of effective tillers /plants, grains, grain yield, straw yield and biological yield of wheat was recorded with 100% NPK + 5 kg hydrogel /ha followed by 100% NPK + 2.5 kg hydrogel /ha than lower rates of NPK with or without hydrogel.

Gaikwad *et al.,* (2017) from Akola reported demonstrated the application of hydrogel at a rate of 2.5 kilograms per hectare with 100% RDF was considerably increased 100 seed wt. (4.33 g) and yield of seed (1241 kg /ha) of sunflower crop over the control.

Singh *et al.,* (2017) did a field study at Banaras Hindu University in Varanasi, Uttar Pradesh, and they discovered that the application of 7.5 kg hydrogel per hectare resulted in the maximum grain, straw, as well as biological yield of wheat. This was the case when the researchers applied the hydrogel.

Singh *et al.,* (2018) at Pantnagar observed substantial variations in several siliquae per plant, 1000-seed weight, and seed production of Indian mustard attributable to hydrogel application. The application of 5.0 kg of hydrogel per hectare yielded the maximum number of siliquae per plant, 1000 seed weight, and seed production in India.

Jat *et al.,* (2018) executed a field experiment in Sardarkrushinagar, Gujarat, and Singh *et al.,* (2017) did a field study at Banaras Hindu University in Varanasi, Uttar Pradesh, and they discovered that the application of 7.5 kg hydrogel per hectare resulted in the maximum grain, straw, as well as biological yield of wheat. This was the case when the researchers applied the hydrogel levels of these metrics.

In Hiriyur (Karnataka), the application of Pusa hydrogel at 5.0 kg/ha to maize considerably enhanced yield parameters, including cob length, cob girth, kernel count, 100-grain weight, and both kernel and stover yield (GM Chaithra and S Sridhara, 2018).

A field experiment was executed at the Agricultural Research Station of the

Agriculture University in Kota, Rajasthan. The results indicated that the application of hydrogel at 5.0 kg/ha before to sowing produced significantly greater pod count per plant (66.5), seeds per pod, and grain yield (1210 kg/ha) of lentil compared to the control and the application of hydrogel at 2.5 kg/ha (Ram *et al.,* 2018b).

Bharat *et al.,* (2019a) executed an experiment in order to explore the effects of irrigation schedule and hydrogel application on Indian mustard (*Brassica juncea* L.). The experiment was conducted in Jammu that was conducted. When compared to the control and alternative treatments, the application of hydrogel resulted in a significant improvement in the yield characteristics as well as the overall yield of Indian mustard. The application of hydrogel at a rate of 5.0 kg per hectare led to the maximum number of seeds produced by Indian mustard, as well as the highest number of seeds produced per siliqua from each plant.

Kumar *et al.,* (2019b) at Durgapura found that the application of Pusa hydrogel resulted in the highest number of ear heads per square meter, spike length, number of grains per, ear, test weight, and yields of grain, straw, and biological yield of wheat compared to the control group without hydrogel.

A field trial in Bihar showed that a hydrogel application of 2.5 kg/ha yielded the maximum measurements for all studied parameters, including spikes/m^2, grains/ear, grain yield, and biological yield of wheat (Pal, 2019).

Shivakumar *et al.,* (2019) in order to evaluate the effects of hydrogel and mulching on the yield, yield characteristics, as well as economic viability of maize (Zea mays L.), a field experiment was conducted on sandy soil. The study demonstrated that the highest number of grains per cob, as well as cob, grain, and stover yields, were achieved with the application of hydrogel at 2.5 kg/ha.

Meena *et al.,* (2020) The application of hydrogel at a rate of 5.0 kg/ha resulted in a considerable increase in the number of siliqua per plant (312.80), the number of seeds per siliqua (12.77), the test weight (4.89), the seed yield, the stover yield, and the biological yield. This information was reported from Varanasi (1721, 5416, and 7136 kg/ha, respectively) of Indian mustard compared to the control group.

B. S. Meena *et al.,* (2020) executed a field experiment at ARS, Kota, revealing that the application of hydrogel at 5.0 kg/ha, Both the number of siliquae per plant (236.67), the number of seeds per siliqua (16.23), the weight of 1000 seeds (5.47 g), and the seed yield (2651.89 kg/ha) of mustard were greatly increased when coupled with two sprays of salicylic acid at a concentration of 200 parts per million throughout the blooming and siliqua formation stages.

Naik *et al.,* (2020) conducted a field trial in Hiriyur, Karnataka, and discovered substantial differences in the yield characteristics and yield of castor under several hydrogel treatments. Data indicated that the highest maximum number of spikes per plant, primary spike length, number of capsules per spike, and seed production of castor were observed with the administration of 100% of the approved amount of hydrogel, in comparison to other treatments.

In Gujarat, the application of hydrogel at 5.0 kg/ha to pearl millet considerably enhanced yield parameters, including the number of ear heads (15.34 per meter row), ear head girth (11.24 cm), ear head length (23.27 cm), grain weight per ear head (12.65 g), and 1000-grain weight (13.02 g). Consequently, there was a markedly superior grain and stover production of pearl millet compared to the other treatments (Saini *et al.,* 2018).

Singh and Singh (2020) conducted an experiment conducted in the field at the Research Farm of the Central Agricultural University in Imphal and reported that the maximum seed yield (1416.3 kg/ha) and productivity efficiency (45.5 kg/ha/day) were achieved in the treatment that received 100% RFD, 2.5 kg/ha of hydrogel, and 0.05% thiourea at 50% flowering and 50% siliqua formation.

S. K. Yadav *et al.,* (2020b) conducted an experiment on pearl millet and reported that the soil application of Pusa hydrogel significantly enhanced effective tillers per plant, number of grains per ear, ear length, test weight, and grain yield compared to the control group. The increase in grain yield was 21.04 percent compared to the control group.

A field experiment was carried out at Agronomy Farm, S.K.N. College for the purpose of determining the effect that hydrogel and salicylic acid have on the production and profitability of taramira, Jobner Agriculture will conduct an investigation during the rabi season of 2019-20. The results of the study showed that the application of hydrogel at a rate of 5.0 kg/ha, in conjunction with two applications of salicylic acid at a concentration of 100 ppm, during the blooming and siliqua formation stages, led to the highest number of siliqua per plant (133.20), seeds per siliqua (19.47), test weight (3.97 g), and seed yield (12.39 q/ha) of taramira. The application of hydrogel at a rate of 5.0 kg/ha in conjunction with salicylic acid at a concentration of 75 ppm throughout the blooming and maintenance stages was statistically equivalent to this treatment's siliqua production periods (Priyanka Kumawat, 2021).

Banjara and Pallavi (2022) indicated that the use of hydrogel at 5.0 kg/ha prior to planting in chickpeas resulted in considerably enhanced seed production and stover output in Raipur.

In a field experiment that was carried out by Choudhary *et al.,* (2023) at the ICAR-Directorate of Rapeseed-Mustard Research in Bharatpur, the researchers discovered that the application of Pusa hydrogel at a rate of 5.0 kg/ha resulted in the highest number of siliquae, length of siliqua, number of seeds per siliquae, seed yield, and stover yield of mustard. This was significantly higher than the control group.

A field experiment done by Koushal *et al.,* (2024) in the Rabi season of 2022–2023 in the selected villages of KVK, Katra Block, Reasi district, Jammu region, assessed the effects of irrigation levels and moisture conservation methods on the growth and production of wheat (*Triticum aestivum* L.). The findings demonstrated that heightened irrigation frequency markedly enhanced wheat production and biomass accumulation. Wheat getting five irrigations achieved the maximum grain and straw yield, exceeding the yields from the three-irrigation and one-irrigation treatments. Similarly, the straw yield augmented by 5.84 q/ha and 26.65 q/ha with three and five irrigations, respectively, in comparison to one irrigation. Moisture conservation measures significantly contributed to production improvement. The utilization of Pusa hydrogel at 5 kg/ha in conjunction with farmyard manure at 2.5 t/ha led to a 31.0% enhancement in dry matter production per hectare and a 38.4% rise in grain yield relative to the control group. This indicates that the use of hydrogel and organic amendments can significantly improve soil moisture retention, resulting in increased wheat productivity.

2.2.3 Effect on nutrient content, uptake, and quality

Tyagi *et al.,* (2015b) an experiment was carried out in the field at BHU, Varanasi, which revealed a considerable increase in the amount of nitrogen, phosphorus, and potassium that wheat grain and straw were able to absorb. As a result of the application of 100% NPK in conjunction with 5 kilogram of hydrogel per hectare, the highest values were recorded. This was followed by the application of 100% NPK in conjunction with 2.5 kg of hydrogel per hectare, compared to lower rates of NPK with or without hydrogel.

The study conducted at Research Farm, Central Agricultural University, Imphal, reveals that plots treated with 100% RFD, 2.5 kg/ha of hydrogel, and 0.05% thiourea at the 50% during the blooming and 50% siliqua development phases, the seed and stover of

Indian mustard exhibited considerably increased levels of oil content, protein content, as well as nitrogen, phosphorus, and potassium absorption (A. Singh *et al.,* 2016).

A field experiment was carried out by S. P. Singh and colleagues (2017) during the Rabi season at the Agricultural Research Farm of Banaras Hindu University in Varanasi, Uttar Pradesh. The purpose of the experiment was to investigate the effects of various irrigation schedules and strategies for moisture conservation on wheat (*Triticum aestivum* L.). According to the findings, the usage of hydrogel at a rate of 7.5 kg per hectare resulted in a considerable improvement in the uptake of nitrogen, phosphate, as well as potassium in the grain and straw of wheat in comparison to other treatments.

The increase in nutrient intake was attributed to enhanced soil moisture retention and availability, leading to improved nutrient absorption by the plants.

Bana *et al.,* (2018) conducted an experiment in Delhi on wheat, revealing that the application of hydrogel at 2.5 kg/ha under guaranteed irrigation significantly enhanced the concentrations of N, P, and K in both grain and straw, as well as the total uptake of N, P, and K compared to the control group.

Dujeshwar and Singh (2018) noted that the A furrow application of hydrogel at 5 kg/ha, in conjunction with seeds that had been treated with Trichoderma, led to a significantly higher protein content (21.91%), protein yield (322.2 kg/ha), along with oil yield (603.7 kg/ha) in linseed. This was comparable to the method of seed soaking in hydrogel at 5 kg/ha, followed by seed treatment with Trichoderma at 10 g/kg.

Jat *et al.,* (2018c) executed a field trial in Sardarkrushi Nagar, Gujarat, they stated that the application of hydrogel at a rate of 5.0 kg/ha resulted in the highest oil yield as well as water productivity of mustard in comparison to the control group.

Bharat *et al.,* (2019b) conducted field studies in Jammu, revealing that the highest oil output and total water usage of Indian mustard occurred with the application of hydrogel at 5.0 kg/ha, in contrast to the absence of hydrogel application.

R. S. Meena *et al.,* (2020b) In order to evaluate the effects of hydrogel and mulching on the absorption of nitrogen, phosphorus, and potassium by maize, an experiment was carried out. They discovered that the application of hydrogel to the soil at a rate of 2.5 kilogrammes per hectare led to the highest accumulation of nitrogen, phosphorus, and potassium, significantly outperforming other treatments.

In a study at BHU, Varanasi, B. S. Meena *et al.,* (2020) shown that the application of hydrogel at 5.0 kg/ha significantly enhanced protein content (22.04%), When compared to the control group, the level of oil content (37.16%), oil yield (658 kg/ha), as well as protein production (390.36 kg/ha) of Indian mustard were significantly higher.

The findings of a field experiment conducted at ARS, Kota indicated that the protein content, protein yield, oil content, and oil yield of Indian mustard were maximized with the application of hydrogel at 5.0 kg/ha, supplemented by two sprays of salicylic acid at 200 ppm during the flowering and siliqua formation stages (B. S. Meena *et al.,* 2020).

An investigation on pearl millet indicated that the soil application of Pusa hydrogel results in the largest accumulation of nitrogen, phosphorus, and potassium in both grain and straw, as well as the total uptake of these nutrients by pearl millet. (S. K. Yadav *et al.,* 2020b)

2.2.4 Effect on economics

A field study was carried out by Jat *et al.,* (2018b) in Sardarkrushi Nagar, Gujarat, and the experimental findings showed that the application of hydrogel at 5.0 kg /ha produced maximum monetary returns, production efficiency, and economic efficiency of mustard.

From the results obtained by (Ram *et al.,*2018a) at Agricultural Research Station, Kota (Rajasthan), significant variation was observed for the net returns and B: C ratio of lentils due to the application of different hydrogel levels. The highest values of these parameters were recorded by drilling hydrogel at 5.0 kg /ha before sowing.

In order to determine the impact that restricted and appropriate irrigation as well as moisture conservation methods (rice straw mulch and hydrogel) have on the yield, water usage efficiency, as well as economics of wheat, a field experiment was carried out. According to Singh *et al.,* (2018), the findings of the experiment demonstrated that the application of 7.5 kg of hydrogel per hectare resulted in the highest amounts of net returns and the highest B:C ratio of wheat.

Saini *et al.,* (2018) the maximum net return (Rs 66011 /ha) and benefit: cost ratio (1.53) was recorded with the application of 5.0 percent hydrogel, according to the results of a field experiment that was performed in Gujarat to investigate the impact of irrigation, fertility, and hydrogel levels on yield and yield characteristics of summer pearl millet kg hydrogel /ha.

Bharat *et al.,* (2019c) at Jammu, reported that the application of hydrogel had a

There was a considerable impact on the gross returns, net returns, and B: C ratio of Indian mustard, and the application of hydrogel at a rate of 5.0 kg/ha resulted in the highest possible values of these parameters in the comparison of no application of hydrogel.

Kumar *et al.,* (2019c) at Durgapura reported that following the application of herbal hydrogel, the B: C ratio of wheat was found to be at its highest point, which was 1.62 @ 400 ml 100 /kg seed followed by hydrogel whereas, the maximum gross and net returns of wheat was obtained with the application of Pusa Hydrogel @ 2.5 kg /ha.

A trial was conducted by Pal (2019b) to evaluate the appropriate dose of hydrogel for getting a better yield of wheat in Rohtas district of Bihar. The economic analysis of the findings reflected that the highest B: C ratio was recorded with the application of 2.5 kg /ha hydrogel.

In order to investigate the effects of hydrogel application on the growth, yield, and economics of rainfed castor, a field experiment was carried out at the Zonal Agricultural and Horticultural Research Station, which is located at Babbur Farm in Hiriyur, Karnataka. According to the findings, the application of hydrogel to the soil at a dose of one hundred percent of the prescribed amount resulted in the highest gross return, net return, as well as the B: C ratio of castor (Naik *et al.,* 2020).

The application of hydrogel at a rate of 5.0 kg per hectare resulted in considerably higher net returns and B: C ratios of Indian mustard when compared with the control treatment, according to the findings of a field trial that was carried Varanasi (Meena *et al.,* 2020a).

According to Meena *et al.,* (2020 b), the application of hydrogel at a rate of 5 kilograms per hectare in conjunction with two sprays of salicylic acid at a concentration of 200 parts per million throughout the flowering and siliqua formation stages resulted in a considerable increase in the gross return (Rs 1,13,404 /ha) and net return (Rs 82,818 /ha) of Indian mustard in comparison to the control treatment.

According to the findings of a field study that Singh and Singh (2020) carried out at the Research Farm of Central Agricultural University in Imphal, the highest net return (Rs 22,288/ha), economic efficiency (Rs 184.7/ha/day), as well as favorable benefit-to-cost ratio (0.75) for Indian mustard were achieved with the application of 100% recommended fertilizer dose plus 2.5 kg hydrogel/ha. This was followed by the application of 0.05% thiourea at 50% flowering and 50% pod formation.

Kumawat *et al.,* (2021) carried out a field experiment at Jobner, which revealed that the application of hydrogel at a rate of 5.0 kg/ha in conjunction with salicylic acid at a concentration of 100 ppm during the flowering and siliqua formation stages produced results that were comparable to the application of hydrogel at a rate of 5.0 kg/ha in conjunction with salicylic acid at a concentration of 75 ppm during the same stages. Both methods achieved higher gross returns alongside net returns (Rs 47,082 and Rs 29,202/ha, respectively) for taramira.

2.3 Effect of salicylic acid:

2.3.1 Effect on Growth Attributes

The application of salicylic acid led to significant increases in vegetative growth characteristics such as plant height, leaf area, leaf area index, dry weight, crop growth rate, and net assimilation rate except for the plant height of pearl millet, which significantly reduced with increasing salicylic acid concentration (Nishi Mathur, 2007).

Kakhki *et al.,* (2013) observed that the greatest plant height of the mustard crop was obtained from the application of 200 ppm SA. The maximum photosynthetic amount and membrane stability index (MSI) were observed where 100 ppm of SA was applied.

Sharma *et al.,* (2018) from Faizabad reported that the application of salicylic acid to the mustard crop significantly improved plant height (156.81 cm), number of branches /plant (35.83), and chlorophyll content at 60 and 90 DAS.

Sruthi *et al.,* (2020) experimented at field of Allahabad. They reported the foliar spray of 1% DAP and 100 ppm salicylic acid was applied twice, 25 and 45 days after sowing. The results showed that the plant reached its maximum height of 33.48 centimeters and accumulated 82.47 grams of dry matter per square meter green gram.

Merinda Wangkheirakpam (2020) investigated no-tilled rapeseed (*Brassica campestris*) in rainfed conditions and discovered that foliar application of salicylic acid markedly improved plant height, leaf area, and dry matter accumulation. The ideal concentration was established at 100 ppm, enhancing vegetative growth metrics relative to the control group.

Vishnu *et al.,* (2021a) The results of a field experiment that was carried out in Allahabad revealed that the application of 150 parts per million of salicylic acid at 25 and 45 days after planting resulted in the largest plant height, number of nodules per pod, as well as the dry weight of green gram after the trial was completed.

González-Villagra *et al.,* (2022) studied the effect of salicylic acid on *Aristotelia chilensis* under moderate drought stress (60% field capacity). SA application increased plant growth by 13.5%, restored photosynthetic rate (by 41.9%) and stomatal conductance (by 40.7%), and enhanced SOD and APX activities by 85% and 60%, respectively. It also improved phenolic content and antioxidant capacity, indicating strengthened oxidative defense and improved drought tolerance.

Rundla *et al.,* (2022) study demonstrate that the foliar application of 200 ppm salicylic acid during flower initiation and full bloom stages markedly improved plant height, dry matter accumulation, branch count, leaf area index (LAI), crop growth rate (CGR), relative growth rate (RGR), net assimilation rate (NAR), and leaf area duration (LAD).

Kamboj *et al.,* (2023a) executed a field experiment to evaluate the effects of salicylic acid and thiourea on Indian mustard (*Brassica juncea*) under conditions of moisture stress. The research demonstrated that foliar treatment of salicylic acid markedly increased plant height, branch quantity, leaf area index, and dry matter accumulation at harvest. The highest measured plant height was 133.33 cm, accompanied by significant enhancements in all growth metrics relative to the control group.

Salicylic acid's impact on *Brassica napus* L.'s ability to withstand drought and salt was investigated by Ali *et al.,* in 2023. According to the findings, applying SA under stress enhanced the amount of chlorophyll, photosynthetic rate, relative water content (RWC), and biomass of roots and shoots. When compared to untreated controls, the SA-treated plants displayed reduced buildup of malondialdehyde (MDA) and improved membrane stability. This study showed that SA improves growth and output under stress by bolstering photosynthetic and antioxidant defense systems in rapeseed, hence mitigating combined drought and salinity stress.

Awadalla *et al.,* (2024) evaluated eight wheat genotypes under normal and drought conditions with or without salicylic acid (SA) application. Drought reduced relative water content and chlorophyll while increasing membrane leakage, but SA improved osmolyte accumulation, antioxidant activity, and water regulation. The SA-treated drought-stressed plants (DSA) showed enhanced drought tolerance, especially in genotypes IPK_046 and WAS_031. The study concluded that SA effectively mitigates drought-induced damage, improving physiological and biochemical resilience in *Triticum aestivum*.

Guin *et al.,* (2024) assessed the synergistic effects of manganese and salicylic acid on Indian mustard in a separate study. The external application of 0.5 mM manganese combined with 150 ppm salicylic acid led to a 10.83% enhancement in plant height, a 49.6% augmentation in total dry matter, and a 51.61% rise in chlorophyll content compared to the control group. The data indicate a synergistic effect of manganese and salicylic acid on growth dynamics.

2.3.2Effect on yield attributes and yield

The findings of Muhal *et al.,* (2014a) in Udaipur indicated that the use of a 100-ppm salicylic acid foliar spray yielded the highest seed, stover, and biological yields of mustard compared to water spray.

Abdel-Lattif (2019) experimented to evaluate the impact of salicylic acid on enhancing wheat productivity. The results indicated that the application of 100 mg/L of salicylic acid to wheat considerably enhanced grain yield in comparison to the control group.

Sruthi *et al.,* (2020) conducted a field experiment in Allahabad and reported that foliar spraying with 1% DAP and 100 ppm salicylic acid twice at twenty-five and forty-five days after sowing saw the highest number of pods per plant (55.60), the highest number of grains per pod (9.93), the highest test weight (36.84), the highest grain yield (855.55 kg/ha), and the highest stover yield (2233.33 kg/ha) of green gram.

A field experiment was carried out by Vishnu *et al.,* (2021b) at Allahabad and they found that the application of 150 ppm salicylic acid at 25 and 45 DAS recorded a maximum number of seeds per pod (10.64), The harvest index was 38.98%, the number of pods produced by each plant was 38.04, the seed yield was 1346.67 kg/ha, and the stover output was 2143.33 kg/ha of green gram.

Meena *et al.,* (2020) assessed the synergistic effects of hydrogel and SA on Indian mustard under limited watering conditions. The research demonstrated that a foliar spray of 100 ppm salicylic acid, in conjunction with hydrogel treatment, markedly enhanced the number of siliquae per plant, seeds per siliqua, and 1000-seed weight, resulting in superior seed and stover yields relative to the control group.

The research undertaken by Dharm Singh Meena (2023) at the Vivekananda Global University Research Farm. A study was conducted during the rabi season of 2022-23 with the purpose of determining the effect that foliar sprays containing thiourea and salicylic acid had on the growth and yield of Taramira. The results showed that there were significant improvements in yield measures, such as test weight, grain yield, as well as straw yield, following foliar treatments. The simultaneous application of thiourea at 50% flowering and pod formation (500 ppm) yielded the most significant advantages, leading to the biggest enhancements in plant height, dry matter accumulation, and yield-related characteristics. This treatment resulted in the highest seed production, stover yield, and biological yield. This study indicates that the foliar application of thiourea and salicylic acid can markedly improve the growth and productivity of Taramira, with thiourea application being the most efficacious treatment for optimizing yield and growth characteristics.

Kamboj *et al.,* (2023b) reported that the implementation of SA resulted in substantial enhancements in yield attributes. The treatment produced superior seed yield (2213.33 kg/ha), stover output (5980.00 kg/ha), and harvest index (27.01%) relative to the control group.

In a study that was carried out by Guin *et al.,* (2024), the researchers investigated the effects of varying amounts of salicylic acid (SA) and manganese (Mn) on the growth, yield, and quality of mustard. Based on the data, it was determined that the concurrent application of 0.5 mM manganese and 150 ppm salicylic acid resulted in significant improvements in yield metrics. Through the use of this treatment, the grain yield was increased by 41.26%, and the stover production was increased by 48.76% in contrast to the group that served as the control. Because of the positive correlation between growth features and yield, it is more likely that the utilization of both 0.5 mM manganese as well as 150 ppm salicylic acid will be successful to augment mustard output.

2.3.3 Effect on nutrient concentration, uptake, and quality

Hussain *et al.,* (2010) studied the alleviation of salt stress effects by exogenous application of SA in pearl millet seedlings. SA-treated pearl millet plants under NaCl salinity recorded higher N content as compared to the control.

From the results obtained by Muhal *et al.,* (2014b) at Udaipur, significant variation was observed for oil content, oil yield, nitrogen uptake, and phosphorus uptake by seed and stover of mustard due to the foliar spray of salicylic acid. The maximum values of these parameters were seen following the application of a 100-ppm salicylic acid foliar spray in contrast to a water spray.

Rundla *et al.,* (2022) observed that the application of 200 ppm salicylic acid to Indian mustard enhanced growth, yield metrics, and nutritional content and absorption. Significantly, there was a considerable increase in nitrogen, phosphate, and potassium concentrations in seeds and stover, accompanied by improved oil content and quality compared to untreated plants.

Guin *et al.,* (2024) noted that the simultaneous treatment of manganese and salicylic acid not only augmented growth and yield metrics but also enhanced nutritional content and absorption. A notable enhancement in nitrogen, phosphate, and potassium levels in seeds and stover was observed, along with elevated oil content and quality relative to untreated plants.

2.3.4 Effect on economics

Muhal *et al.,* (2014c) An experiment was carried out in Udaipur, and the results showed that the foliar spray of 100 ppm salicylic acid produced the highest net returns of mustard when compared to the water spray.

Sruthi *et al.,* (2020) executed a field trial in Allahabad, revealing that a foliar application of 1% DAP combined with 100 ppm salicylic acid, administered twice at 25- and 45-days post-sowing, yielded the highest net returns (Rs. 65,577/ha) and benefit-to-cost ratio (1.69) for green gram.

Meena *et al.,* (2020) indicated that the synergistic application of hydrogel and 100 ppm SA in Indian mustard agriculture under restricted irrigation conditions yielded enhanced net returns and benefit-cost ratios. This combination demonstrated economic superiority compared to alternative treatments, indicating its potential to enhance profitability in mustard cultivation.

A field experiment was carried out by Reddy and Singh (2021) at Allahabad, and they found that the maximum net return and B: C ratio of green gram was obtained with the application of 150 ppm salicylic acid at 25 and 45 DAS.

MATERIALS AND METHODS

A field experiment was executed at the Agricultural Research Farm of Lovely Professional University during the *rabi* sessions of 2021-22 and 2022-23 to examine the **"Effect of Superabsorbent polymer and Salicylic acid along with different Sources of sulphur on growth, yield, and quality of Gobhi Sarson (*Brassica napus* L.) under controlled irrigation"** This chapter comprehensively reviews the materials and procedures employed during the research.

3.1 Experimental Field and Geographical Details:

The experiment was conducted in the Agronomy farm of Lovely Professional University in Phagwara, Punjab, India. The farm is situated at a latitude of 31.2°N, a longitude of 75.7°E, and an elevation of 234 meters above sea level. *Brassica napus* L., known as Gobhi Sarson, is a crop optimally adapted to the *rabi* season in the region, characterized by a subtropical environment featuring scorching summers and moderate winters. The soil at the experimental site sandy loam.

Fig. 3.1: Agriculture Field, School of Agriculture (Source: Google Earth)

3.2 Climatic Profiles

Figures 3.2.1 and 3.2.2 illustrate the maximum and minimum temperatures (in °C) and daily precipitation (in mm) throughout the *rabi* seasons of 2021–22 and 2022–23. The green line denotes the maximum temperature, the blue line illustrates the minimum temperature, and the gray bars signify daily precipitation. During the 2021–22 season, the highest temperatures significantly diminished from approximately 40°C in October to roughly 20°C in January, thereafter increasing to around 30°C by April. Minimum temperatures exhibited a comparable pattern, declining from roughly 25°C in October to below 5°C in January, before increasing again. Precipitation occurrences were irregular, with pronounced increases in January and March, exhibiting considerable variability. A comparable trend was noted throughout the 2022–23 season. The maximum temperature consistently declined from approximately 40°C in October to about 18°C in January, thereafter rising to over 30°C by April. Minimum temperatures declined to below 5°C in January and thereafter increased steadily. Precipitation transpired in sporadic instances, with elevated maxima noted in January and February relative to the 2021–22 season.

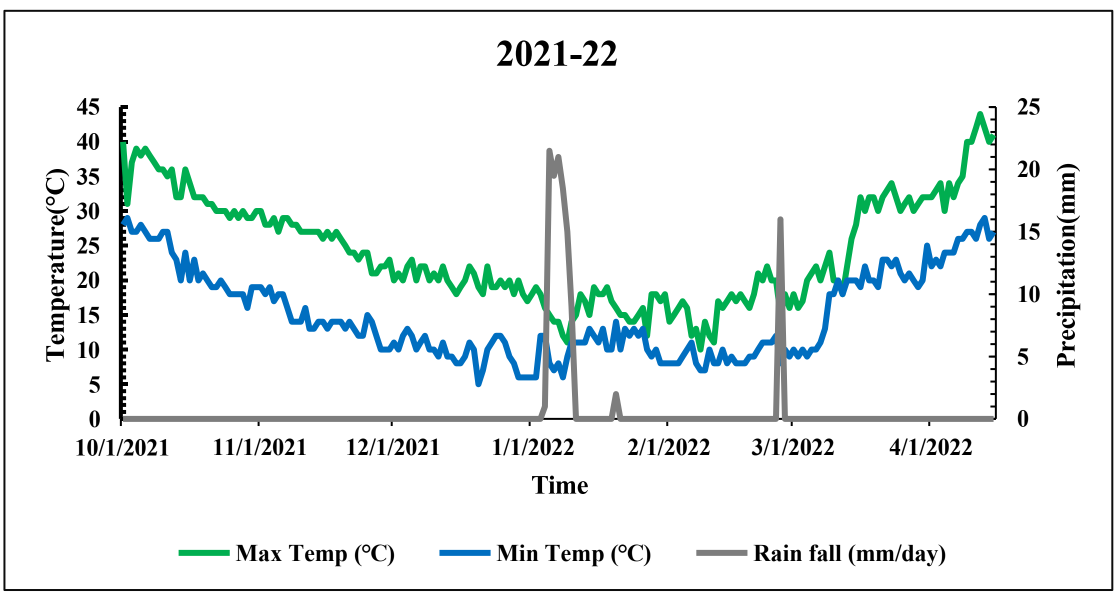


Fig. 3.2.1: Temperature and Rainfall Trends in Rabi 2021–22

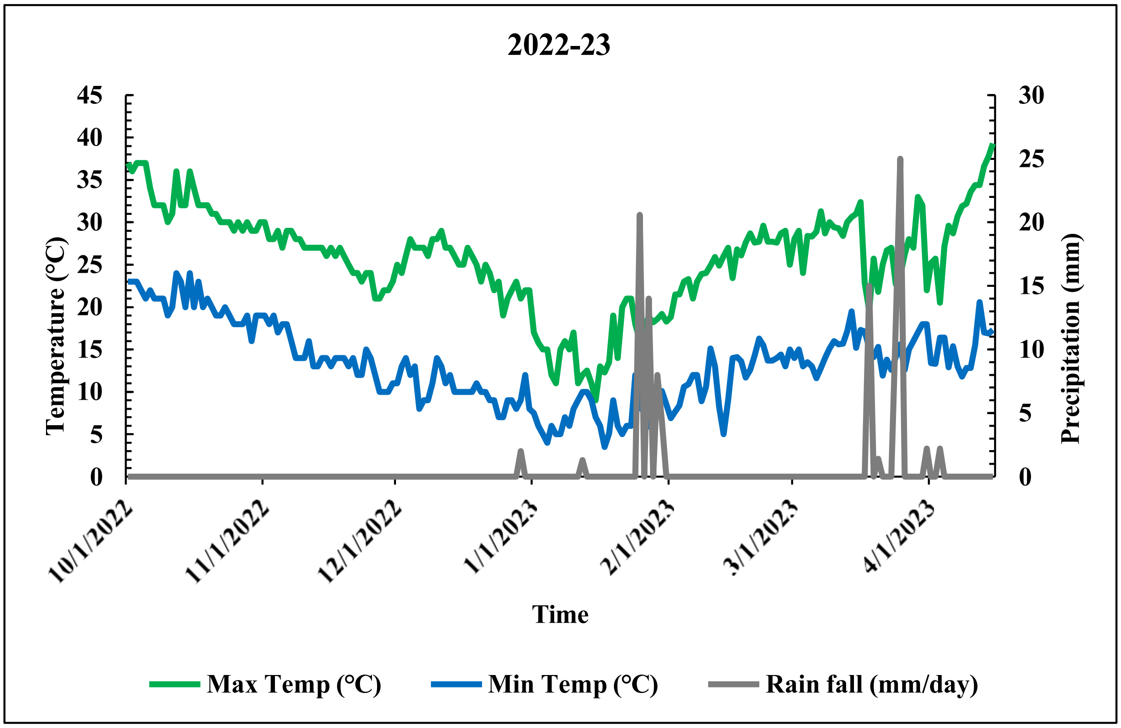


Fig. 3.2.2: Temperature and Rainfall Trends in Rabi 2022–23

Two Figures 3.2.3 and 3.2.4 depict wind speed (in km/hr) and wind direction (from 0° to 360°) over time during the *rabi* seasons of 2021–22 and 2022–23. The blue line indicates wind speed, whilst the orange line illustrates wind direction. During the 2021–22 season, wind velocities predominantly stayed under 6 km/hr, with rare waves reaching 18 km/hr. Wind direction varied considerably, across a broad spectrum from 0° to 360°. Comparable patterns were noted throughout the 2022–23 season, with wind velocities primarily remaining below 6 km/hr, punctuated by maxima nearing 18 km/hr. The wind direction in this season exhibited significant variety, fluctuating between 0° and 360°. The data indicate seasonal variations in wind speed and direction, lacking consistent trends throughout the two years, underscoring the dynamic characteristics of wind patterns throughout the research period.

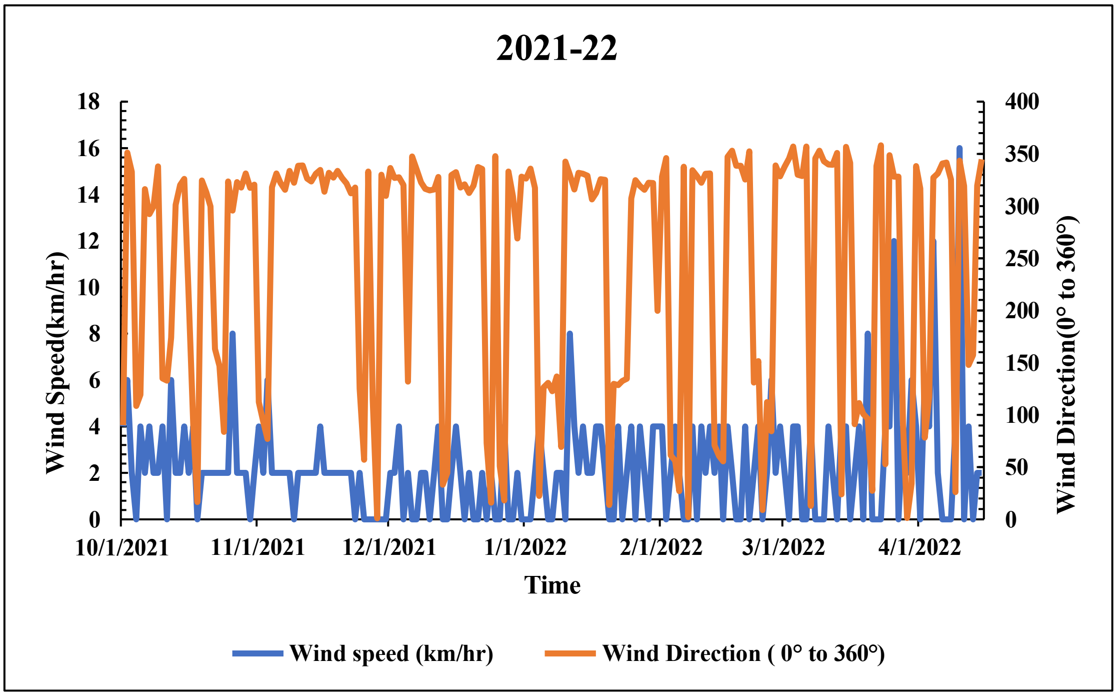


Fig.3.2.3: Seasonal Patterns of Wind Speed and Direction During Rabi 2021–22

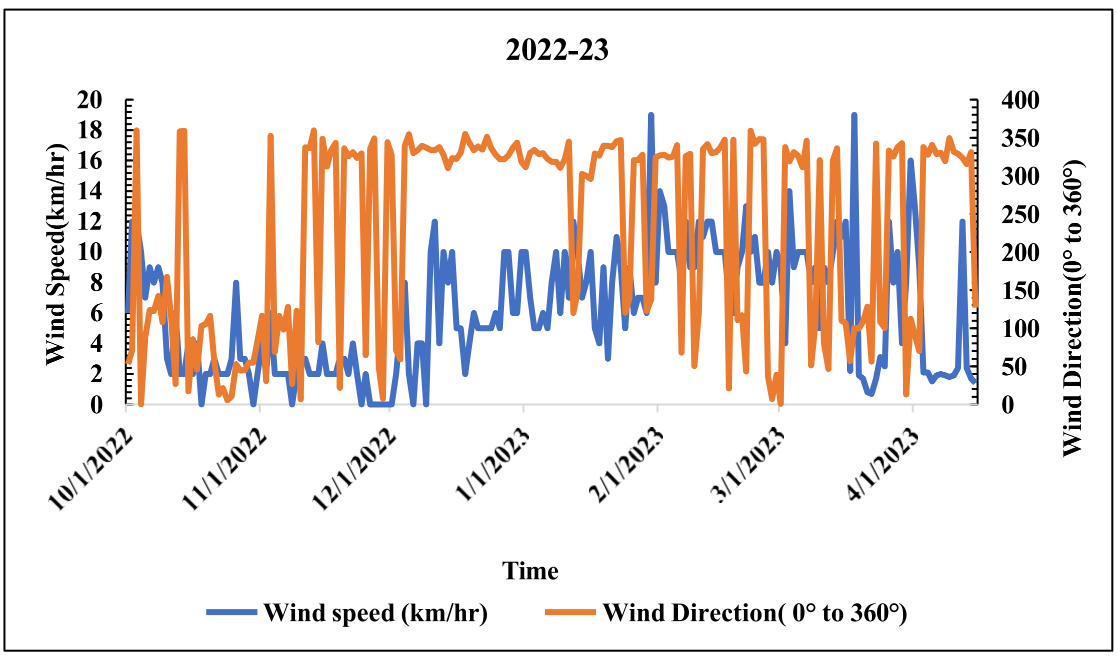


Fig.3.2.4: Seasonal Patterns of Wind Speed and Direction During Rabi 2022–23

3.3 Cropping history of the experimental field

The production capacity of the experimental field can be evaluated depending on its cropping history. The cropping plan from 2019–2020 to 2022–2023 illustrates the rotation of crops grown during the *kharif* and *rabi* seasons to enhance seasonal conditions and preserve soil health. During the 2019–2020 period, sesame was cultivated in the kharif season, taking advantage of its adaptation to warm and humid circumstances, whilst barley was grown in the *rabi* season, benefiting from the cooler, arid winter climate. During the 2020–2021 period, cluster bean, a drought-resistant legume, was cultivated in the kharif season, succeeded by mustard, a commonly cultivated winter oilseed crop. In 2021–2022, pearl millet, a fundamental cereal for semi-arid areas, was cultivated in the kharif season. During the kharif season of 2022–2023, sesame was farmed again, demonstrating its commercial and agronomic viability, whilst rapeseed was planted in the *rabi* season, presumably due to its significant economic value and adaptability to winter temperatures. This cropping cycle shows strategic planning to enhance productivity and adjust to altering seasonal climatic circumstances.

Table 3.3.1 Historical cropping data of the experimental field

Year	***Kharif***	***Rabi***
2019-2020	Sesame	Barley
2020-2021	Cluster bean	Mustard
2021-2022	Pearl millet	Rapeseed*
2022-2023	Sesame	Rapeseed*

*Experiment crop

3.4 Physicochemical properties of the experimental field

Soil samples were obtained from nine randomly chosen locations within the field of experimentation at a depth of 0-15 cm to assess the physicochemical parameters. A combined sample was subsequently generated by mixing and analyzing all of the soil samples. Mechanical, physical, and chemical analyses were conducted on the uniform composite soil sample. Tables 3.4.1, 3.4.2, and 3.4.3 present the results of these analyses with the methodology utilized for their assessment. The results showed that the soil in the experimental field had a loamy sand texture, an alkaline response, low accessible nitrogen, a lack of organic carbon, and moderate phosphate and potassium concentrations.

Fig.3.4.1 Soil Sampling

Table 3.4.1: Mechanical analysis of soil

S. No.	Particulars	2021	2022	Method
I.	Coarse sand (%)	21.26	20.89	International Pipette method (Piper, 1966)
II.	Fine sand (%)	59.07	58.87	International Pipette method (Piper, 1966)
III.	Silt (%)	11.14	11.35	International Pipette method (Piper, 1966)
IV.	Clay (%)	8.51	8.85	International Pipette method (Piper, 1966)
V.	Textural class	Loamy sand	Loamy sand	Soil survey staff, 1975

Table 3.4.2: Physical properties of soil

S. No.	Particulars	2021	2022	Method
1.	Bulk density (Mg/m^3)	1.55	1.52	Core Cutter Method (Black, C. A, 1965).
2.	Particle density (Mg/m^3)	2.63	2.59	Pycnometer Method (Black, C. A, 1965).
3.	Porosity (%)	40.63	41.15	Derived Calculation from Bulk Density and Particle Density (Richards, L. A.,1954).
4.	Field Capacity (%)	12.9	12.7	Pressure Plate Apparatus or Gravimetric Method (Richards, L. A.,1954).
5.	Permanent Wilting Point (%)	2.64	2.69	Pressure Plate Apparatus (Moisture Retention at -15 Bars) (Richards, L. A.,1949).

Table 3.4.3: Chemical analysis of soil

S. No.	Particulars	2021	2022	Method
1.	Organic carbon (%)	0.23	0.27	Wet digestion method (Walkley and Black,1934)
2.	Available N (kg/ha)	130.08	132.25	Alkaline potassium permanganate method
3.	Available P_2O_5 (kg/ha)	16.22	15.41	Olsen's method (Olsen *et al.*, 1954)
4.	Available K_2O (kg/ha)	148.09	147.24	Flame Photometric Method (Jackson, 1973)
5.	Available S (mg/ha)	9.20	9.24	Chesnin and Yien (1951)
6.	EC (dS/m)	1.22	1.19	Electrical Conductivity (Sparks 1996)
7.	Soil pH	8.21	8.15	Glass electrode pH meter (Sparks 1996)

Fig 3.4.2: Soil Analysis

Fig 3.4.3: Bulk Density of Soil

3.5 Details of the experiment:

A field experiment was carried out to evaluate the impacts of salicylic acid, super absorbent polymer, and different sulphur sources on the growth, yield, and quality of the Gobhi Sarson (*Brassica napus* L.) variety GSC-7. The research was conducted during two successive *Rabi* seasons (2021–22 and 2022–23) at the Agronomy Research Farm of Lovely Professional University (LPU) in Phagwara, Punjab. A split-plot design was utilized, with the main plots designated for three sulphur sources and the sub-plots assigned to eight agrochemical treatments, including Hydrogel, Salicylic acid, and control conditions, across several irrigation regimes. ainThe experiment had 24 treatment combinations, each replicated thrice, creating a total of 72 plots. Each gross sub-plot measured 15 m² (5 m × 3 m), but the net sub-plot, after deducting boundary rows, measured 8 m² (4 m × 2 m). The Agronomy Research Farm of LPU supplied optimal agro-climatic conditions and well-maintained infrastructure, ensuring the reliability and validity of the experimental framework for examining the chosen treatments.

Table 3.5.1: Experimental details

Crop	Gobhi sarson (*Brassica napus* L.)
Variety	GSC-7
Years of experimentation	Rabi seasons of 2021-22 to 2022-23
Treatment combinations	24 (3 x 8)
Replications	3
Overall plot Count	72
Sub-plot size (Gross)	$5m^2$ x $3m^2$ = $15m^2$
Net sub-plot size	$4m^2$ x $2m^2$ = $8m^2$
Experimental Design	Split plot design
Location	Agronomy Research Farm of LPU, Phagwara

Experimental design:

Table 3.5.2: Experimental treatment details with their symbols

Name of the treatments	Symbol used for specific treatment
(Sources of Sulphur)	
Gypsum	S_1
Bentonite sulphur	S_2
Elemental sulphur	S_3
(Agrochemicals)	
Control (Irrigation as per requirement)	A_0
Hydrogel (2.5 kg/ha) as a basal application	A_1
Salicylic acid (150 ppm) foliar spray at 50% flowering stage	A_2
Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	A_3
Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	A_4
Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	A_5
Basal treatment of hydrogel (2.5 kg/ha) combined with foliar spray of salicylic acid (150 ppm) at both the 50% flowering and Stage of 50% pod formation.	A_6
Control (Restricted irrigation)	A_7

*Restricted irrigation: Irrigation was not given at the rosette stage (30-35 DAS) and pod formation stage (90-95 DAS)

Main irrigation channel				
S_2A_0		S_3A_7		S_1A_5
S_2A_1		S_3A_3		S_1A_6
S_2A_4		S_3A_5		S_1A_1
S_2A_2		S_3A_6		S_1A_3
S_2A_7		S_3A_0		S_1A_2
S_2A_3		S_3A_4		S_1A_7
S_2A_5		S_3A_2		S_1A_4
S_2A_6		S_3A_1		S_1A_0
S_1A_5		S_2A_0		S_3A_7
S_1A_6		S_2A_1		S_3A_3
S_1A_1		S_2A_4		S_3A_5
S_1A_3	Irrigation Channel	S_2A_2	Irrigation Channel	S_3A_6
S_1A_2		S_2A_7		S_3A_0
S_1A_7		S_2A_3		S_3A_4
S_1A_4		S_2A_5		S_3A_2
S_1A_0		S_2A_6		S_3A_1
S_3A_7		S_1A_5		S_2A_0
S_3A_3		S_1A_6		S_2A_1
S_3A_5		S_1A_1		S_2A_4
S_3A_6		S_1A_3		S_2A_2
S_3A_0		S_1A_2		S_2A_7
S_3A_4		S_1A_7		S_2A_3
S_3A_2		S_1A_4		S_2A_5
S_3A_1		S_1A_0		S_2A_6

Fig 3.5.1 Layout of Experimental Field

3.6 Crop Irrigation Schedule:

The irrigation schedule for Gobhi Sarson (*Brassica napus* L.) variety GSC-7, a 150-day maturing *rabi* crop, was carefully planned to adhere to the agronomic guidelines of Punjab Agricultural University (PAU) and to enhance growth and yield. It's essential to ensure that each irrigation provides sufficient moisture to meet the crop's needs during its critical growth stages. The total water requirement for mustard crops typically ranges between 310 to 400 mm (31 to 40 cm) per season, depending on soil type, climate, and crop variety. The irrigation design aimed to maintain sufficient soil moisture during crucial growth phases while recreating water-stress situations for experimental analysis. Based on PAU regulations and the water needs of mustard throughout its growth cycle, the total irrigation demand for the 576 m² experimental area (which includes 72 plots) for the cropping season was estimated to be between 166,560 and 196,320 liters. In order to build the root system and promote early vegetative growth, the primary irrigation must be applied 30 to 35 days after sowing (DAS) during the rosette period. To ensure sufficient soil moisture for root development and leaf expansion, the water demand for this phase ranges from 34,560 to 40,320 liters for the entire area. Because water availability directly affects the plant's ability to absorb nutrients and grow rapidly, this period is particularly vulnerable to moisture stress. In order to promote flower development, the crop receives a second watering during its flowering phase, when its water absorption is at its peak. The required volume of water generally ranges between 34,560 and 40,320 liters. In order to prevent flower abortion, enhance pollination, and ensure a significant number of viable pods—the forerunners of the final crop—enough water is essential during this stage. In order to maintain soil moisture levels that are conducive to pod growth, 34,560 to 40,320 liters of water are required for pod production. Because the water supply directly affects pod commencement and elongation, this period is crucial. At this stage, water stress can markedly diminish both the quantity and size of pods, resulting in decreased seed output. The fourth irrigation, conducted during seed filling, necessitates 34,560 to 40,320 liters. This phase ascertains the dimensions of the seeds and the oil concentration. Sufficient soil moisture during this stage guarantees that the seeds attain ideal weight and quality. Extended water stress can negatively impact oil build-up and seed quality. Under arid conditions, the fifth irrigation of 28,800 to 34,560 liters may be administered to finalize seed growth and guarantee adequate maturation.

To find out how water stress affected Gobhi Sarson's growth and yield, the irrigation schedule was designed by skipping some irrigations at different stages. The first irrigation was skipped at (30–35 DAS). The experiment examined the crop's ability to grow roots when it lacked water in the early stages by not giving it water during the rosette stage. In the real world, early-season droughts or delayed irrigation are common in places with few water sources. The way the plant reacts to this stress shows how resilient and adaptable it is. The third irrigation (90–95 DAS) was not applied because water was not allowed to be used during the pod formation stage to study how the lack of water affected pod start, growth, and seed set. Such a method shows the susceptibility of crops during times of high demand and how well they can handle not having enough water. To mitigate the adverse effects of water stress, hydrogel and salicylic acid were incorporated into the experimental treatments. In addition to simulating real-life scenarios where water is scarce, these planned irrigation management and stress-reduction techniques provide a means of optimizing resource utilization to achieve the highest possible mustard yield and quality under various environmental circumstances.

Treatment application:

Gypsum ($CaSO_4 \cdot 2H_2O$): It has approximately 18% sulphur content by weight. Gypsum is a naturally occurring mineral consisting of calcium sulphate dihydrate. It is extensively utilized in agriculture to enhance soil structure and serve as a source of calcium and sulphur for plants. Because it increases soil porosity and water infiltration, gypsum is particularly helpful in improving sodic soils. The sulphur in gypsum is easily accessible to plants as sulphate (SO_4^{2-}), the most available form for absorption. Sulphate anions (SO_4^{2-}) surround the calcium cation (Ca^{2+}), and water molecules are incorporated into the crystal lattice. Gypsum was applied before sowing as per treatment and was incorporated well into the soil.

Fig. 3.7.1: Source of Sulphur (Gypsum)

Bentonite Sulphur: Sulphur (S) mixed with bentonite clay, which contains 85–90% sulphur by weight, is the chemical makeup of bentonite sulphur. A synthetic material called bentonite sulphur is created by combining elemental sulphur with bentonite clay. When bentonite is applied before to seeding, it expands in the wetness, reducing the sulphur to small pieces and speeding up its microbial oxidation to sulphate (SO_4^{2-}), which plants can use. It is a slow-releasing sulphur source that works particularly well in low-sulphur soils.

Fig. 3.7.2: Source of Sulphur (Bentonite Sulphur)

Elemental sulphur (S_8): It has a sulphur content of 99% by weight. Elemental sulphur serves as a concentrated source of sulphur. In order for plants to absorb sulphate (SO_4^{2-}), the soil must undergo microbial oxidation. Oxidation is a slow and gradual temperature-sensitive process, rendering it appropriate for sustained sulphur provision. Due to its acidifying effect upon oxidation, it is commonly used to reduce soil pH in alkaline soils.The chemical structure of sulphur is a cyclic molecule with eight sulphur atoms (S_8) organized in a crown-like configuration.

Fig. 3.7.3: Source of Sulphur (Elemental Sulphur)

Hydrogel: Pusa Hydrogel, a superabsorbent polymer produced by the Indian Agricultural Research Institute (IARI) in New Delhi, was applied in this study to improve soil water retention and maximize water use efficiency under regulated irrigation circumstances. Up to 400 times its weight in water may be absorbed and retained by this cutting-edge polymer, which was created for agricultural applications. By gradually releasing absorbed water, Pusa Hydrogel, when mixed with soil and applied in furrows during sowing, provides a steady supply of hydration to the crop. This reduces the frequency of watering and minimizes water loss through evaporation or deep percolation, ensuring consistent water availability during critical growth phases. The hydrogel's remarkable efficacy across a range of soil types and agroclimatic conditions can help water-scarce areas, such as parts of Punjab. Additionally, because it is environmentally friendly and biodegradable, it supports sustainable farming methods by enhancing crop performance, nutrient uptake, and root development. The study is to examine the efficacy of Pusa Hydrogel to enhance the growth, yield production, and quality of *Brassica napus* L. var. GSC-7 under different irrigation regimes.

Fig:3.7.4 Hydrogel

Salicylic acid: Salicylic acid (SA) was used in this study as a foliar spray to enhance the physiological and biochemical processes of the crop during critical growth stages. The necessary amount of SA was dissolved in distilled water to create a 150 ppm salicylic acid solution. At 50% flowering and pod development, two critical phases of the crop's lifetime, the foliar treatment was applied. These phases were chosen especially to optimize the advantages of SA, such as increased nutrient absorption, stress tolerance, and the development of yield-related characteristics. The solution was uniformly sprayed across the designated plots using a knapsack sprayer equipped with a flat fan nozzle to ensure even coverage. The spray treatments were given early in the morning to maximize absorption and reduce evaporation losses. The integrity of the experimental design was preserved by carefully controlling the salicylic acid treatment to avoid drift into nearby plots. The incorporation of SA into the study aimed to evaluate its role in improving the growth, yield, and quality of *Brassica napus* L. var. GSC-7 under varied irrigation and agrochemical treatment conditions.

Fig. 3.7.5: Salicylic acid

3.7 Description of variety:

The rapeseed variety GSC-7 was used for seeding in this study. This high-yield variety, created by Punjab Agricultural University (PAU), is optimized for irrigated environments. GSC-7 reaches maturity in approximately 150 days and is distinguished by its 4–6 compact, prolific branches. The variety exhibits resistance to lodging, hence assuring improved standability under field circumstances. The GSC-7 seeds are light brown and possess roughly 40% oil content, rendering them a significant crop for oilseed production.

Rapeseed, or gobhi sarson (*Brassica napus*), differs from regular mustard (*Brassica juncea*) in a number of ways. Erucic acid levels in mustard are often higher (48–50%), while rapeseed varieties like Gobhi Sarson are cultivated to produce oil with significantly lower erucic acid levels. Rapeseed-mustard oil needs to have less than 2% erucic acid in order to be considered canola grade. The national average yield for rapeseed in India is around 1.2 t/ha, underscoring the significance of high-performing cultivars such as GSC-7 in closing the yield gap and improving oilseed production efficiency in irrigated environments.

Fig. 3.8.1: Source of seed

3.8 Agronomic Practices:

Cultural practices were carried out according to the approved package and practices of Punjab Agricultural University (PAU), Ludhiana, in order to ensure optimal crop growth. This comprised adequate land preparation, timely sowing, and accurate application of specified fertilizers and insect prevention techniques.

3.8.1 Allotment of experimental field:

At the research farm of the School of Agriculture, Lovely Professional University, Punjab, India, the experimental field was set aside for the *rabi* seasons of 2021–22 and 2022–23.

3.8.2 Field preparation:

A systematic methodical approach was used to prepare the experimental field. The field was first cultivated with a tractor-mounted rotavator, thereafter undergoing primary tillage with a disc harrow. Later, secondary tillage was conducted, along with leveling operations to ensure uniformity. The layout was finalized to prepare the plots for the experiment.

Fig. 3.9.2.1: Field preparation

3.8.3 Sowing, seed rate, spacing, and sowing method:

The GSC-7 variety of Gobhi Sarson, i.e., *B. napus* L., was selected for an experiment. The seeds were sown at a specified rate of 5 kg/ha to achieve optimal plant density, with a spacing of 45 x 15cm in order to encourage adequate growth and aeration. The line sowing method was used for manual sowing in order to promote good germination and consistent seed placement.

Fig.3.9.3.1 Sowing

3.8.4 Thinning:

In the GSC-7 variety of Gobhi Sarson (*Brassica napus* L.), thinning was performed 2-3 times to ensure optimal plant population and spacing. The seeds of GSC-7 generally require 12-14 days to germinate, hence the initial thinning occurred at the 2-3 leaf stage, approximately 20-25 days post-sowing. Further thinning was conducted at intervals based on crop development to eliminate weak, overcrowded, or uneven plants. As a result, the crop's overall performance and output were enhanced, resource competition was reduced, and uniform growth was promoted.

Fig:3.9.4.1 Thinning

3.9.4 Inter-cultural operations

Intercultural practices, such as thinning, hoeing, and weeding, were carried out at pivotal stages to guarantee the optimal growth of the GSC-7 variety of Gobhi Sarson (*Brassica napus* L.). To guarantee proper spacing and get rid of weak specimens, thinning was done two or three times, starting at the two to three leaf stage (20 to 25 days after seeding). While regular weeding guaranteed a weed-free environment, reducing competition for nutrients, moisture, and light, hoeing improved soil aeration and water infiltration, promoting vigorous root development. Together, these methods enhanced the potential for production and promoted strong plant growth.

3.9.5 Harvesting, Threshing, and Winnowing

Plants were manually harvested from a 1 m^2 section of each plot, which was marked for sampling by using a sickle. Following harvest, the plants were bundled, labelled for identification, and then transported to the threshing floor. The bundles were neatly organized and dried in the sun to guarantee complete moisture loss. After drying, the total biological yield from each plot was measured with an electronic scale. Threshing was performed manually by turning and rotating the stalks to detach the seeds from the siliquae. The threshed material was further winnowed using standard methods to acquire clean seeds. This systematic method maintained accurate data collection for yield estimation.

Fig. 3.9.5.1 Harvesting, Threshing, Winnowing

Figure 3.9.5.2(a): Pictorial Representation of the Entire Research Work

Figure 3.9.5.2(b): Pictorial Representation of the Entire Research Work

3.9 Observations recorded

Observations were recorded periodically to evaluate the values of various treatments. Growth factors were evaluated at 30, 60, 90, and 120 days after sowing (DAS) to assess plant development. Yield parameters, oil content, and nutrient absorption have been documented to evaluate crop performance and quality. To give a thorough analysis of the treatments, the economic viability, including the benefit-cost ratio and net returns, was examined.

3.9.1 Plant Growth Attributes

3.9.1.1 Plant height

The height of five initially tagged plants was monitored at 30 DAS, 60 DAS, 90 DAS, and 120 DAS from each plot. A measuring tape or meter scale was utilized, positioned at the base of the plant in contact with the soil surface, and extended vertically along the main stem to the top of the plant, excluding flowers or siliques unless otherwise stated. The measured heights were recorded in centimeters, and the mean plant height was computed for each plot to enable subsequent analysis.

3.9.1.2 Dry matter accumulation

Dry matter accumulation was assessed at 30, 60, 90, and 120 DAS. Plants from a one-meter segment were randomly taken from sample rows of each plot. After the extraction of the root section, the samples were first air-dried for several days and then dried in an electric oven at 70°C until a stable weight was achieved. The weight was noted and interpreted as average dry matter accumulation (g).

3.9.1.3 Leaf area index

The Leaf Area Index (LAI) was evaluated at regular intervals of 30 days. Two samples from each size category were chosen, and their areas were separately measured using an automated leaf area meter. The mean leaf area value was recorded, and the results were aggregated to estimate the total leaf area of the sample. The Leaf Area Index is a dimensionless parameter.

LAI has been calculated by the subsequent relationship (Watson, 1958).

$$\text{Leaf area index} = \frac{\text{Leaf area (cm}^2\text{)}}{\text{Ground area (cm}^2\text{)}}$$

3.9.1.4 Number of branches

Branches have been recorded on five randomly picked and labeled plants in each plot at 30, 60, 90, and 120 days after sowing (DAS), and the mean was documented as the number of branches per plant.

3.9.1.5 Number of leaves per plant:

The leaf count per plant of the Gobhi Sarson (*Brassica napus* L.) variety GSC-7 was determined by recording the fully expanded leaves on the main stem of randomly chosen plants within each plot. Observations were carried out at 30 DAS, 60 DAS, 90 DAS, and 120 DAS to evaluate leaf production across various treatments. Five plants were chosen from one plot, and the mean leaf count single plant was computed to derive a representative value for each treatment. This measure provided an understanding of the vegetative growth and photosynthetic capacity of the plants.

3.9.1.6 Root Length

The root length was determined by carefully extracting the plants from the soil, causing not much harm to the root system. The roots were gently rinsed with water to eliminate any attached dirt particles. The primary root's length was measured from the root-shoot junction to the tip of the longest root using a measuring scale. Measurements were taken in centimeters.

3.9.1.7 Root Volume

The root volume has been determined utilizing the water displacement method. The purified roots were immersed in a graduated container containing a specified volume of water. The rise in water volume, as measured by the graduated cylinder, signified the root volume. The volume was measured in milliliters (mL).

3.9.1.8 Root Dry Weight

The cleaned roots were wiped to eliminate surface moisture before being placed in paper bags. The samples were dehydrated in a hot air oven at 70°C until a consistent weight was achieved. The dry weight of the roots was quantified using a digital scale and expressed in grams (g).

3.9.2 Yield attributes of the Plant

3.9.2.1 Number of siliquae /plants

To ascertain the quantity of siliquae per plant, five plants were randomly selected from each plot. Siliquae were manually counted on each plant, and the mean quantity of siliquae per plant was computed to signify the corresponding treatment.

3.9.2.2 Number of seeds per siliqua

A random sample of 10 siliquae was collected from each selected plant across the plots to determine the number of seeds per siliqua. Seeds from each siliqua were counted manually, and the average number of seeds per siliqua was determined for per treatment.

3.9.2.3 Length of siliqua

The length of siliquae has been determined using a ruler. A randomly selected sample of 10 siliquae was obtained from each plant, and their lengths were measured from the base to the apex of the siliqua. The mean length of siliqua was quantified and recorded in centimeters.

3.9.2.4 1000-Seed Weight

A randomly selected sample of seeds was obtained from the harvested crop of each plot to ascertain the 1000-seed weight. The mass of 1000 seeds were quantified in grams utilizing a precision digital balance. Efforts were made to guarantee that the seeds were clean and devoid of debris or damage.

Fig. 3.10.2.4.1: Seed counting

3.9.2.5 Seed Yield

Harvesting the crop from the assigned net plot area when it reached maturity allowed for the evaluation of seed production. To attain a consistent moisture level, the seeds were removed from the siliquae, cleaned, and dried. After that, the yield was measured and expressed in kilograms per hectare.

3.9.2.6 Straw Yield

The straw yield was ascertained by measuring the weight of the residual straw, encompassing siliqua husks and plant residues, after the separation of the seeds. The measurement was also represented in kilograms per hectare (kg/ha).

3.9.2.7 Biological Yield

Biological yield was determined by measuring the total weight of above-ground biomass, encompassing both seeds and straw, collected from the net plot area. It was quantified in kilograms per hectare (kg/ha).

3.9.2.8 Harvesting Index

The harvest index was determined using the following formula and represented as a percentage (Singh and Stoskoff, 1971).

$$\text{Harvest index (\%)} = \frac{\text{Economic yield}}{\text{Biological yield}} \times 100$$

3.9.3 Nutrient content, uptake, and quality

3.9.3.1 Nutrient concentration

Representative samples of seed and straw were obtained from each treatment for nutrient content measurement at the time of threshing. These samples were air-dried, ground into a fine powder using a mechanical grinder, and passed through a 2 mm sieve to ensure uniform particle size for analysis. The Kjeldahl method, which measures total nitrogen by digestion, distillation, and titration, was used to ascertain the nitrogen (N) concentration. Following the samples' acid digestion, the phosphorus (P) level was measured using a spectrophotometer and the vanadium molybdate yellow color method. Potassium (K) content was estimated using a flame photometer, while sulphur (S) content was determined using the turbidimetric method, which measures sulphate concentration after acid digestion. Protein content in seeds was calculated by multiplying the nitrogen content by a standard conversion factor (usually 6.25 for oilseeds). These nutrient analyses provided insights into the nutrient uptake and partitioning in seeds and straw under various experimental treatments.

3.9.3.2 Nutrient uptake

Nutrient uptake (kg/ha) is determined by multiplying the percentage of nutrient (N, P, K, S) content in seed or straw by the seed or straw yield (kg/ha) using the formula:

$$\text{Nutrient uptake (kg/ha)} = \frac{\text{Percent nutrient (NPKS) content in seed or straw} \times \text{Seed or straw yield (kg/ha)}}{100}$$

The percent nutrient content of seed and straw was determined through laboratory analysis, as previously described. Seed and straw yields (kg/ha) were derived from the data collected from the harvested plots. The values were inserted into the formula to determine the nutrient uptake for each nutrient by seed and straw individually. The results were noted in kilograms per hectare (kg/ha), offering insights into nutrient utilization efficiency and the role of seed and straw in nutrient cycling within the soil across various experimental treatments.

3.9.3.3 Protein content in seed

The amount of protein in the seed of Gobhi Sarson (*Brassica napus* L.) was assessed by multiplying the nitrogen content by a conversion factor of 6.25. The utilized formula is:

$$\text{Protein content (\%)} = \text{Nitrogen Content in seed (\%)} \times 6.25$$

3.9.3.4 Protein Recovery Yield (%)

The protein content is expressed as a percentage of the seed's dry weight. This method effectively assesses the nutritional quality of the crop and facilitates comparisons of the effects of various treatments on protein accumulation. Protein recovery yield indicates the total quantity of protein recoverable from harvested seeds, taking into account both the protein content within the seeds and the overall seed yield.

$$\text{Protein recovery yield (\%)} = \text{Protein Content (\%)} \times \text{Seed Yield(kg/ha)} / 100$$

3.9.3.5 Oil Content

The oil content (%) in seeds is quantified by extracting oil from a seed sample. The oil content was quantified as a percentage of the total seed weight, determined by the subsequent formula:

$$\text{Oil Content (\%)} = (\text{Weight of Oil Extracted} / \text{Weight of Seed Sample}) \times 100$$

Fig. 3.10.3.5.1: Extraction of oil

3.9.3.6 Oil Yield

Seed yield data were collected from the harvested seeds in each plot, and oil content was determined using the Soxhlet method. Oil yield is an essential measure of the oil potential for the production of the crop through different treatments and growing conditions.

$$\text{Oil Yield (Kg/ha)} = \text{Oil Content (\%)} \times \text{Seed Yield (Kg/ha)} / 100$$

3.9.3.7 Glucosinolate Content

Glucosinolate content in Brassica seeds was determined using the standard HPLC desulfation method. Finely ground seed samples (0.25–0.50 g) were extracted with preheated 70% methanol to inactivate myrosinase and release glucosinolates. The extract was centrifuged, and the supernatant was passed through a DEAE-Sephadex ion-exchange column. Bound glucosinolates were converted to desulfo-glucosinolates by adding arylsulfatase and incubating overnight. The desulfo-glucosinolates were then eluted with water, filtered, and injected into an HPLC system equipped with a C18 column and UV detector (229 nm). Individual peaks were identified using standards, and total glucosinolate content was expressed in μmol g^{-1} seed.

3.9.3.8 Erucic Acid

By converting the oil to fatty acid methyl esters (FAMEs) and using GC-FID analysis, the amount of erucic acid in Brassica seed oil was ascertained. An accurately weighed aliquot (~50–100 mg) of oil extracted from seeds (Soxhlet or cold-press) was put in a reaction vial, spiked with an internal standard (such as C17:0 methyl ester), and then transesterified by adding methanolic NaOH (0.5–1.0 M), followed by BF_3–methanol (or 14% BF_3 in methanol) or methanolic HCl, and heated briefly (60–90 °C, 5–10 min). Following cooling, FAMEs were extracted using hexane (or hexane:diethyl ether), cleaned with saturated NaCl, dried over anhydrous Na2SO4, filtered into GC vials, and analyzed on a capillary column appropriate for cis/trans C18–C24 resolution (e.g., SP-2560 or CP-Sil 88, 100 m × 0.25 mm, 0.2 μm) with helium carrier gas and an oven program that separates long-chain monoenoic methyl esters; injector and FID temperatures are normally between 240 and 260 °C. Peaks were found by comparing them to real FAME standards (such as erucic acid methyl ester, C22:1) and quantifying them in relation to the internal standard using response factors or calibration curves; the results are expressed as g/100 g oil or as a percentage of total fatty acids.

3.9.3.9 Iodine Value

The Wijs reagent method was used to determine the oil's iodine value. After dissolving a known weight of oil sample in chloroform and treating it with an excess of Wijs reagent, it was left to react with the double bonds in the dark for a predetermined amount of time. Once the reaction was finished, the unreacted iodine was released by adding potassium iodide solution, which was then diluted with distilled water. Using starch as an indication, the released iodine was subsequently titrated using a standardized sodium thiosulphate solution. The results were expressed as grams of iodine absorbed per 100 grams of oil. A reagent blank was run alongside the sample, and the iodine value was computed from the difference between the blank and sample titration readings.

3.9.3.10 Saponification Value

A known weight of oil was refluxed with a specified volume of alcoholic potassium hydroxide (KOH) solution to calculate the oil's saponification value. To guarantee full saponification of the ester linkages in the oil, the mixture was heated under reflux. Following the reaction period, phenolphthalein was used as an indicator to titrate the hot solution containing excess KOH against a standardized solution of sulfuric acid or hydrochloric acid (HCl). A similar procedure was used to reflux and titrate a blank that contained solely alcoholic KOH. The difference between the blank and sample titration readings was used to calculate the saponification value, which was then represented as the milligrams of KOH needed to saponify one gram of oil.

3.9.3.11 Peroxide Value

The standard iodometric technique was used to determine the oil's peroxide value. After dissolving a known weight of oil in a solution of acetic acid and chloroform, a measured volume of potassium iodide (KI) solution was added to react with the peroxides and release iodine. After a few minutes in the dark, the mixture was diluted with distilled water. To find the endpoint, the released iodine was titrated with a standardized sodium thiosulphate solution using starch as an indicator. At the same time, a reagent blank was run. The difference between the blank and sample titration readings was used to compute the peroxide value, which was then expressed as milliequivalents of active oxygen per kilogram of oil.

3.10.4 Economics

An economic evaluation of the experiment was conducted to determine the profitability and feasibility of different treatments. The cultivation cost (Rs/ha) for each treatment was calculated by evaluating the prevailing market prices of materials, land preparation fees, labor, and additional operational expenditures. The net returns (Rs/ha) were computed to identify the preferred treatment by subtracting the cultivation costs from the gross returns, which were determined by the market prices of the output. The economic feasibility of the treatments was assessed by calculating the benefit-cost (B:C) ratio using the following formula:

$$\text{B: C ratio} = \frac{\text{Gross returns (Rs/ha)}}{\text{Cost of cultivation (Rs/ha)}}$$

3.10.5 Statistical assessment

The results obtained from the field experiment were statistically analyzed using Statistix 10 software to assess the impact of treatments on the growth, yield, and yield attributes of rapeseed. A two-way analysis of variance (ANOVA) was conducted to ascertain the significance of the main effects and their interactions among the treatments. The Least Significant Difference (LSD) test was used at a 5% level of significance ($p \leq 0.05$) to compare the means and find significant differences between treatments. This exacting statistical approach guaranteed the precision and dependability of the findings, offering a solid foundation for assessing how well treatments worked.

CHAPTER-IV

RESULTS AND DISCUSSION

This study entitled **"Effect of Superabsorbent polymer and Salicylic acid along with different Sources of sulphur on growth, yield, and quality of Gobhi Sarson (*Brassica napus* L.) under controlled irrigation"** was conducted during the *rabi* seasons of 2021-2022 and 2022-2023 at the Agronomy Farm, Lovely Professional University, Phagwara. This study sought to assess the synergistic impacts of sulphur sources (gypsum, bentonite sulphur, and elemental sulphur), superabsorbent polymers (hydrogel), and Salicylic Acid on the growth and yield of Gobhi Sarson GSC-7 variety under controlled irrigation conditions. The experiment was primarily designed to evaluate morphophysiological characteristics at 30, 60, 90 and 120 days after sowing (DAS). The growth indicators were correlated with yield parameters, including seed and oil production, to assess the impact of various treatments on the crop's quantity and quality. Sulphur, a vital component for oilseed crops such as Gobhi Sarson, was applied in different forms to assess its impact on growth and output. Furthermore, salicylic acid, recognised for its capacity to augment stress resilience and bolster plant defense systems, was applied during pivotal growth phases. The integration of hydrogel aimed to enhance soil moisture retention, essential for controlled irrigation settings, hence promoting continuous plant growth. The study examined the relationship between these treatments and their efficacy in alleviating environmental stress, particularly during periods of water scarcity, hence improving growth and increasing seed and oil yield. In addition to growing performance, biochemical parameters were assessed to determine their impact on oil content and overall seed quality. The outcomes of this field study have been thoroughly analyzed and stated, providing insights into the influence of agrochemicals and Sulphur sources on enhancing the performance of Gobhi Sarson. The results seek to offer feasible recommendations for enhancing growth, output, and quality in controlled irrigation environments.

4.1 Morphological Parameters

4.1.1 Plant Height: The impact of various sulphur sources and agrochemicals on plant height (cm) was studied in the GSC-7 variety of rapeseed during the *rabi* seasons of 2021-

2022 and 2022-2023. Data was collected at 30, 60, and 90 days after sowing, as presented in Tables 4.1.1.1, 4.1.1.2, and Figures 4.1.1.1(a), 4.1.1.2(b). During 2021-2022 and 2022-2023, an impressive difference was seen in plant height between sources of Sulphur and agrochemicals. Gypsum (S1) significantly enhanced the height of the plant at 30, 60, 90, and 120 days after sowing, whereas elemental sulphur (S3) exhibited the lowest growth. Bentonite sulphur (S2) was at par with gypsum at 90 and 120 DAS. Among agrochemicals, A6 exhibited the most significant plant height and was comparable to A0 (well-irrigated control) at all stages. A4 and A5 were equivalent to A0 at 30, 60, 90, and 120 days after sowing (DAS). Conversely, A2, A3, and A7 exhibited significantly lower plant heights consistently, whilst A1 was substantially shorter than A0 starting from 60 DAS. The percentage was determined by comparing the means of various sources of Sulphur, whereas for agrochemicals, it was assessed by comparing all treatments against the control. The plant height varied at 30 DAS, with gypsum (S1) achieving 49.51 cm and elemental sulphur (S3) achieving 45.23 cm, an 8.63% reduction from gypsum, as well as bentonite sulphur (S2), which had a value of 47.98 cm, approximately 3% lower than gypsum. After 60 days of growth, gypsum (S1) once again had the tallest plants at 148.23 cm, whereas elemental sulphur (S3) had the shortest plants at 134.50 cm, a decline of 9.26% from S1. Bentonite sulphur (S2) resulted in a plant height of 142.36 cm, which was 3.95% lower than gypsum but on par with S1. At 90 DAS, the plant heights of gypsum (S1) and elemental sulphur (S3) were 170.22 and 155.06 cm, respectively, representing an 8.91% decrease. At 120 days after sowing, gypsum (S1) resulted in the greatest plant height of 175.40 cm. In Bentonite sulphur (S2),173.35 cm of plant height was obtained, which is only 1.17% less, and was considered significantly equivalent to gypsum. Elemental sulphur (S3) exhibited the minimum height of 160.28 cm, representing an 8.63% reduction compared to gypsum.

In the case of agrochemicals, at 30 DAS, the minimum height of the plant (42.83 cm) was observed under restricted irrigation (A7), showing a 13.32% decrease compared to the control (A0). Treatments A4, A5, and A6 (ranging between 50.21 and 51.16 cm) were statistically comparable to A0. At 60 DAS, A0 exhibited the greatest height of 148.77 cm, whereas A7 demonstrated the minimum height of 132.28 cm, reflecting a reduction of 11.08%. A6, A5, and A4 retained parity with A0. Further, at 90 days after sowing, the height of plants in A0 attained 176.20 cm, whereas A7 decreased to 148.24 cm, reflecting a 15.86%

reduction. A6 achieved the greatest height (177.69 cm), somewhat exceeding A0 by 0.85%, and was equivalent to A4 and A5. At 120 DAS, A0 attained a height of 182.19 cm, whilst A7 recorded the lowest value at 153.62 cm, reflecting a 15.68% decrease. A6 attained the highest value of 183.02 cm, exceeding A0 by just 0.45%, while A4 and A5 were similarly comparable. Among various sulphur sources, gypsum (S1) consistently yielded the tallest plants at all the phases of growth, elemental sulphur (S3) resulted in the shortest, while bentonite sulphur (S2) was generally comparable to gypsum in the later stages. Treatments incorporating hydrogel and salicylic acid (A4, A5, A6) were comparable to the control (A0), however, limited irrigation (A7) consistently resulted in diminished growth. The combination S1A6 achieved the maximum plant height at all stages, measuring 52.62 cm at 30 DAS, 153.09 cm at 60 DAS, 183.93 cm at 90 DAS, and 189.21 cm at 120 DAS. It somewhat exceeded the control S1A0 (51.22, 152.77, 182.31, and 188.19 cm, respectively) and was statistically comparable. Treatments S1A4 and S1A5 revealed the same effectiveness. The smallest values were continuously observed in S3A7, which measured 39.41 cm at 30 DAS, 123.85 cm at 60 DAS, 139.76 cm at 90 DAS, and 145.11 cm at 120 DAS—indicating a decrease of approximately 22–23% relative to S1A0. Consequently, S1A6 proved to be the most efficacious treatment, followed by S1A0, whereas S3A7 was the least effective.

A comparable pattern was noted in the *rabi* season of 2022–23, when various sulphur sources and agrochemical applications significantly affected plant height at multiple growth stages (30, 60, 90, and 120 DAS), matching the results from the previous year's study. Among sulphur sources, Gypsum (S1) consistently yielded the tallest plants, measuring 51.04 cm, 148.35 cm, 171.75 cm, and 176.09 cm at 30, 60, 90, and 120 DAS, which were statistically comparable to Bentonite Sulphur (S2) but greatly above Elemental Sulphur (S3). Elemental Sulphur exhibited the smallest plant heights of 45.26, 134.65, 153.16, and 158.44 cm at their respective growth phases. In comparison to Elemental Sulphur, Gypsum enhanced plant height by 12.8% at 30 DAS, 10.2% at 60 DAS, 12.1% at 90 DAS, and 11.1% at 120 DAS. In terms of agrochemical applications, A6 markedly enhanced plant height, achieving peak values of 51.83, 150.04, 178.12, and 183.41 cm at 30, 60, 90, and 120 days after sowing, respectively. A0 and A5 closely followed, demonstrating statistical comparability to A6 in the early stages, but exhibiting somewhat inferior performance in the later stages. The lowest plant height was observed in A7, measuring 44.27, 132.58, 148.92, and 153.88 cm at 30, 60, 90, and 120 DAS, reflecting significant decreases of 14.6%, 11.6%, 16.4%, and

16.1%, respectively, relative to A6. Treatments A2, A3, and A7 performed significantly inferior to other agrochemical combinations, particularly in the later stages. The simultaneous application of Hydrogel and Salicylic acid throughout the flowering and pod formation stages (A6), in conjunction with Gypsum as a sulphur source (S1), showed the highest effectiveness in enhancing the height of Gobhi Sarson under regulated irrigation conditions. The S1A6 treatment achieved the highest plant height at all intervals: 54.32 cm at 30 DAS, 155.05 cm at 60 DAS, 185.41 cm at 90 DAS, and 189.94 cm at 120 DAS. Although the S1A6 treatment showed the greatest plant height at all stages, in comparison to the control treatment S1A0 (53.18, 155.98, 184.77, and 189.42 cm, at 30, 60, 90, and 120 DAS respectively) having minor differences and not statistically significant, suggesting both treatments were equally effective in promoting plant growth. Similar outcomes were observed with S2A6 (52.79, 153.55, 183.60, and 189.39 cm) and S2A0 (52.76, 153.47, 183.14, and 189.18 cm), indicating that the combination of gypsum and bentonite sulphur with hydrogel and salicylic acid at both flowering and pod formation stages resulted in optimal development. The minimum plant height was continuously observed under restricted irrigation with elemental sulphur (S3A7), measuring 41.01 cm at 30 DAS, 124.38 cm at 60 DAS, 138.24 cm at 90 DAS, and 143.38 cm at 120 DAS, indicating a decrease of approximately 24–26% relative to the optimal treatment (S1A6). Therefore, S1A6 emerged as the most efficacious treatment, whereas S3A7 proved to be the least effective during all growth stages. Gypsum (S1) reliably yielded the tallest plants during all stages, especially when paired with hydrogel + salicylic acid (A6), whereas treatments involving elemental sulphur (S3) and limited irrigation (A7) contributed to the shortest plant heights. Despite differences at earlier stages, some treatments displayed non-significant (NS) differences in plant height at maturity. At 120 DAS, for instance, treatments such as S1A1 and S2A1 did not vary much, despite having higher early growth. This could be the result of compensatory growth, environmental variables such as soil moisture and nutrient availability, or the GSC-7 variety's genetic potential. Similarly, treatments with NS differences at lower heights, such as S3A2 and S3A3, indicate that final height was more influenced by treatment–environment interactions and natural plant variability than by the treatments themselves. These NS findings emphasize the importance of evaluating treatment effects on oilseed crop development with sensitivity. These NS results highlight the need for cautious interpretation of treatment effects on growth in oilseed crops. Treatments that included hydrogel and salicylic acid, particularly when used together, demonstrated effectiveness in encouraging growth as compared to other treatments when applied individually. This analysis emphasizes the beneficial effects of gypsum-based treatments with hydrogel and salicylic acid in enhancing plant height in rapeseed (Gobhi Sarson) across various irrigation and sulphur management strategies. Sulphur is an important macronutrient integral to the synthesis of amino acids, proteins, and other vital plant enzymes. It is vital for plant growth and development, especially in oilseed crops such as rapeseed, since it facilitates the synthesis of sulphur- containing chemicals necessary for oil production and overall biomass accumulation. This study tested three sources of Sulphur— gypsum (S1), bentonite Sulphur (S2), and elemental Sulphur (S3)—to determine their effects on the plant height of Gobhi Sarson (*Brassica napus* L.). The exceptional efficacy of gypsum is due to its prompt availability as a sulphate (SO_4^{2-}), which is the principal form of sulphur assimilated by plants. Sulphate is highly soluble and is easily absorbed by roots, facilitating effective nutrient utilization. The continual presence of sulphur facilitates the production of amino acids like cysteine and methionine, which are crucial for protein synthesis and, consequently, for plant development and cellular division. Bentonite sulphur, while efficacious, requires prior microbial oxidation to transform elemental sulphur into its sulphate form. This microbial oxidation process is contingent upon environmental conditions such as soil moisture, temperature, and microbial activity. Consequently, plants subjected to bentonite sulphur may encounter a postponed availability of accessible sulphur during the initial growth phases, explaining why gypsum surpassed bentonite sulphur at 30 and 60 days after sowing (DAS). As microbial oxidation advances, the efficacy of bentonite sulphur enhances, elucidating why the plant height at 120 DAS is virtually equivalent to that of gypsum. Conversely, elemental Sulphur (S3) necessitates an extended oxidation process to transform into the plant-accessible Sulphate form, elucidating its suboptimal efficacy during the initial growth phases (30 and 60 DAS). Elemental Sulphur is gradually oxidized by soil bacteria, resulting in reduced Sulphur availability for plants during the crucial early phases of growth. The postponed availability of Sulphur may restrict the synthesis of essential proteins and enzymes required for fast growth and development, ultimately leading to reduced plant height during the growth cycle. Several further studies support the results of this experiment about the influence of Sulphur sources on plant height and overall crop performance. Rashmi *et al.,* 2018 indicated that gypsum markedly enhanced plant height and biomass accumulation in oilseed crops owing to its prompt availability as a sulphate source. The research highlighted that plants cultivated with gypsum had superior root and shoot development relative to those treated with elemental Sulphur. The fast absorption of Sulphate guarantees the availability of sulphur during essential growth phases, facilitating optimal plant development. (Al-Mayahi *et al.,* 2024) indicated that crops treated with accessible sulphur sources, such as gypsum, exhibited enhanced shoot height and biomass output relative to those treated with elemental sulphur, especially under poor soil conditions. The research indicated that gypsum sustains elevated Sulphur concentrations in the root zone, facilitating improved Sulphur absorption and usage by plants, resulting in greater growth. (Ahmad *et al.,* 2005) conducted a study on the impact of sulphur fertilization on rapeseed, revealing that gypsum applications markedly enhanced plant height, chlorophyll content, and overall yield. The research further verified that the transformation of elemental sulphur into plant-accessible Sulphate is gradual and may result in Sulphur deficits during the initial growth phases, adversely affecting plant height and yield. Gypsum is the optimal sulphur source for rapeseed development, owing to its capacity to fulfill the crop's immediate sulphur needs. Its prompt availability as sulphate guarantees that plants obtain a sufficient supply of Sulphur during all growth phases. To get optimal results, gypsum must be applied at the basal dose to guarantee the availability of Sulphur during the crucial early vegetative stages, which significantly influence final plant height and overall crop output. Gypsum is especially beneficial for farmers or researchers, where microbial activity is constrained by soil temperature or moisture, as it circumvents the requirement for microbial oxidation, in contrast to bentonite or elemental Sulphur. Bentonite sulphur, although efficacious, should be contemplated in soils exhibiting elevated microbial activity, where oxidation may transpire more swiftly. Elemental sulphur is undesirable for rapeseed, particularly during the initial growth phases, unless applied enough before sowing to provide proper microbial oxidation. When using elemental Sulphur, it should be integrated with methods that promote microbial activity, such as incorporating organic matter or employing soil inoculants, to expedite the conversion process. Therefore, from the obtained results, it can be concluded that sulphur sources significantly influence plant height in rapeseed. Gypsum, being the most accessible source of sulphur, yielded optimal results regarding plant height across all growth phases. The postponed accessibility of sulphur from bentonite and elemental sulphur constrained their efficacy in the initial phases, however, bentonite sulphur exhibited comparable performance to gypsum in the subsequent phases. Recent research supports these findings, emphasizing the need to utilize accessible sulphur sources to guarantee maximum plant growth and productivity in oilseed crops (Khalifa *et al.,* 2024; Kumar Singh *et al.,* 2012; Nabati *et al.,* 2025; Nadeem *et al.,* 2023; A. Yadav *et al.,* 2023).

Moreover, hydrogel, a superabsorbent polymer, possesses the capacity to absorb and retain substantial quantities of water within its mass. This attribute renders it an invaluable instrument for enhancing water accessibility in plants, especially in moisture-stressed environments. In the study, hydrogel was applied at a rate of 2.5 kg/ha, and the findings indicated that hydrogel treatments resulted in enhanced plant height at all growth stages in comparison to the control (limited irrigation). The enhancement in plant height resulting from hydrogel application is mostly due to its capacity to promote soil water retention, particularly in scenarios of restricted irrigation or moisture stress. Hydrogel absorbs water during rainfall or irrigation and gradually delivers moisture to the plant root zone over time. This guarantees that plants obtain a more reliable water supply during essential growth phases, mitigating the impacts of water stress, which can substantially limit cell division and overall growth. Water stress adversely impacts the elongation of plant cells by diminishing turgor pressure, essential for cell expansion and vertical growth. Hydrogel alleviates this stress by preserving elevated soil moisture levels, which sustains turgor pressure, facilitating ongoing cell elongation and growth, particularly during arid conditions (Ashraf *et al.,* 2021; Thirupathaiah, 2019). Patra et al. (2022) conducted a study revealing that hydrogel treatment enhanced water-use efficiency in multiple crops, including oilseeds such as rapeseed, resulting in notable improvements in plant height and biomass accumulation. The study emphasized that hydrogel coatings enabled plants to retain more water content in their tissues, hence enhancing growth in water-scarce environments. (Bai *et al.,* 2020) indicated that hydrogels in rapeseed cultivation markedly enhanced plant height, leaf area, and total biomass under controlled irrigation and moisture-stress conditions. The research demonstrated that hydrogel enhanced the soil's water retention capability, consequently facilitating root development and water uptake over the plant's life cycle. Teng et al. (2024) discovered that hydrogel applications in arid and semi-arid environments enhanced plant height and yield in multiple crops by alleviating drought stress effects. The study advocated for hydrogel as a viable instrument for enhancing agricultural performance, especially in regions susceptible to erratic rainfall patterns. Salicylic acid (SA) is a phytohormone recognized for its function in regulating plant development, enhancing stress tolerance, and facilitating defense mechanisms. Salicylic acid was applied at 150 ppm during two distinct growth phases: at 50% flowering (A2) and 50% pod formation (A3). The results demonstrated that plants treated just with SA exhibited reduced height in comparison to those receiving hydrogel or control treatments with required irrigation. Salicylic acid serves a dual function in plants. It can improve stress resilience and influence development by regulating multiple physiological processes, such as photosynthesis, transpiration, and enzymatic activity. Nonetheless, its impact on plant height may fluctuate depending on the concentration applied, the timing of treatment, and the prevailing climatic conditions. The involvement of SA in enhancing stress tolerance may be advantageous in environmental stress situations, aiding plants in sustaining physiological activity and recuperating from stress-induced damage. The concentration of SA and the timing of its application are crucial in influencing its overall impact on plant height. Recent findings validate the intricate function of salicylic acid in plant development and stress regulation (El-Tohamy *et al.,* 2024; Meena *et al.,* 2020; Song *et al.,* 2023). Li et al. (2023) discovered that salicylic acid can improve stress tolerance in crops by modulating antioxidant enzyme activities; however, it may impede development when applied at elevated doses or in the absence of stress conditions. The study emphasized that SA serves a protective function in alleviating the impacts of environmental challenges such as drought, heat, and salinity; nevertheless, its effect on growth processes, including plant height, may differ. Yang et al. (2023) indicated that the treatment of salicylic acid during pivotal growth phases enhanced stress resilience and augmented biomass in oilseed crops; however, the impact on plant height was contingent upon the time and concentration of application. The study advised the application of SA under stress conditions to equilibrate growth and defensive responses. (Jahan *et al.,* 2023) revealed that salicylic acid enhanced drought and heat tolerance in rapeseed, although its impact on plant height was less significant than that of hydrogels or other growth-promoting agents. Singh et al. proposed that the advantages of SA may be more pronounced in yield quality and stress resilience rather than in direct impacts on indicators of growth, such as the height of the plant. The combination of hydrogel along with salicylic acid (A4, A5, A6) had a synergistic effect, resulting in enhanced plant height relative to treatments with salicylic acid alone. The amalgamation of hydrogel and SA at 50% flowering and pod formation (A6) yielded the tallest plants in the trial, measuring 51.83 cm at 30 DAS and 183.41 cm at 120 DAS, equivalent to or marginally superior to the control with standard irrigation (A0). The synergistic impact results from the hydrogel increasing water availability, hence facilitating general growth, while salicylic acid augments stress tolerance and physiological functions. The combination enables plants to enhance growth and defensive mechanisms, leading to improved overall development and resilience in diverse environmental situations. Yadav et al. (2025) conducted a study indicating that the synergistic application of hydrogel resulted in substantial enhancements in plant height, biomass, and yield of oilseed crops in water-scarce environments. Mahto et al. (2023) indicated that the integration of hydrogel with phytohormones such as salicylic acid enhanced plant height and yield in crops subjected to moisture-stress conditions. The research highlighted the significance of utilizing both compounds concurrently to optimize their respective advantages for plant growth and stress mitigation. In summary, the agrochemicals examined in this study, hydrogel and salicylic acid, exhibited unique and synergistic effects on the height of rapeseed plants. Hydrogel markedly increased plant height by augmenting water retention and accessibility, whilst salicylic acid had a multifaceted effect in modulating growth and stress responses. The concurrent application of hydrogel and SA had a synergistic impact, resulting in enhanced plant height and growth under both optimal and moisture-restricted conditions. Recent investigations corroborate these findings, demonstrating that both hydrogel and salicylic acid significantly contribute to the enhancement of plant height, especially under conditions of environmental stress.

Table 4.1.1.1: Treatment impact on rapeseed height (cm) recorded at periodic intervals in *Rabi* 2021–22 and 2022–23

Treatments	Plant height(cm) 2021-2022				Plant height(cm) 2022-2023			
Intervals	30 DAS	60 DAS	90 DAS	120 DAS	30 DAS	60 DAS	90 DAS	120 DAS
Sulphur sources								
S1: Gypsum	49.51^{a}	148.23^{a}	170.22^{a}	175.40^{a}	51.04^{a}	148.35^{a}	171.75^{a}	176.09^{a}
S2: Bentonite Sulphur	47.98^{b}	142.36^{b}	168.08^{a}	173.35^{a}	49.97^{a}	146.55^{a}	170.09^{a}	175.62^{a}
S3: Elemental Sulphur	45.23^{c}	134.50^{c}	155.06^{b}	160.28^{b}	45.26^{b}	134.65^{b}	153.16^{b}	158.44^{b}
CV (Sulphur Sources)	2.01	4.73	8.65	8.56	7.42	2.34	11.03	11.21
CD @ 5% (Sulphur Sources)	0.77	5.37	11.40	11.64	2.90	2.69	14.59	15.28
Agrochemical								
A0: Control (Irrigation as per requirement)	49.42^{a}	148.77^{a}	176.20^{ab}	182.19^{ab}	51.26^{a}	150.08^{a}	177.55^{ab}	183.03^{ab}
A1: Hydrogel (2.5 kg/ha) as basal application	49.23^{a}	144.22^{b}	159.98^{cd}	164.25^{cd}	50.44^{a}	149.13^{a}	160.38^{cd}	164.82^{cd}
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	42.99^{b}	132.63^{c}	158.14^{d}	163.62^{d}	44.56^{b}	133.09^{b}	158.52^{d}	163.92^{d}
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	44.31^{b}	131.14^{c}	158.85^{d}	163.76^{d}	44.79^{b}	132.25^{b}	159.05^{d}	164.00^{d}
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	51.16^{a}	147.88^{ab}	168.39^{bc}	173.62^{abc}	51.96^{a}	148.14^{a}	168.86^{bc}	173.79^{bc}
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	50.44^{a}	146.95^{ab}	168.15^{bc}	173.31^{bc}	50.92^{a}	150.13^{a}	168.60^{bc}	173.53^{c}
A6: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at both 50% flowering and 50% pod formation stage	50.21^{a}	149.68^{a}	177.69^{a}	183.02^{a}	51.83^{a}	150.04^{a}	178.12^{a}	183.41^{a}
A7: Control (Restricted irrigation)	42.83^{b}	132.28^{c}	148.24^{e}	153.62^{e}	44.27^{b}	132.58^{b}	148.92^{e}	153.88^{e}
CD @ 5% (Agrochemical)	1.99	4.41	9.14	9.40	2.79	3.28	8.95	9.29
CV (Sulphur Sources and agrochemical)	4.41	3.27	5.84	5.82	6.01	2.41	5.7	5.75

Table 4.1.1.2: Interaction effect of treatments on rapeseed plant height (cm) at periodic intervals during *rabi* 2021–22 and 2022–23

Treatments	Plant height(cm) 2021-2022				Plant height(cm) 2022-2023			
Intervals	**30 DAS**	**60 DAS**	**90 DAS**	**120 DAS**	**30 DAS**	**60 DAS**	**90 DAS**	**120 DAS**
S1A0	51.22±0.05	152.77±6.03	182.31±12.05	188.19±9.65	53.18±4.52	155.98±2.89	184.77±10.21	189.42±10.89
S1A1	51.00±1.28	153.71±1.91	165.6±11.10	169.81±11.10	53.22±1.33	153.58±3.60	166.95±11.10	170.69±11.10
S1A2	44.57±3.64	140.52±8.19	163.7±13.67	169.16±13.67	46.40±4.88	139.32±3.90	165.01±13.67	169.76±13.67
S1A3	47.90±2.77	134.62±3.37	164.43±22.47	169.30±25.81	46.64±5.57	137.27±1.68	165.56±22.47	169.84±27.58
S1A4	51.91±1.09	157.16±3.88	174.31±22.88	179.50±22.88	54.00±3.65	151.97±2.44	175.77±28.87	179.98±28.87
S1A5	53.03±1.08	154.94±3.76	174.06±13.67	179.18±13.67	54.43±2.17	155.92±3.45	175.50±13.67	179.71±13.67
S1A6	52.62±0.12	153.09±5.65	183.93±10.68	189.21±10.68	54.32±4.55	155.05±5.95	185.41±10.68	189.94±10.68
S1A7	43.79±1.33	138.99±8.15	153.45±2.54	158.82±2.54	46.11±0.98	137.70±2.27	155.02±2.54	159.36±2.54
S2A0	49.66±2.44	153.24±7.61	180.04±12.45	186.26±13.74	52.76±4.64	153.47±6.12	183.14±13.46	189.18±12.58
S2A1	49.06±2.68	135.99±1.18	163.51±1.18	167.79±1.18	51.76±0.38	152.54±1.48	165.31±1.18	170.19±1.18
S2A2	44.02±3.64	134.50±4.88	161.63±4.88	167.15±4.88	45.95±4.88	136.12±4.88	163.39±4.88	169.27±4.88
S2A3	44.21±3.70	135.24±4.84	162.36±4.84	167.29±4.84	46.19±4.84	135.87±4.84	163.94±4.84	169.35±4.84
S2A4	52.54±2.48	145.91±5.86	172.11±5.86	177.36±5.86	53.50±2.31	150.50±2.62	174.05±5.86	179.46±5.86
S2A5	49.38±0.23	145.37±0.26	171.86±0.26	177.05±0.26	51.08±1.82	154.67±2.05	173.78±0.26	179.19±0.26
S2A6	49.70±3.12	154.66±8.92	181.61±13.49	186.96±13.49	52.79±1.72	153.55±5.46	183.60±13.36	189.39±13.36
S2A7	45.29±1.95	133.99±1.74	151.51±17.82	156.93±17.82	45.69±0.85	135.66±1.19	153.50±10.83	158.90±10.83
S3A0	47.39±0.28	140.30±0.34	166.24±1.20	172.13±0.68	47.83±0.72	140.80±0.51	164.73±0.61	170.48±0.53
S3A1	47.63±0.68	142.97±2.45	150.83±0.89	155.15±0.89	46.35±1.70	141.27±1.18	148.88±0.89	153.57±0.83
S3A2	40.38±0.40	122.88±1.18	149.09±1.18	154.56±1.18	41.33±1.18	123.84±1.18	147.15±1.18	152.74±1.18
S3A3	40.83±0.51	123.56±4.86	149.76±4.86	154.69±4.86	41.54±4.86	123.61±4.86	147.65±4.86	152.81±4.86
S3A4	49.01±2.94	140.56±6.84	158.76±4.95	164.00±4.95	48.39±2.58	141.94±3.41	156.75±4.95	161.93±4.95
S3A5	48.91±0.17	140.54±3.76	158.53±0.89	163.71±0.89	47.25±1.19	139.82±2.70	156.51±0.89	161.69±0.89
S3A6	48.31±0.23	141.30±0.26	167.52±0.27	172.88±0.26	48.38±0.26	141.51±0.26	165.35±0.26	170.90±0.26
S3A7	39.41±0.47	123.85±1.43	139.76±0.27	145.11±0.26	41.01±1.68	124.38±2.79	138.24±0.26	143.38±0.26
CV	4.41	3.27	5.84	5.82	6.01	2.41	5.7	5.75
CD @5%	3.31	8.85	18.49	18.97	NS	5.92	NS	NS

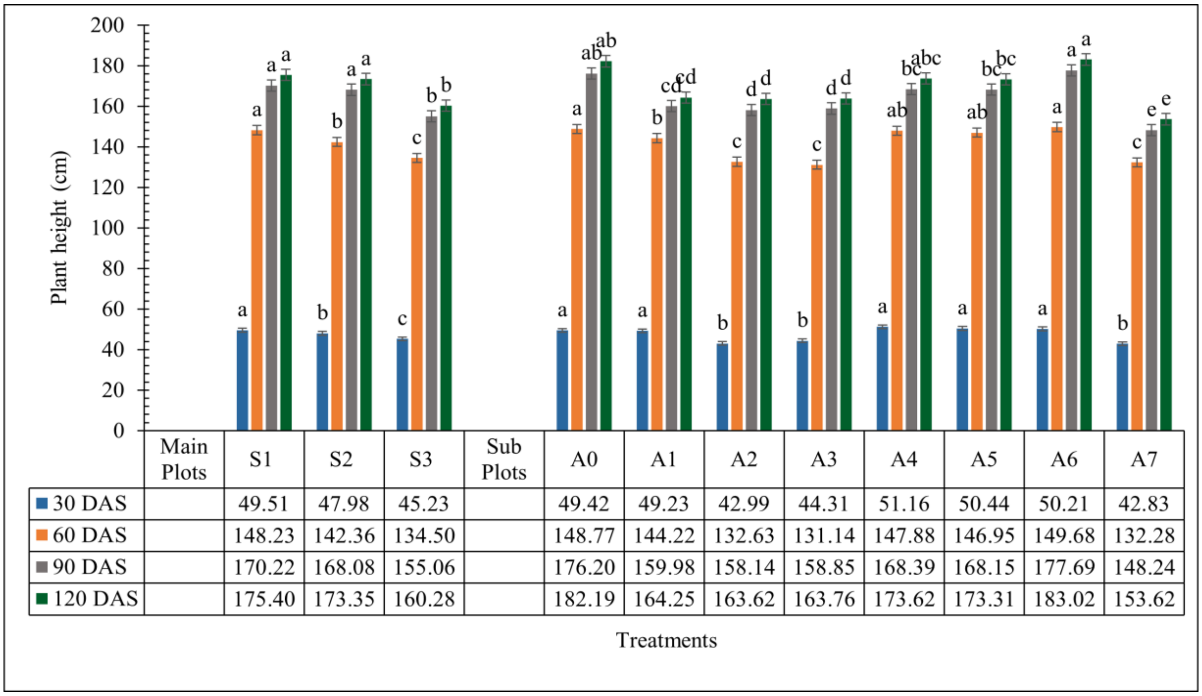


Fig. 4.1.1.1 (a) Treatment impact on rapeseed height (cm) recorded at periodic intervals in *Rabi* 2021–22

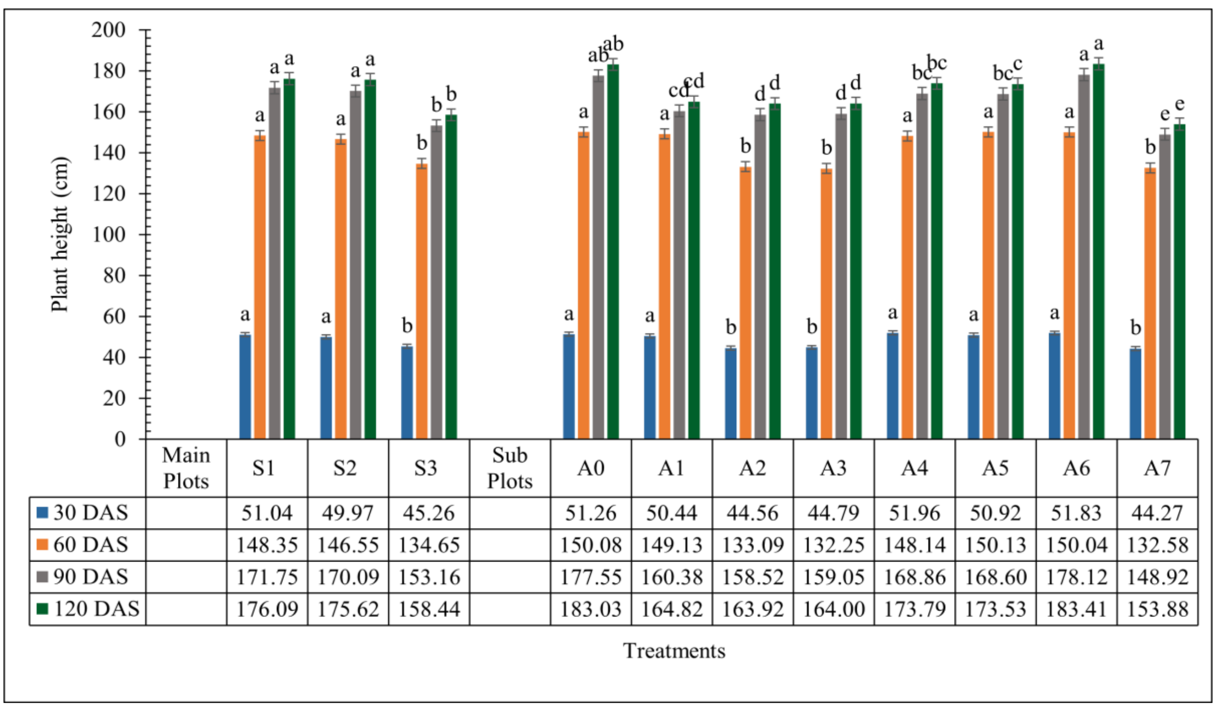


Fig. 4 .1.1.1 (b) Treatment impact on rapeseed height (cm) recorded at periodic intervals in *Rabi* 2022–23

4.1.2 Dry matter accumulation (gm): The evaluation of dry matter accumulation of the gobhi Sarson variety GSC 7 at 30, 60, 90, and 120 days after sowing (DAS) during the *rabi* seasons of 2021-2022 and 2022-2023 indicates significant variations among the sulphur sources and agrochemical treatments, with a distinct trend evident as the crop progressed through its growth stages as shown in Tables 4.1.2.1, 4.1.2.2, and Figures 4.1.2.1(a), 4.1.2.2(b). The outcomes from two consecutive *rabi* seasons offer significant insights into the effects of different sulphur sources and agrochemicals application on dry matter yield in GSC 7. Among the investigated in the year 2021-2022, sulphur sources gypsum (S1) consistently produced the greatest dry matter at all growth stages. Gypsum (S1) had the greatest dry matter accumulation among sulphur sources at all growth stages, with values of 160.72, 259.38, 250.64, and 249.46 g/plant at 30, 60, 90, and 120 days after sowing, respectively. These levels were markedly elevated compared to Bentonite Sulphur (S2) and Elemental Sulphur (S3). The minimal dry matter buildup was recorded in Elemental Sulphur (S3), with values of 141.14, 230.33, 217.68, and 216.37 g/plant at various phases, much lower than those of Bentonite Sulphur (S2) and Gypsum (S1). Bentonite sulphur (S2) exhibited intermediate values, markedly superior to Elemental Sulphur yet considerably inferior to Gypsum. Gypsum (S1) enhanced dry matter accumulation compared to Elemental Sulphur (S3) by 13.9% at 30 DAS, 12.6% at 60 DAS, 15.1% at 90 DAS, and 15.3% at 120 DAS. A6 yielded the greatest dry matter values— 157.54, 261.05, 258.75, and 258.21 g/plant at 30, 60, 90, and 120 DAS, respectively. This treatment was markedly more effective than all other treatments at 90 and 120 DAS and statistically comparable to A0 (Control with irrigation) and A1, A4, A5 during the initial phases (30 and 60 DAS). A0 (Control with irrigation) reported values of 157.46, 261.13, 254.60, and 252.47 g/plant, respectively, exhibiting no significant differences as compared to A6 at 30 and 60 days after sowing (DAS), but demonstrating significantly lower values at subsequent stages. A7 (Control with restricted irrigation) demonstrated the least dry matter accumulation, recording 144.70, 224.92, 212.39, and 211.36 g/plant, which corresponded to reductions of 8.1%, 13.8%, 17.9%, and 18.1% at the corresponding stages compared to A6. Treatments A2, A3, and A7 consistently exhibited the lowest and significantly poorer dry matter values across all growth stages. Treatments A2 and A3, which involved the application of Salicylic acid solely during flowering or pod formation, exhibited considerably worse results than the other treatments at

90 and 120 days after sowing (DAS) and were categorized with A7 at those intervals. In conclusion, Gypsum (S1) as the sulphur source and the combined treatment of Hydrogel + Salicylic acid (A6) was identified as a considerably superior combination for enhancing dry matter formation in Gobhi Sarson under controlled irrigation. The S1A6 treatment exhibited the largest dry matter accumulation across all growth stages: 165.58 g/plant at 30 DAS, 272.95 g at 60 DAS, 273.12 g at 90 DAS, and 271.62 g at 120 DAS. The values for S1A0 (control) were 166.69, 271.84, 269.37, and 269.35 g/plant, respectively. Alternative treatments demonstrating similar outcomes include S1A5 (166.26, 273.68, 255.44, and 254.38 g/plant) and S2A6 (159.24, 264.01, 265.66, and 264.18 g/plant). The minimum dry matter was recorded under S3A7 (Elemental sulphur + salicylic acid at both stages under restricted irrigation), with values of 132.29, 205.31, 194.92, and 194.19 g/plant, indicating a decrease of 22–33% relative to S1A6. Consequently, S1A6 proved to be the most effective treatment for increasing dry matter accumulation, whereas S3A7 was the least effective during all growth stages. Statistically significant changes were observed among treatments, with S1A6 demonstrating superior performance compared to S3A7.

Consistent with the results from the previous *rabi* season, dry matter accumulation (g/plant) in Gobhi Sarson at 30, 60, 90, and 120 DAS during the *rabi* season of 2022–23 exhibited statistically significant variations among sulphur sources and agrochemical treatments at all growth stages. Gypsum (S1) exhibited considerably greater dry matter accumulation at all periods—164.71, 262.57, 252.50, and 249.53 g/plant, respectively. These levels were significantly increased compared to Bentonite Sulphur (S2) and Elemental Sulphur (S3). Elemental Sulphur (S3) regularly exhibited the lowest and statistically lower values of 142.69, 232.17, 219.90, and 215.24 g/plant. Bentonite Sulphur (S2) exhibited acceptable performance, markedly inferior to Gypsum yet notably superior to Elemental Sulphur at all stages. Gypsum enhanced dry matter compared to Elemental Sulphur by 15.4% at 30 days after sowing (DAS), 13.1% at 60 DAS, 14.8% at 90 DAS, and 15.9% at 120 DAS. Among agrochemical treatments, A6 yielded the highest dry matter accumulation at 90 and 120 days after sowing—260.45 and 257.47 g/plant, respectively, while remaining statistically comparable to A0 (Control with irrigation) and A5 (Hydrogel + Salicylic acid at pod formation) at 30 and 60 days after sowing. A0, A4, and A5 exhibited statistical similarity to A6 during early growth stages but demonstrated significantly lower values at 90 and 120 days after sowing (DAS). Conversely, the lowest and markedly poorer dry matter was seen in A7 (Control with restricted irrigation)— 145.38, 231.01, 214.11, and 207.28 g/plant, leading to losses of 10.5%, 11.9%, 17.8%, and 19.5%, respectively, in comparison to A6. Treatments A2 and A3, which utilized salicylic acid application during flowering or pod formation only, exhibited drastically lower outcomes than the majority of other treatments during all stages and were statistically grouped with A7 at 90 and 120 days after sowing (DAS). The utilization of Gypsum (S1) as a sulphur source, in conjunction with the integrated agrochemical treatment A6, emerged as the most effective combination for promoting dry matter buildup in Gobhi Sarson under controlled irrigation. The S1A6 treatment exhibited the highest dry matter production at all growth stages: 173 g/plant at 30 DAS, 274.97 g at 60 DAS, 274.14 g at 90 DAS, and 272.18 g at 120 DAS. The data were marginally elevated compared to S1A0 (control), which documented 171.88, 273.03, 269.83, and 268.86 g/plant, respectively. Alternative treatments demonstrating similar outcomes included S2A6 (165.62, 265.26, 267.58, and 264.72 g/plant) and S2A0 (163.22, 268.74, 260.77, and 259.57 g/plant). The minimum dry matter was recorded under S3A7 (Elemental sulphur + salicylic acid at both stages under restricted irrigation), with values of 134.86, 207.34, 197, and 181.43 g/plant, indicating a decrease of 22–33% relative to S1A6. Consequently, S1A6 proved as the most effective treatment for augmenting dry matter accumulation, whereas S3A7 was the least efficacious during all growth stages.

The variation in dry matter production among different sulphur sources can be attributed to the unique chemical properties and mechanisms of sulphur availability in the soil, which influence plant metabolism, nutrient uptake, and growth. Sulphur is a vital macronutrient that plays a critical role in physiological activities such as protein synthesis, enzyme activation, and chlorophyll formation, all of which significantly impact biomass accumulation. Gypsum ($CaSO_4 \cdot 2H_2O$) consistently yielded the highest dry matter production during all stages of crop growth. This is due to the immediate availability of sulphate (SO_4^{2-}), the form of sulphur that plants absorb most readily. Sulphate exhibits high solubility and does not necessitate microbial oxidation for plant uptake, thus becoming readily available to plants immediately following application. Research indicates that sulphate-based fertilization, such as gypsum, improves nitrogen uptake and utilization efficiency, resulting in enhanced protein synthesis and chlorophyll formation, both essential for photosynthesis and biomass accumulation.

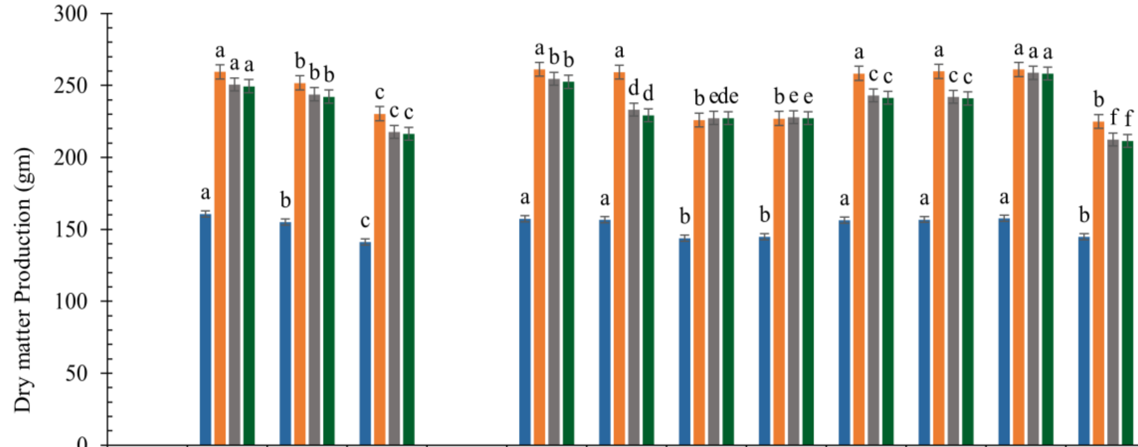
(Narayan *et al.,* 2023; Shafiq *et al.,* 2021). The availability of sulphur in gypsum facilitates root development and nutrient uptake, accounting for the increased dry matter production observed at early growth stages (30 and 60 DAS). As the crop progresses, gypsum consistently provides sulphur effectively, resulting in prolonged plant growth and biomass accumulation. Bentonite Sulphur, a granulated product comprising elemental sulphur and clay, exhibited moderate performance relative to gypsum. Elemental sulphur in bentonite requires microbial oxidation to be transformed into sulphate, which is the absorbable form for plants. The process is slow and contingent upon microbial activity, temperature, and soil moisture conditions, which accounts for the relatively lower dry matter production during the growth. The reduction in dry matter production at 90 DAS in rapeseed (Gobhi Sarson) can be attributed to many physiological and environmental causes during this developmental phase of the plant. Approximately 90 days after sowing, rapeseed plants often commence the reproductive phase, during which the allocation of the plant's resources transitions from vegetative growth (leaves, stems) to reproductive structures (flowers, pods, and seeds). This change diminishes the buildup of dry matter in vegetative structures as the plant diverts more energy towards seed development, which is important for reproductive success. During seed development, the plant allocates assimilates (sugars, nutrients) from vegetative structures (leaves and stems) to reproductive organs (flowers and forming seeds). This reallocation of resources leads to a reduction in dry matter accumulation in the vegetative components, resulting in a noticeable decrease in total dry matter output. During the reproductive phase, the photosynthetic rate in leaves frequently diminishes due to variables such as leaf senescence, reduced leaf area, and diminished chlorophyll content. The reduction in photosynthetic activity results in diminished energy generation, thereby impairing the plant's capacity to produce new biomass. The utilization of gypsum as a sulphur source markedly enhanced biomass and yield in Brassica crops, in contrast to elemental sulphur, owing to the speedy availability of sulphate for plant absorption (Reddy Kodavali & Khurana, 2022). Hydrogels possess the capacity to absorb substantial quantities of water and then release it gradually to plants, which is very advantageous in controlled irrigation systems. This persistent water supply alleviates water stress and promotes plant development, resulting in increased dry matter production. Superabsorbent polymers (SAPs) may assist in nutrient retention within the root zone by minimizing leaching. Enhanced nutrient accessibility enables plants to achieve elevated growth rates and develop greater biomass. Hydrogels enhance root development by facilitating more effective moisture access for roots. Improved root systems can augment the absorption of water and nutrients, hence enhancing dry matter output. In conclusion, Salicylic acid augments stress resilience and metabolic function, whereas superabsorbent polymers promote water accessibility and root efficacy. Collectively, they can synergistically augment dry matter production, particularly in water-scarce conditions (Ali *et al.,* 2024). Salicylic acid (SA) and hydrogels, including superabsorbent polymers (SAPs), can substantially influence dry matter production in plants, especially under controlled irrigation conditions. Salicylic acid functions as a signaling molecule in plants, facilitating the induction of systemic acquired resistance (SAR) and enhancing tolerance to abiotic conditions such as drought and salinity. By mitigating stress-induced damage, plants can redirect additional energy towards growth, hence enhancing biomass and dry matter output. SA optimizes photosynthesis by modulating stomatal function and augmenting chlorophyll concentration, resulting in improved carbon assimilation and increased dry matter yield. SA modulates several growth hormones, such as auxins, which can enhance root and shoot development, thus improving the plant's capacity to absorb water and nutrients, leading to increased dry matter accumulation. The data reveal a distinct trend where gypsum treatments consistently yielded the maximum dry matter production, followed by Bentonite, whereas Elemental Sulphur showed the least efficacy. The utilization of agrochemicals, specifically Hydrogel and Salicylic acid, together with gypsum, markedly improved dry matter formation, especially during pivotal growth phases. (Raza *et al.,* 2022).

Table 4.1.2.1: Treatment impact on dry matter production (gm) of rapeseed at periodic intervals in *rabi* 2021–22 and 2022–23

Treatments	Dry matter production (gm) 2021-2022				Dry matter production (gm) 2022-2023			
Intervals	**30 DAS**	**60 DAS**	**90 DAS**	**120 DAS**	**30 DAS**	**60 DAS**	**90 DAS**	**120 DAS**
Sulphur sources								
S1: Gypsum	160.72^{a}	259.38^{a}	250.64^{a}	249.46^{a}	164.71^{a}	262.57^{a}	252.50^{a}	249.53^{a}
S2: Bentonite Sulphur	154.98^{b}	251.75^{b}	243.82^{b}	242.20^{b}	157.84^{b}	253.75^{b}	245.44^{b}	242.33^{b}
S3: Elemental Sulphur	141.14^{c}	230.33^{c}	217.68^{c}	216.37^{c}	142.69^{c}	232.17^{c}	219.90^{c}	215.24^{c}
CV (Sulphur Sources)	2.11	1	1.44	1.03	1.51	0.95	1.41	0.87
CD @5% (Sulphur Sources)	2.57	1.98	2.74	1.94	1.87	1.89	2.70	1.65
Agrochemical								
A0: Control (Irrigation as per requirement)	157.46^{a}	261.13^{a}	254.60^{b}	252.47^{b}	160.84^{ab}	262.59^{a}	254.95^{b}	254.41^{b}
A1: Hydrogel (2.5 kg/ha) as basal application	156.55^{a}	259.24^{a}	233.10^{d}	229.25^{d}	159.01^{b}	262.28^{ab}	234.80^{e}	229.08^{d}
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	143.77^{b}	225.88^{b}	227.38^{e}	227.34^{de}	145.00^{c}	229.56^{cd}	228.87^{f}	227.69^{d}
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	144.92^{b}	226.98^{b}	227.81^{e}	227.21^{e}	145.34^{c}	227.89^{d}	229.84^{f}	227.53^{d}
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	156.46^{a}	258.32^{a}	242.98^{c}	241.33^{c}	161.34^{a}	259.70^{b}	247.24^{c}	241.04^{c}
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	156.84^{a}	259.70^{a}	242.00^{c}	240.91^{c}	161.36^{a}	260.82^{ab}	243.98^{d}	241.10^{c}
A6: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at both 50% flowering and 50% pod formation stage	157.54^{a}	261.05^{a}	258.75^{a}	258.21^{a}	162.39^{a}	262.13^{ab}	260.45^{a}	257.47^{a}
A7: Control (Restricted irrigation)	144.70^{b}	224.92^{b}	212.39^{f}	211.36^{f}	145.38^{c}	231.01^{c}	214.11^{g}	207.28^{e}
CD @5% (Agrochemical)	4.36	3.51	3.52	2.00	2.24	2.69	2.99	2.82
CV (Sulphur Sources and agrochemical)	3.01	1.49	1.56	0.89	1.52	1.13	1.31	1.26

Table 4.1.2.2: Interaction effect of treatments on dry matter production (gm) of rapeseed during *rabi* 2021–22 and 2022–23

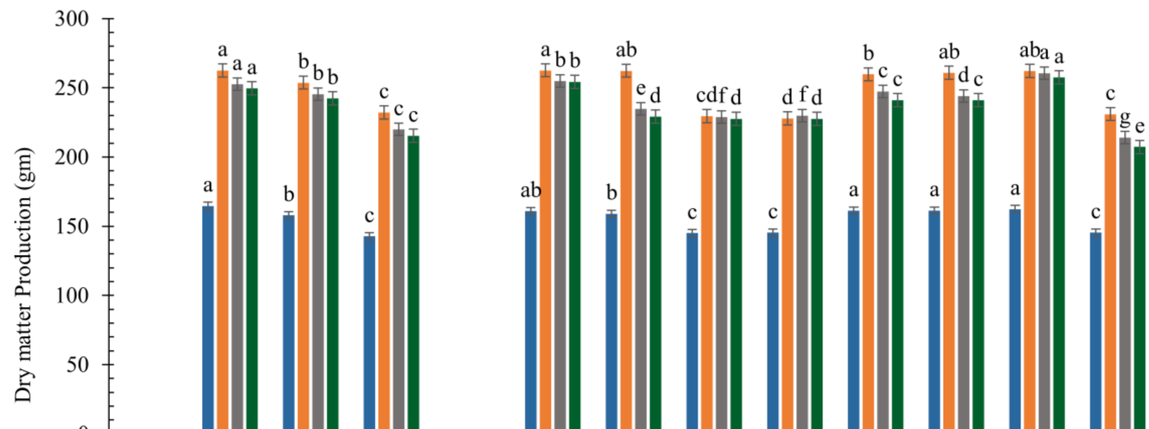
Treatments	Dry matter production (gm) 2021-2022				Dry matter production (gm) 2022-2023			
Intervals	30 DAS	60 DAS	90 DAS	120 DAS	30 DAS	60 DAS	90 DAS	120 DAS
S1A0	166.69±2.38	271.84±0.52	269.37±1.73	269.35±0.54	171.88±2.50	273.03±2.47	269.83±1.49	268.86±0.56
S1A1	166.37±5.44	270.33±0.94	246.04±1.01	241.74±0.12	167.68±1.67	274.62±5.35	247.14±1.01	240.64±4.41
S1A2	150.21±3.48	238.44±1.76	240.01±1.16	240.59±2.12	153.32±3.25	245.09±3.30	240.90±1.16	242.66±3.58
S1A3	153.21±0.65	240.47±0.65	240.46±0.65	240.11±0.65	155.45±3.71	242.34±1.30	241.92±1.30	240.28±1.30
S1A4	164.57±0.90	269.43±1.88	256.47±1.87	254.82±1.87	173.23±2.33	271.13±1.59	263.92±4.84	253.78±2.60
S1A5	166.26±3.54	273.68±2.15	255.44±2.27	254.38±2.27	170.07±1.55	273.51±3.71	256.80±2.27	254.61±2.27
S1A6	165.58±3.40	272.95±0.85	273.12±0.85	271.62±0.85	173.00±2.48	274.97±0.85	274.14±0.85	272.18±0.85
S1A7	152.87±0.16	237.87±3.31	224.18±0.16	223.09±0.16	153.07±1.23	245.90±0.16	225.36±0.16	223.27±0.16
S2A0	159.43±9.77	265.28±4.03	262.21±2.65	259.89±0.40	163.22±0.93	268.74±1.14	260.77±1.46	259.57±1.23
S2A1	157.07±2.40	262.90±3.86	239.32±0.51	235.42±1.67	162.16±3.17	265.18±4.42	241.23±0.51	235.94±1.58
S2A2	148.39±9.95	232.25±9.95	233.45±9.95	233.09±3.26	148.50±0.26	234.52±0.26	235.13±0.50	231.99±1.10
S2A3	148.62±9.17	232.93±9.17	233.89±9.17	232.97±0.78	147.29±2.21	231.76±4.05	236.13±9.17	233.69±4.42
S2A4	158.36±2.35	263.31±2.70	249.47±2.35	247.84±2.35	162.41±2.99	261.26±2.35	252.07±2.35	247.98±2.35
S2A5	159.84±2.80	261.73±2.45	248.46±9.17	247.41±4.42	165.35±2.25	263.46±4.05	250.66±9.17	247.63±9.17
S2A6	159.24±2.11	264.01±2.86	265.66±2.19	264.18±2.19	165.62±1.92	265.26±2.01	267.58±2.19	264.72±2.19
S2A7	148.92±7.06	231.58±2.14	218.06±0.94	216.81±3.21	148.22±1.57	239.79±0.12	219.97±0.94	217.15±2.79
S3A0	146.27±2.91	246.27±2.64	232.22±1.85	228.17±1.58	147.40±0.97	245.99±3.52	234.26±2.06	234.82±0.19
S3A1	146.22±3.00	244.50±4.19	213.93±0.09	210.59±0.09	147.18±2.78	247.03±2.96	216.03±0.09	210.67±0.09
S3A2	132.72±0.12	206.94±0.12	208.68±0.12	208.36±0.12	133.18±0.12	209.07±0.12	210.58±0.12	208.43±0.12
S3A3	132.93±0.49	207.54±0.49	209.08±0.49	208.56±0.49	133.29±0.49	209.57±0.49	211.47±0.49	208.62±0.49
S3A4	146.45±3.75	242.21±1.00	223.00±0.50	221.33±0.50	148.37±5.42	246.71±4.69	225.74±0.50	221.37±0.50
S3A5	144.42±4.16	243.70±5.17	222.10±1.09	220.95±1.09	148.66±3.45	245.50±3.62	224.48±1.09	221.06±0.09
S3A6	147.79±1.00	246.20±1.40	237.47±2.05	238.82±3.37	148.54±1.00	246.16±3.72	239.63±2.05	235.51±0.15
S3A7	132.29±2.51	205.31±3.95	194.92±2.05	194.19±5.01	134.86±1.00	207.34±1.93	197.00±2.05	181.43±4.36
CV	3.01	1.49	1.56	0.89	1.52	1.13	1.31	1.26
CD @5%	7.48	6.00	6.28	3.75	4.05	4.72	5.50	4.84



	Main Plots	S1	S2	S3	Sub Plots	A0	A1	A2	A3	A4	A5	A6	A7
30 DAS		160.72	154.98	141.14		157.46	156.55	143.77	144.92	156.46	156.84	157.54	144.70
60 DAS		259.38	251.75	230.33		261.13	259.24	225.88	226.98	258.32	259.70	261.05	224.92
90 DAS		250.64	243.82	217.68		254.60	233.10	227.38	227.81	242.98	242.00	258.75	212.39
120 DAS		249.46	242.20	216.37		252.47	229.25	227.34	227.21	241.33	240.91	258.21	211.36

Treatments

Fig. 4 .1.2.1 (a) Treatment impact on dry matter production (gm) of rapeseed at periodic intervals in *rabi* 2021–22



	Main Plots	S1	S2	S3	Sub Plots	A0	A1	A2	A3	A4	A5	A6	A7
30 DAS		164.71	157.84	142.69		160.84	159.01	145.00	145.34	161.34	161.36	162.39	145.38
60 DAS		262.57	253.75	232.17		262.59	262.28	229.56	227.89	259.70	260.82	262.13	231.01
90 DAS		252.50	245.44	219.90		254.95	234.80	228.87	229.84	247.24	243.98	260.45	214.11
120 DAS		249.53	242.33	215.24		254.41	229.08	227.69	227.53	241.04	241.10	257.47	207.28

Treatments

Fig. 4 .1.2.2 (b) Treatment impact on dry matter production (gm) of rapeseed at periodic intervals in *rabi* 2022–23

4.1.3 Leaf Area Index: The study of the Leaf Area Index (LAI) of rapeseed subjected to various treatments of sulphur sources and agrochemicals during the *rabi* season of 2021–2022 revealed notable discrepancies at all growth stages i.e.,30, 60, 90, and 120 days after sowing as shown in Tables 4.1.3.1, 4.1.3.2, and Figures 4.1.3.1(a), 4.1.3.2(b). The impact of different sulphur sources and agrochemical applications on the leaf area index (LAI) of Gobhi Sarson during the *rabi* season of 2021–22 exhibited significant variations at all growth stages. Among sulphur sources, S1: Gypsum had the highest Leaf Area Index (LAI) values at all stages, measuring 1.09, 4.67, 6.40, and 5.44 at 30, 60, 90, and 120 days after sowing (DAS), respectively, greatly surpassing S2 and S3. S3: Elemental Sulphur exhibited the lowest Leaf Area Index (LAI) values of 0.75, 3.93, 5.46, and 4.64, reflecting respective decreases of 31.2%, 15.8%, 14.7%, and 14.7% in comparison to S1. In the case of agrochemicals, the highest Leaf Area Index (LAI) was seen in treatment A6, with values of 1.01, 4.55, 6.51, and 5.53 at 30, 60, 90, and 120 days after sowing (DAS), greatly surpassing most other treatments. A0 (Irrigation as needed) and A4 closely followed this. The minimum LAI was recorded in A7 (Control with limited irrigation) at 0.83, 3.97, 5.38, and 4.57 for the various stages, reflecting decreases of 17.8%, 12.7%, 17.4%, and 17.3% relative to A6. Throughout all four growth phases, treatments A6 and A0 exhibited statistically comparable results, however, A2 and A3 demonstrated significantly reduced LAI compared to the majority of combined treatments, indicating the advantages of the integrated application of hydrogel and salicylic acid under restricted irrigation situations. In the interaction treatment S1A6 (Gypsum + hydrogel + salicylic acid during flowering and pod development), the maximum Leaf Area Index (LAI) was seen at all growth stages: 1.17 at 30 days after sowing (DAS), 4.92 at 60 DAS, 6.89 at 90 DAS, and 5.86 at 120 DAS. The control treatment S1A0 exhibited commendable performance, with LAI values of 1.15, 4.91, 6.82, and 5.80, respectively.

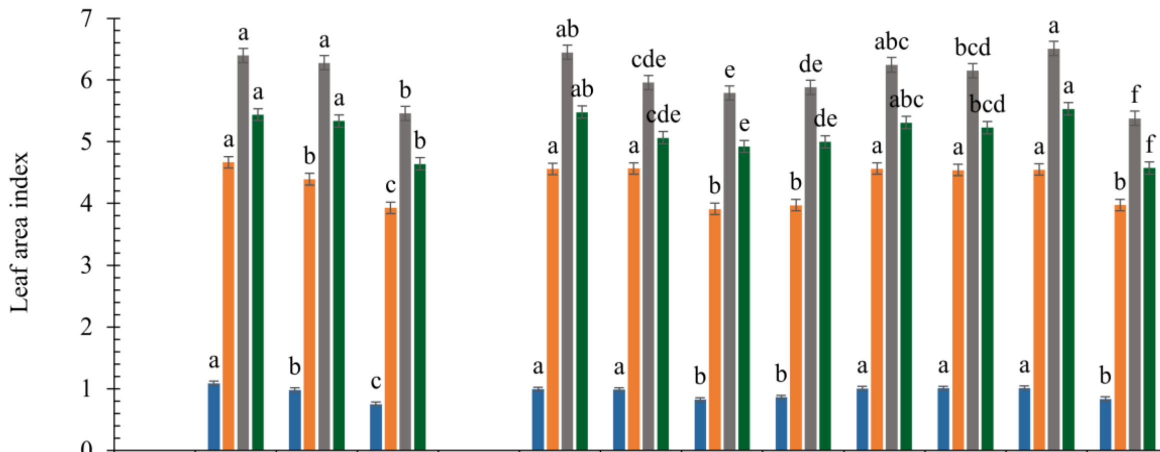
Similar outcomes were seen in S2A0 (1.03, 4.64, 6.70, and 5.69) and S2A6 (1.05, 4.61, 6.76, and 5.74). The minimum LAI obtained across all intervals was in S3A7 (Elemental sulphur + salicylic acid at both stages under limited irrigation), with values of 0.67, 3.74, 4.86, and 4.13, reflecting a 25–43% decrease relative to S1A6. Consequently, S1A6 demonstrated the highest efficacy in enhancing LAI per plant, whereas S3A7 consistently exhibited the lowest performance. Statistically significant differences across treatments were observed at all growth stages, with S1A6 significantly surpassing S3A7.Continuing upon the previous year, the impact of sulphur sources and agrochemical applications on the leaf area index (LAI) during the *rabi* season of 2022– 23 demonstrated significant differences throughout all growth phases. Among sulphur treatments, S1: Gypsum had the greatest Leaf Area Index (LAI) values of 1.13, 4.63, 6.42, and 6.26 at 30, 60, 90, and 120 days after sowing (DAS), respectively. The values were markedly elevated compared to S3 (Elemental Sulphur) and statistically comparable to S2 (Bentonite Sulphur) at 60, 90, and 120 days after sowing; however, considerably superior at 30 days after sowing. The minimum LAI was recorded under S3, with values of 0.77, 3.95, 5.54, and 5.40, indicating decreases of 31.9%, 14.7%, 13.7%, and 13.7%, respectively, in comparison to S1. Among agrochemical treatments, A6 yielded the greatest Leaf Area Index (LAI) values of 1.03, 4.52, 6.55, and 6.42 across the four growth phases. These were statistically comparable to A0 (Irrigation as per requirement), A4, and A5 at 30 and 60 days after sowing (DAS) but were significantly elevated at 90 and 120 DAS. A7 (Restricted irrigation) had the lowest LAI values of 0.85, 3.98, 5.45, and 5.28 at the corresponding phases, leading to reductions of 17.5%, 11.9%, 16.8%, and 17.8% relative to A6. Statistical analysis verified that variations resulting from agrochemical treatments were significant throughout all growth stages. In contrast, differences among sulphur sources were significant at 30, 90, and 120 days after sowing (DAS), and non-significant at 60 DAS. In the interaction treatment S1A6 (Gypsum + hydrogel + salicylic acid during flowering and pod development), the Leaf Area Index (LAI) reached its peak at all growth stages: 1.20 at 30 days after sowing (DAS), 4.85 at 60 DAS, 6.89 at 90 DAS, and 6.75 at 120 DAS. The control S1A0 exhibited values of 1.19, 4.89, 6.95, and 6.72, respectively. Comparable high performance was seen in S2A0 (1.07, 4.55, 6.74, and 6.72) and S2A6 (1.07, 4.58, 6.79, and 6.63). The minimal LAI values during the crop stages were recorded in S3A7 (Elemental sulphur + salicylic acid at both stages under limited irrigation), measuring 0.71 at 30 DAS, 3.65 at 60 DAS, 4.97 at 90 DAS, and 4.83 at 120 DAS, indicating a 28–46% decrease relative to S1A6. Consequently, S1A6 proved to be the most efficacious treatment for enhancing leaf area index, whereas S3A7 consistently exhibited the lowest values at all stages. Statistically significant changes were seen among treatments at all periods, with S1A6 demonstrating improved LAI throughout the crop growth cycle. The results demonstrate the persistent superiority of gypsum (S1) among sulphur sources and the combined treatment of hydrogel and salicylic acid at flowering and pod development (A6) among agrochemical treatments for enhancing the LAI of rapeseed across all growth stages. Despite differences at early stages, some treatments displayed non-significant (NS) differences in LAI at 90 and 120 DAS. Probably as a result of compensatory growth, canopy closure, or environmental factors such as soil nutrition and moisture availability, early differences in LAI among treatments, such as S1A1, S1A2, and S3A1–S3A7, did not persist at later stages. These NS findings imply that natural plant variability and the genetic potential of the GSC-7 variety contributed more to the final canopy development than did the treatments. Hydrogel, salicylic acid, and sulphur sources are recognized for their impact on several physiological processes in plants, including leaf area index (LAI), via distinct pathways. The impact of these treatments on LAI can be elucidated by analyzing their contributions to water retention, stress tolerance enhancement, and nutrient uptake promotion, respectively. Sulphur is an essential macronutrient essential to various metabolic activities, including protein synthesis, chlorophyll formation, and stress regulation. The origin of sulphur, including gypsum, bentonite, or elemental sulphur, markedly affects its bioavailability and impact on leaf area index (LAI). Sulphur is crucial for the synthesis of amino acids (including cysteine and methionine) and enzymes that enable photosynthesis. It is essential for chlorophyll synthesis, which is essential to optimal light absorption and photosynthetic efficacy. Increased chlorophyll levels enhance photosynthesis, leading to enhanced leaf growth and an elevated leaf Area Index (LAI). Sulphur enhances the defense of antioxidants by facilitating the production of glutathione, which protects plants against oxidative stress induced by drought and heat. The presence of sulphur from sources such as gypsum and bentonite enhance plant stress resilience, resulting in improved leaf area preservation. Gypsum, because of its rapid sulphur release, facilitated rapid leaf development and improved photosynthesis, hence enhancing leaf Area Index (LAI). Bentonite sulphur, exhibiting a slower release rate, facilitated prolonged leaf growth; however, its efficacy was marginally inferior to that of gypsum, especially during the first phases of plant development, such as 30 DAS. Elemental sulphur, owing to its gradual microbial decomposition and postponed sulphur availability, produced the lowest leaf Area Index (LAI), as it failed to supply adequate nutrients for early leaf development. (Mukwevho *et al.,* 2014; Narayan *et al.,* 2023; Raza *et al.,* 2018; Zenda *et al.,* 2021).

Table 4.1.3.1: Treatment effect on leaf area index of rapeseed at periodic intervals in *rabi* 2021–22 and 2022–23

Treatments	Leaf Area Index (2021-2022)				Leaf Area Index (2022-2023)			
Intervals	30 DAS	60 DAS	90 DAS	120 DAS	30 DAS	60 DAS	90 DAS	120 DAS
Sulphur sources								
S1: Gypsum	1.09[a]	4.67[a]	6.40[a]	5.44[a]	1.13[a]	4.63[a]	6.42[a]	6.26[a]
S2: Bentonite Sulphur	0.98[b]	4.39[b]	6.28[a]	5.34[a]	1.01[b]	4.37[a]	6.31[a]	6.16[a]
S3: Elemental Sulphur	0.75[c]	3.93[c]	5.46[b]	4.64[b]	0.77[c]	3.95[b]	5.54[b]	5.40[b]
CV (Sulphur Sources)	6.36	4.41	8.14	8.16	5.91	0.33	8.68	8.96
CD @5% (Sulphur Sources)	0.05	0.15	0.39	0.34	0.05	0.33	0.42	0.43
Agrochemical								
A0: Control (Irrigation as per requirement)	0.99[a]	4.56[a]	6.45[ab]	5.48[ab]	1.02[a]	4.52[a]	6.52[a]	6.41[a]
A1: Hydrogel (2.5 kg/ha) as basal application	0.98[a]	4.57[a]	5.96[cde]	5.06[cde]	1.03[a]	4.49[a]	5.98[bcd]	5.80[cd]
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	0.82[b]	3.91[b]	5.79[e]	4.92[e]	0.85[b]	3.95[b]	5.82[d]	5.68[d]
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	0.86[b]	3.97[b]	5.88[de]	5.00[de]	0.88[b]	4.05[b]	5.96[cd]	5.80[cd]
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	1.00[a]	4.56[a]	6.25[abc]	5.31[abc]	1.04[a]	4.50[a]	6.21[bc]	6.12[ab]
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	1.01[a]	4.54[a]	6.15[bcd]	5.23[bcd]	1.04[a]	4.52[a]	6.23[b]	6.04[bc]
A6: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at both 50% flowering and 50% pod formation stage	1.01[a]	4.55[a]	6.51[a]	5.53[a]	1.03[a]	4.52[a]	6.55[a]	6.42[a]
A7: Control (Restricted irrigation)	0.83[b]	3.97[b]	5.38[f]	4.57[f]	0.85[b]	3.98[b]	5.45[e]	5.28[e]
CD @5% (Agrochemical)	0.05	0.17	0.33	0.28	0.05	0.20	0.25	0.31
CV (Sulphur Sources and agrochemical)	5.24	4.01	5.66	5.63	4.99	0.20	4.39	5.53

Table 4.1.1.2: Interaction effect of treatments on leaf area index of rapeseed during *rabi* 2021–22 and 2022–23

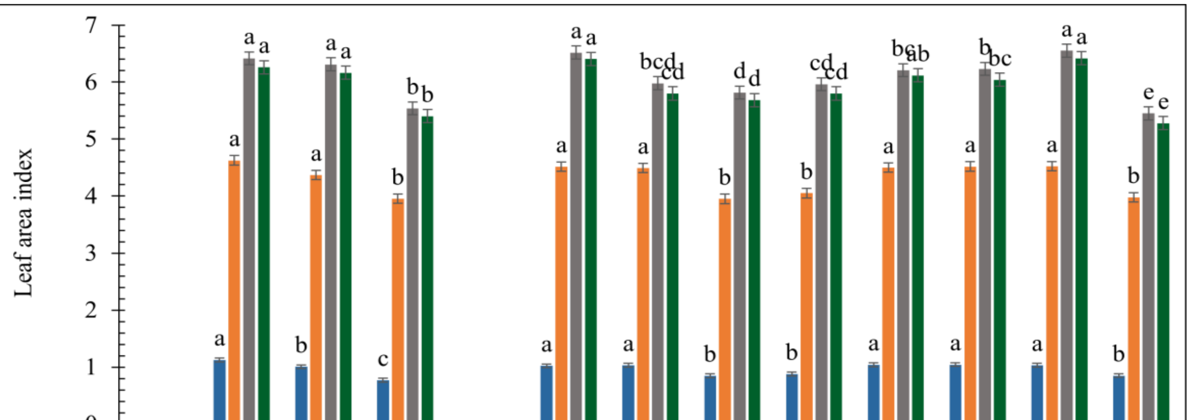
Treatments	Leaf Area Index (2021-2022)				Leaf Area Index (2022-2023)			
Intervals	**30 DAS**	**60 DAS**	**90 DAS**	**120 DAS**	**30 DAS**	**60 DAS**	**90 DAS**	**120 DAS**
S1A0	1.15±0.04	4.91±0.48	6.82±0.66	5.80±0.56	1.19±0.01	4.89±0.48	6.95±0.48	6.72±0.60
S1A1	1.14±0.04	4.99±0.02	6.31±0.50	5.36±0.43	1.21±0.06	4.81±0.17	6.29±0.02	6.10±0.40
S1A2	0.94±0.09	4.18±0.09	6.13±0.50	5.21±0.42	0.98±0.03	4.21±0.09	6.12±0.09	6.00±0.39
S1A3	1.00±0.06	4.25±0.06	6.22±0.06	5.29±0.05	1.02±0.06	4.32±0.06	6.27±0.06	6.12±0.03
S1A4	1.18±0.07	4.96±0.11	6.61±0.51	5.62±0.43	1.22±0.03	4.86±0.31	6.53±0.51	6.45±0.48
S1A5	1.17±0.04	4.95±0.44	6.51±0.83	5.54±0.70	1.22±0.09	4.85±0.33	6.56±0.83	6.38±0.80
S1A6	1.17±0.10	4.92±0.07	6.89±0.66	5.86±0.57	1.20±0.10	4.85±0.66	6.89±0.66	6.75±0.66
S1A7	0.94±0.09	4.19±0.07	5.69±0.16	4.84±0.13	0.97±0.09	4.23±0.05	5.73±0.16	5.57±0.16
S2A0	1.03±0.06	4.64±0.08	6.70±0.40	5.69±0.34	1.07±0.07	4.55±0.39	6.74±0.45	6.72±0.55
S2A1	1.02±0.09	4.58±0.04	6.19±0.04	5.26±0.04	1.08±0.09	4.51±0.02	6.20±0.04	6.02±0.03
S2A2	0.88±0.04	3.99±0.03	6.01±0.03	5.11±0.03	0.87±0.09	4.04±0.03	6.03±0.03	5.88±0.03
S2A3	0.89±0.03	4.06±0.08	6.11±0.23	5.19±0.19	0.91±0.02	4.14±0.09	6.18±0.09	6.02±0.03
S2A4	1.02±0.02	4.68±0.15	6.49±0.04	5.51±0.03	1.09±0.09	4.50±0.08	6.44±0.04	6.35±0.05
S2A5	1.05±0.02	4.59±0.19	6.39±0.49	5.43±0.41	1.08±0.07	4.57±0.10	6.46±0.03	6.27±0.08
S2A6	1.05±0.04	4.61±0.28	6.76±0.44	5.74±0.38	1.07±0.03	4.58±0.37	6.79±0.48	6.63±0.85
S2A7	0.88±0.02	3.99±0.10	5.59±0.83	4.75±0.70	0.87±0.03	4.06±0.11	5.65±0.30	5.43±0.75
S3A0	0.79±0.02	4.12±0.02	5.83±0.03	4.95±0.03	0.81±0.02	4.11±0.06	5.86±0.04	5.78±0.08
S3A1	0.78±0.02	4.13±0.10	5.38±0.03	4.57±0.02	0.79±0.02	4.16±0.12	5.45±0.03	5.28±0.03
S3A2	0.65±0.04	3.56±0.04	5.23±0.04	4.45±0.03	0.69±0.03	3.60±0.04	5.30±0.04	5.17±0.03
S3A3	0.69±0.04	3.61±0.04	5.31±0.04	4.51±0.04	0.70±0.04	3.69±0.04	5.43±0.04	5.27±0.03
S3A4	0.81±0.01	4.06±0.14	5.64±0.05	4.80±0.04	0.81±0.01	4.14±0.03	5.66±0.05	5.55±0.05
S3A5	0.80±0.01	4.09±0.14	5.55±0.03	4.71±0.02	0.83±0.05	4.13±0.12	5.68±0.03	5.47±0.03
S3A6	0.81±0.03	4.11±0.03	5.88±0.03	5.00±0.03	0.82±0.03	4.14±0.03	5.97±0.03	5.87±0.03
S3A7	0.67±0.05	3.74±0.43	4.86±0.03	4.13±0.03	0.71±0.01	3.65±0.08	4.97±0.03	4.83±0.03
CV	5.24	4.01	5.66	5.63	4.99	0.20	4.39	5.53
CD @5%	0.09	0.31	NS	NS	0.09	NS	0.58	NS



	Main Plots	S1	S2	S3	Sub Plots	A0	A1	A2	A3	A4	A5	A6	A7
30 DAS		1.09	0.98	0.75		0.99	0.98	0.82	0.86	1.00	1.01	1.01	0.83
60 DAS		4.67	4.39	3.93		4.56	4.57	3.91	3.97	4.56	4.54	4.55	3.97
90 DAS		6.40	6.28	5.46		6.45	5.96	5.79	5.88	6.25	6.15	6.51	5.38
120 DAS		5.44	5.34	4.64		5.48	5.06	4.92	5.00	5.31	5.23	5.53	4.57

Treatments

Fig. 4 .1.3.1 (a) Treatment effect on leaf area index of rapeseed at periodic intervals in *rabi* 2021–22



	Main Plots	S1	S2	S3	Sub Plots	A0	A1	A2	A3	A4	A5	A6	A7
30 DAS		1.13	1.01	0.77		1.02	1.03	0.85	0.88	1.04	1.04	1.03	0.85
60 DAS		4.63	4.37	3.95		4.52	4.49	3.95	4.05	4.50	4.52	4.52	3.98
90 DAS		6.42	6.31	5.54		6.52	5.98	5.82	5.96	6.21	6.23	6.55	5.45
120 DAS		6.26	6.16	5.40		6.41	5.80	5.68	5.80	6.12	6.04	6.42	5.28

Treatments

Fig:4.1.3.2(b) Treatment effect on leaf area index of rapeseed at periodic intervals in *rabi* 2022–23

4.1.4. No. of branches per plant: The quantity of branches per plant during the 2021-22 and 2022-23 growing season was markedly affected by various sulphur sources and agrochemicals applications at all growth stages at 30, 60, 90, and 120 days after sowing shown in Tables 4.1.4.1, 4.1.4.2, and Figures 4.1.4.1(a) and 4.1.4.2(b). In the year 2021-22, the treatment of gypsum (S1) yielded the highest number of branches per plant, with values of 5.20, 17.41, 23.06, and 21.78 at 30, 60, 90, and 120 days after sowing (DAS), respectively. Gypsum (S1) exhibited increases of 17.1%, 25.9%, 12.7%, and 13.6% compared to elemental sulphur (S3) at the various stages. Bentonite sulphur (S2) exhibited 4.96, 16.65, 22.29, and 21.01 branches per plant, demonstrating non-significant differences from gypsum (S1) but statistically significant superiority over elemental sulphur (S3), which recorded the lowest values of 4.44, 13.82, 20.46, and 19.17. In agrochemical applications, A6 yielded the highest number of branches per plant, which had counts of 5.15, 16.68, 23.88, and 22.25 at the respective stages. In comparison to A7 (limited irrigation), A6 exhibited increases of 14.4%, 11.6%, 23.6%, and 19.3%, with these differences being statistically significant at 90 and 120 days after sowing (DAS), but not significant at 30 and 60 DAS. A7 exhibited the minimum branch count per plant, recording values of 4.50, 14.95, 19.32, and 18.65 at the respective stages. In the case of interaction analysis for the number of branches per plant at 30 DAS, the maximum number of branches (5.67) was seen in the treatment S1A4, followed closely by S1A6 (5.48) and S1A5 (5.45). The minimum number of branches (4.07) was seen in S3A2, indicating a 39.31% increase relative to S1A4 compared to S3A2. Treatments incorporating gypsum (S1) have consistently shown superior results compared to elemental sulphur (S3) and bentonite sulphur (S2). At 60 DAS, the highest number of branches (18.64) was reported in S1A0, followed by S1A5 (18.58) and S1A6 (18.24), whilst the lowest (12.77) was observed in S3A2, indicating a 46.03% increase in branch count in S1A0 compared to S3A2. It can be clearly interpreted from the data that gypsum-based treatments were more effective than other sulphur sources at this stage as well. At 90 DAS, the maximum number of branches (25.10) was reported for S1A6, followed by S1A0 (24.60) and S2A6 (24.25), while the minimum value (18.03) was observed for S3A7, reflecting a 39.26% increase in S1A6 compared to S3A7. Treatments using both hydrogel and salicylic acid markedly surpassed the untreated controls and those lacking additives. At 120 DAS, the maximum number of branches (23.46) was again observed in S1A6, followed by S1A0 (22.56) and S1A4 (22.45).

The minimum value (17.31) was recorded under S3A7, indicating a 35.49% increase compared to S1A6. The amalgamation of gypsum with hydrogel and salicylic acid demonstrated persistent superiority at every step. Statistically significant variations (CD at 5%) were observed at all phases, validating the effect of various treatments on the number of branches of each plant.

Similarly, in 2022-23, Gypsum (S1) exhibited the highest branch number per plant across sulphur sources, with values of 5.28, 17.38, 23.13, and 22.16 at the 30, 60, 90, and 120 days after sowing, respectively. In comparison to elemental sulphur (S3), S1 produced increases of 16.5%, 24.3%, 11.6%, and 13.9% at the corresponding phases. Bentonite sulphur (S2) exhibited 5.13, 16.71, 22.72, and 21.23 branches per plant. While statistically comparable to gypsum at all intervals except 30 DAS, it demonstrated significant enhancements of 13.2%, 19.5%, 9.7%, and 9.2% over elemental sulphur (S3), which recorded the lowest values of 4.53, 13.98, 20.72, and 19.45 branches per plant. A6 (Hydrogel @ 2.5 kg/ha + Salicylic acid @ 150 ppm at 50% flowering + at 50% pod development) exhibited the maximum number of branches per plant, with counts of 5.31, 16.91, 24.05, and 22.61 at the corresponding stages. A6 exhibited statistically significant increases at all phases compared to A7 (limited irrigation), with percentage gains of 15.9%, 15.8%, 22.3%, and 19.6%, respectively. A7 consistently exhibited the lowest branch count per plant, with values of 4.58, 14.60, 19.66, and 18.91. A6 demonstrated considerable superiority at 30 and 90 DAS, while being comparable to A0, A4, and A5 at other stages. In the interaction of this year, after 30 DAS, the maximum number of branches per plant (5.66) was seen in both S1A4 and S1A6 (Gypsum + Hydrogel + Salicylic acid), with S1A5 following closely at 5.54. The minimum result (4.10) was recorded under S3A2, indicating a 38.05% increase in S1A4/S1A6 relative to S3A2. Treatments incorporating gypsum (S1) typically surpassed those utilizing bentonite (S2) and elemental sulphur (S3). At 60 DAS, the highest number of branches (18.58) was observed in S1A5, closely followed by S1A1 (18.47) and S1A0 (18.34), but the lowest count (13.12) was observed in S3A2, indicating a 41.56% increase in S1A5 compared to S3A2. Gypsum-based treatments have shown superiority in facilitating early vegetative branching. At 90 days after sowing, treatment S1A6 exhibited the highest branch count (25.06), followed by S1A0 (24.39) and S2A6 (24.64), while the lowest count (18.35) was seen in S3A7, indicating a 36.54% increase in S1A6 relative to S3A7. The combined application of hydrogel and salicylic acid significantly improved branching. At 120 DAS, the peak value of 23.88 was recorded in S1A6, followed by S1A0 at 23.27 and S2A6 at 22.96. The minimum value (17.55) was recorded in S3A7, indicating a 36.09% enhancement in S1A6 compared to S3A7. This phase validated the reliable efficacy of gypsum-based interventions in promoting increased branching. Statistically significant changes (CD at 5%) were seen at all growth stages, confirming the influence of sulphur sources and agrochemicals combinations on the number of branches each plant. At 30, 90, and 120 DAS in both years, certain treatments demonstrated non-significant (NS) variations in the number of branches per plant. This suggests that the crop's genetic potential, not the sulphur sources, salicylic acid, or hydrogel treatments that were used, was what largely controlled branching. While compensatory branching preserved comparable branch counts across treatments, consistent growing conditions and regulated irrigation probably reduced the impacts of the treatments.

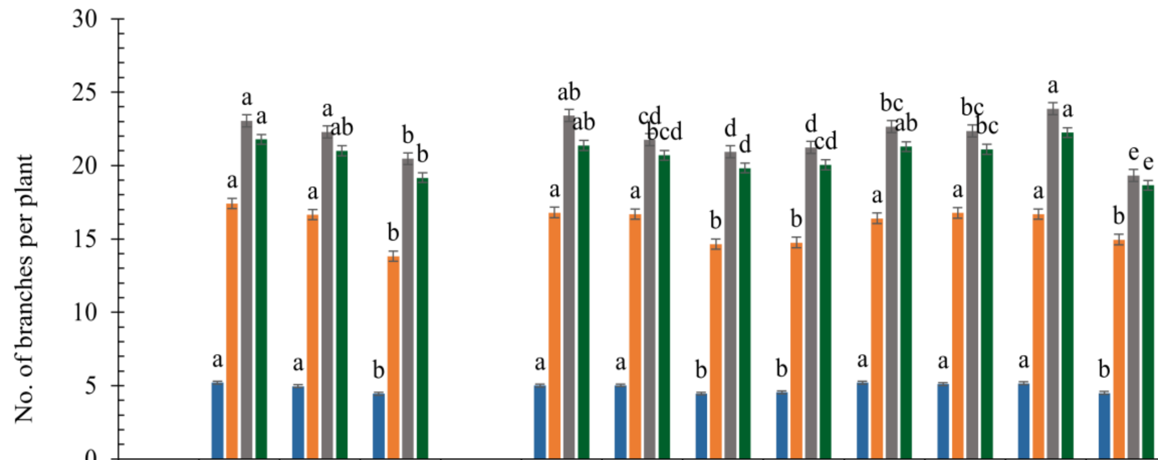
Sulphur is an essential macronutrient for plants, affecting various physiological processes, such as protein synthesis, chlorophyll production, and overall growth. Gypsum serves as a highly accessible source of calcium and sulphur, enhancing soil structure and facilitating nutrient absorption. It fosters superior root development, augments nutrient absorption, and facilitates the production of new branches by enhancing the plant's general health. Calcium in gypsum is crucial for cell wall integrity and stability, hence indirectly promoting increased branch numbers through enhanced plant architecture. Bentonite Sulphur (S2) offers elemental sulphur in a slow-release format, enhancing the efficacy of long-term sulphur availability. Nonetheless, it may not be as readily accessible for immediate absorption as gypsum, resulting in marginally fewer branch numbers during the initial phases. Soil bacteria must convert elemental sulphur into its sulphate form for plant uptake. This protracted procedure may inadequately supply sulphur to facilitate early plant growth and branching, particularly under conditions of water scarcity. Research has extensively shown the significance of sulphur in plant growth, indicating that sulphur deficiency leads to stunted growth, diminished chlorophyll synthesis, and inadequate branching (Cera *et al.,* 2023; Kadirimangalam *et al.,* 2024; Mibang *et al.,* 2023; Oldham, 2019; Shukla *et al.,* 2024). Hydrogels are polymers that absorb water, aiding in moisture retention in soil, particularly during times of reduced precipitation or water scarcity. Hydrogels alleviate water stress by consistently supplying moisture to the plant root zone, hence fostering optimal development and branching. Optimal soil moisture during essential growth phases facilitates metabolic processes that may further enhance branching. Furthermore, salicylic acid is a phytochemical that has a role in stress responses, growth modulation, and the improvement of photosynthetic efficacy. Salicylic acid at 150 ppm during flowering and pod formation has been demonstrated to enhance branch quantity by stimulating hormonal activity that facilitates lateral shoot development. The combined action of hydrogel and salicylic acid guarantees continuous moisture availability, while salicylic acid enhances the plant's resilience to biotic and abiotic challenges, such as drought. The application of salicylic acid during blooming and pod formation phases promotes increased branching by augmenting plant metabolic processes and improving nutrient absorption. It functions as an antioxidant and enhances the plant's stress tolerance by upregulating the expression of stress-related genes. (Alam *et al.,* 2023; Dar *et al.,* 2017; Laxmi *et al.,* 2019; Li *et al.,* 2022; Ogunsiji *et al.,* 2023; Oladosu *et al.,* 2022; Sharma *et al.,* 2020). Research conducted by Hayat et al. (2010) revealed that salicylic acid promoted plant growth by augmenting photosynthetic efficiency, chlorophyll levels, and branch formation across multiple crops. Saini & Malve (2023) observed that the use of hydrogel boosted water retention, mitigated drought stress, and promoted branching in crops such as maize and wheat. Water stress is a critical constraint on plant growth. The restricted irrigation treatment (A7) implemented in the study simulates water-deficit conditions, resulting in diminished water availability to the plant roots and inducing various physiological alterations. Under water stress conditions, stomatal closure minimizes water loss, leading to diminished CO_2 absorption and, therefore, a reduction in photosynthesis. This leads to diminished energy availability for plant growth and branching. Water stress disrupts the hormonal equilibrium in plants, notably diminishing the synthesis of growth hormones such as auxins, cytokinins, and gibberellins, which are crucial for branching and general development (Kalra *et al.,* 2024). In water-deficient conditions, root nutrient absorption is also compromised, especially for sulphur and other vital components, which further obstructs plant growth and branch development. A study conducted by Tardieu et al. (2014) demonstrated that water deficit conditions diminished branch production and affected the physiological processes that facilitate branching. A study conducted by Acosta Gallegos & Kohashi Shibata (1989) demonstrated that water stress results in diminished lateral shoot development and total plant growth. In the later growth phases (90 DAS and 120 DAS), the quantity of branches generally declines during the majority of treatments. As the plant advances toward reproductive phases, resources (e.g., carbohydrates, nutrients) are reallocated from vegetative growth (branch development) to reproductive structures (flowers and seeds). The reallocation of energy may result in diminished lateral branch development as the plant ages, especially under stress conditions. Resources like water, nitrogen, and carbohydrates are progressively allocated to seed formation and pod growth, resulting in a reduction in branching. Under limited irrigation conditions, plants diminish their vegetative growth to conserve water and reallocate resources to essential survival functions, potentially restricting the formation of new branches (Acosta Gallegos & Kohashi Shibata, 1989; Loescher *et al.,* 2019; Poethig, 2013; Resentini *et al.,* 2023). The treatments that integrated effective sulphur sources (gypsum), agrochemicals (hydrogel and salicylic acid), and optimal water management were most advantageous for enhancing branch growth, particularly in the later growth phases. These treatments mitigated the adverse consequences of water stress by augmenting nutritional availability, bolstering plant metabolism, and raising stress resilience. Conversely, limited irrigation resulted in a reduction in branch quantity due to physiological disturbances caused by water stress.

Table 4.1.4.1: Treatment effect on number of branches per plant in rapeseed at periodic intervals in *rabi* 2021–22 and 2022–23

Treatments	No. of branches per plant (2021-2022)				No. of branches per plant (2022-2023)			
Intervals	**30 DAS**	**60 DAS**	**90 DAS**	**120 DAS**	**30 DAS**	**60 DAS**	**90 DAS**	**120 DAS**
Sulphur sources								
S1: Gypsum	5.20^{a}	17.41^{a}	23.06^{a}	21.78^{a}	5.28^{a}	17.38^{a}	23.13^{a}	22.16^{a}
S2: Bentonite Sulphur	4.96^{a}	16.65^{a}	22.29^{a}	21.01^{ab}	5.13^{b}	16.71^{a}	22.72^{a}	21.23^{a}
S3: Elemental Sulphur	4.44^{b}	13.82^{b}	20.46^{b}	19.17^{b}	4.53^{c}	13.98^{b}	20.72^{b}	19.45^{b}
CV (Sulphur Sources)	10.18	7.26	9.56	11.2	3.64	4.18	9.94	10.28
CD @5% (Sulphur Sources)	0.40	0.93	1.68	1.85	0.15	0.81	1.77	1.73
Agrochemical								
A0: Control (Irrigation as per requirement)	5.00^{a}	16.80^{a}	23.39^{ab}	21.37^{ab}	5.13^{b}	16.73^{a}	23.33^{ab}	21.79^{ab}
A1: Hydrogel (2.5 kg/ha) as basal application	5.01^{a}	16.69^{a}	21.75^{cd}	20.69^{bcd}	5.12^{b}	16.59^{a}	22.06^{cde}	20.88^{bcd}
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	4.45^{b}	14.64^{b}	20.92^{d}	19.82^{d}	4.51^{c}	14.82^{b}	21.32^{e}	20.10^{d}
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	4.54^{b}	14.75^{b}	21.22^{d}	20.05^{cd}	4.60^{c}	14.94^{b}	21.52^{de}	20.35^{cd}
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	5.20^{a}	16.39^{a}	22.65^{bc}	21.29^{ab}	5.29^{ab}	16.84^{a}	22.96^{abc}	21.55^{ab}
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	5.10^{a}	16.77^{a}	22.35^{bc}	21.10^{bc}	5.29^{ab}	16.75^{a}	22.61^{bcd}	21.39^{bc}
A6: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at both 50% flowering and 50% pod formation stage	5.15^{a}	16.68^{a}	23.88^{a}	22.25^{a}	5.31^{a}	16.91^{a}	24.05^{a}	22.61^{a}
A7: Control (Restricted irrigation)	4.50^{b}	14.95^{b}	19.32^{e}	18.65^{e}	4.58^{c}	14.60^{b}	19.66^{f}	18.91^{e}
CD @5% (Agrochemical)	0.32	0.57	1.09	1.12	0.18	0.64	1.16	1.18
CV (Sulphur Sources and agrochemical)	7.01	3.74	5.23	5.69	3.74	6.28	5.47	5.92

Table 4.1.4.2: Interaction effect of treatments on number of branches per plant in rapeseed during *rabi* 2021–22 and 2022–23

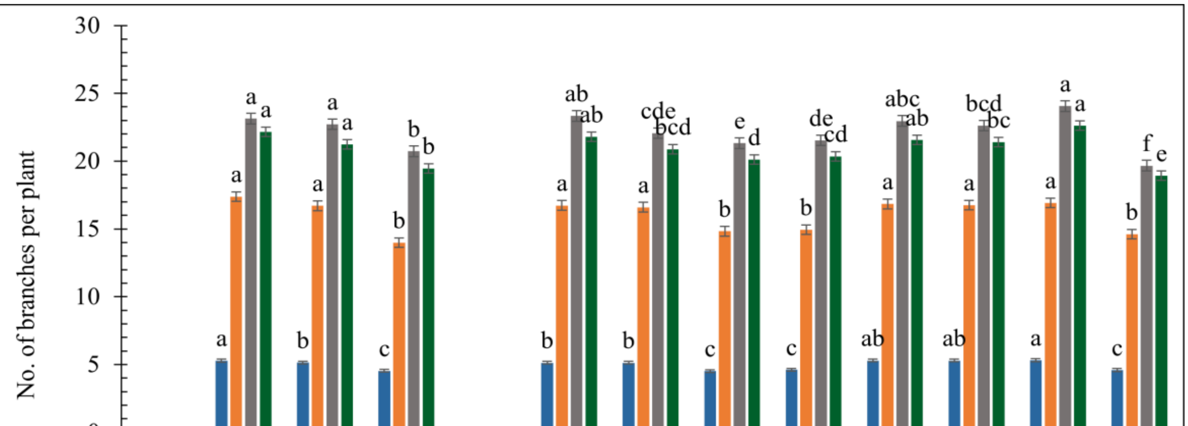
Treatments	No. of branches per plant (2021-2022)				No. of branches per plant (2022-2023)			
Intervals	30 DAS	60 DAS	90 DAS	120 DAS	30 DAS	60 DAS	90 DAS	120 DAS
S1A0	5.35±0.65	18.64±0.65	24.60±0.54	22.56±1.01	5.45±0.24	18.34±0.32	24.39±0.67	23.27±0.36
S1A1	5.32±0.33	17.85±0.58	22.86±0.88	21.82±0.88	5.40±0.28	18.47±0.86	22.99±0.88	22.06±0.88
S1A2	4.74±0.50	15.95±0.78	21.99±0.78	20.90±0.78	4.81±0.33	15.93±0.93	22.21±0.78	21.23±0.78
S1A3	4.83±0.06	16.07±0.06	22.31±0.06	21.14±0.06	4.90±0.06	16.06±0.71	22.42±2.05	21.50±2.05
S1A4	5.67±0.35	17.87±0.74	23.81±0.51	22.45±0.51	5.66±0.26	18.27±0.34	23.92±0.51	22.76±0.51
S1A5	5.45±0.45	18.58±0.63	23.49±0.83	22.25±0.83	5.54±0.31	18.58±0.35	23.56±0.83	22.60±0.83
S1A6	5.48±0.66	18.24±0.19	25.10±0.66	23.46±0.66	5.66±0.10	18.18±0.66	25.06±0.66	23.88±0.66
S1A7	4.79±0.15	16.09±0.51	20.31±0.16	19.67±0.16	4.81±0.08	15.18±0.53	20.48±0.16	19.98±0.16
S2A0	5.07±0.09	17.40±1.13	23.86±2.71	21.72±3.09	5.23±0.10	17.46±1.78	23.75±2.71	21.80±2.84
S2A1	5.14±0.53	17.77±0.29	22.09±0.04	21.04±0.04	5.34±0.43	17.26±1.16	22.61±0.04	21.20±0.04
S2A2	4.55±0.03	15.20±0.03	21.25±0.03	20.16±0.03	4.62±0.03	15.41±0.03	21.85±0.03	20.41±0.03
S2A3	4.64±0.04	15.32±0.04	21.55±0.04	20.39±0.04	4.71±0.04	15.53±0.04	22.05±0.04	20.66±0.91
S2A4	5.20±0.23	17.21±0.30	23.00±0.04	21.66±0.04	5.39±0.14	17.92±0.59	23.53±0.04	21.88±0.04
S2A5	5.24±0.57	17.05±0.81	22.70±2.96	21.46±2.96	5.52±0.15	17.39±0.10	23.17±2.96	21.72±2.96
S2A6	5.26±0.14	17.29±1.86	24.25±2.69	22.63±2.97	5.44±0.04	17.58±1.86	24.64±2.69	22.96±2.69
S2A7	4.57±0.34	15.92±1.38	19.62±3.41	18.97±3.41	4.78±0.19	15.10±0.85	20.15±3.41	19.20±3.41
S3A0	4.58±0.09	14.35±0.07	21.72±0.33	19.81±0.56	4.70±0.05	14.38±0.17	21.86±0.44	20.29±0.60
S3A1	4.57±0.58	14.43±0.30	20.30±0.03	19.21±0.03	4.63±0.31	14.04±0.45	20.59±0.03	19.38±0.03
S3A2	4.07±0.04	12.77±0.04	19.52±0.04	18.40±0.04	4.10±0.04	13.12±0.04	19.90±0.04	18.66±0.04
S3A3	4.15±0.04	12.86±0.04	19.80±0.04	18.61±0.04	4.19±0.04	13.22±0.04	20.09±0.04	18.89±0.04
S3A4	4.72±0.22	14.10±0.57	21.14±0.05	19.76±0.05	4.81±0.18	14.32±0.30	21.43±0.05	20.00±0.05
S3A5	4.60±0.33	14.68±0.50	20.86±0.03	19.59±0.03	4.81±0.11	14.28±0.59	21.10±0.03	19.85±0.03
S3A6	4.71±0.03	14.52±0.03	22.29±0.03	20.65±0.03	4.83±0.03	14.97±0.03	22.45±0.03	20.99±0.03
S3A7	4.12±0.55	12.82±0.03	18.03±0.03	17.31±0.03	4.15±0.08	13.53±0.25	18.35±0.03	17.55±0.03
CV	7.01	3.74	5.23	5.69	3.74	6.28	5.47	5.92
CD @5%	NS	1.29	NS	NS	0.32	1.30	NS	NS



	Main Plots	S1	S2	S3	Sub Plots	A0	A1	A2	A3	A4	A5	A6	A7
30 DAS		5.20	4.96	4.44		5.00	5.01	4.45	4.54	5.20	5.10	5.15	4.50
60 DAS		17.41	16.65	13.82		16.80	16.69	14.64	14.75	16.39	16.77	16.68	14.95
90 DAS		23.06	22.29	20.46		23.39	21.75	20.92	21.22	22.65	22.35	23.88	19.32
120 DAS		21.78	21.01	19.17		21.37	20.69	19.82	20.05	21.29	21.10	22.25	18.65

Treatments

Table 4.1.4.1(a) Treatment effect on number of branches per plant in rapeseed at periodic intervals in *rabi* 2021–22



	Main Plots	S1	S2	S3	Sub Plots	A0	A1	A2	A3	A4	A5	A6	A7
30 DAS		5.28	5.13	4.53		5.13	5.12	4.51	4.60	5.29	5.29	5.31	4.58
60 DAS		17.38	16.71	13.98		16.73	16.59	14.82	14.94	16.84	16.75	16.91	14.60
90 DAS		23.13	22.72	20.72		23.33	22.06	21.32	21.52	22.96	22.61	24.05	19.66
120 DAS		22.16	21.23	19.45		21.79	20.88	20.10	20.35	21.55	21.39	22.61	18.91

Treatments

Table 4.1.4.2(b) Treatment effect on number of branches per plant in rapeseed at periodic intervals in *rabi* 2022–23

4.1.5 Number of leaves per plant: Leaf number in GSC 7 was markedly affected by the utilization of various sulphur sources and agrochemicals at distinct growth stages (30, 60, 90, and 120 days after sowing) shown in Tables 4.1.5.1, 4.1.5.2, and Figures 4.1.5.1(a) and 4.1.5.2(b). In 2021- 22, gypsum (S1) had the highest leaf count per plant, with values of 5.58, 25.34, 27.70, and 23 at different days intervals 30, 60, 90, and 120 DAS, respectively. In comparison to elemental sulphur (S3), these results demonstrate significant increases of 30.7%, 22.2%, 21.5%, and 17.9%, respectively. Bentonite sulphur (S2) has shown superior performance compared to elemental sulphur, yielding values of 5.26, 23.73, 26.47, and 21.81, which correspond to increases of 23.2%, 14.4%, 16.1%, and 11.8% in leaf numbers relative to S3, the lowest performer, which recorded values of 4.27, 20.74, 22.79, and 19.51 respectively. Among agrochemical treatments, A6 (Hydrogel @ 2.5 kg/ha + Salicylic acid @ 150 ppm at 50% flowering + at 50% pod formation) again exhibited the highest leaf count per plant, with values of 4.70, 25.45, 28.12, and 23.86, representing increases of 5.6%, 27.3%, 27.7%, and 30.1% compared to the treatment A7 (restricted irrigation), which recorded 4.45, 20, 22.02, and 18.35 leaves per plant. Statistically, A6 demonstrated considerable superiority at 60, 90, and 120 days after sowing, and was at par with A0 at 60 DAS. The minimum leaf counts have consistently been recorded under A7. Similarly, keeping to the same pattern in the subsequent year 2022-23, the results show that gypsum (S1) consistently produced the highest leaf count per plant, with values of 5.62, 25.01, 27.84, and 23.12 at 30, 60, 90, and 120 days after sowing (DAS), respectively. In comparison to elemental sulphur (S3), these results demonstrate notable increases of 23.5%, 17.1%, 20.9%, and 16.8%, respectively. Bentonite sulphur (S2) surpassed elemental sulphur, with increment of 17.6%, 14.4%, 15.4%, and 12.7%, with values of 5.35, 24.44, 26.59, and 22.31, respectively. Similar to other parameters elemental sulphur exhibited the lowest values at all stages, with 4.55, 21.36, 23.03, and 19.79 leaves per plant. Among agrochemical treatments, A6 exhibited the highest leaf count at 90 and 120 days after sowing (DAS) with 28.39 and 24.01, respectively. Conversely, A0 (control with irrigation as required) demonstrated the highest values at 30 and 60 DAS with 6.02 and 27.32, respectively. The minimal values were continuously seen under A7 (limited irrigation) at 4.81, 20.69, 22.45, and 18.85, reflecting reductions of 20.1%, 24.3%, 21.6%, and 20.4%, respectively, in comparison to A6. Statistically, A6 demonstrated considerable superiority at 90 and 120 days after sowing, whereas A0 showed superiority during the early stages. Treatments A1 to A5 exhibited moderate efficacy, although they showed significantly lower leaf counts compared to A6 and A0 during all stages.

The interaction effect of sulphur sources and agrochemicals in year 2021-22, reveal that treatment S1A6 (Gypsum + hydrogel + salicylic acid during flowering and pod development) had the highest leaf count per plant at all different growth stages viz., 6.09 at 30 DAS, 26.68 at 60 DAS, 30.39 at 90 DAS, and 25.57 at 120 DAS. S1A0 (6.29, 28.10, 29.76, and 24.74) and S2A0 (4.95, 25.05, 28.87, and 23) closely followed, showing that gypsum is more efficient than other sources of sulphur. The minimum leaf count was observed in S3A7 (Elemental sulphur + salicylic acid at both stages under restricted irrigation), with values of 3.70, 17.51, 19.57, and 16.68 at the respective stages, showing declines of 39.26%, 34.33%, 35.58%, and 34.75% relative to the optimal treatment S1A6. At 30 days after sowing (DAS), S1A6 exhibited a 64.59% increase in leaf count compared to S3A7; similarly, the increments were 52.38% at 60 DAS, 55.25% at 90 DAS, and 53.27% at 120 DAS, clearly displaying the cumulative advantages of keeping moisture and stress relaxation facilitated by gypsum and hydrogel-enhanced conditions. Statistically significant differences were observed at all growth stages, with S1A6 exhibiting markedly greater leaf counts than S3A7. For the next year 2022-23, treatment S1A6 (Gypsum + hydrogel + salicylic acid during flowering along with pod development) exhibited the highest leaf count per plant at 90 DAS (30.59) and 120 DAS (25.60), while S2A0 recorded the maximum at 30 DAS (6.65) and 60 DAS (28.54). The treatments were closely succeeded by S1A0 (6.34, 26.45, 29.96, and 24.63) and S2A6 (5.74, 26.97, 29.29, and 24.77), both exhibiting continuously elevated leaf counts across all stages. Conversely, the minimum leaf count was observed in S3A7 (Elemental sulphur + salicylic acid at both stages under limited irrigation), with values of 4.71 at 30 DAS, 18.34 at 60 DAS, 20 at 90 DAS, and 17 at 120 DAS, indicating reductions of 29.16%, 35.74%, 34.59%, and 33.59%, respectively, relative to the most effective treatments at those intervals. At 90 DAS, S1A6 exhibited 52.95% more leaves than S3A7, and at 120 DAS, the increase was 50.59%, demonstrating the significant advantage of integrating gypsum, hydrogel, and salicylic acid during crucial growth phases. The beneficial effects of moisture conservation and stress mitigation via S1A6 and S2A6 treatments were visible during the crop cycle. Statistically significant differences were observed at all growth stages, with S1A6 and S2A0 exhibiting markedly greater leaf counts than S3A7. There were non-significant (NS) variations in the number of leaves per plant at 90 and 120 DAS in 2021–2022 and at 120 DAS in 2022–2023. This suggests that hydrogel, salicylic acid, and various sulphur sources did not significantly affect leaf retention in later stages. The crop's natural genetic stability and consistent environmental circumstances under regulated irrigation, which reduced treatment variability, may be responsible for the NS impact. Natural senescence and source-sink balance probably balanced the number of leaves among treatments as plants progressed toward the reproductive period, indicating that the crop's physiological regulation was more important in regulating leaf count during these phases than outside influences.

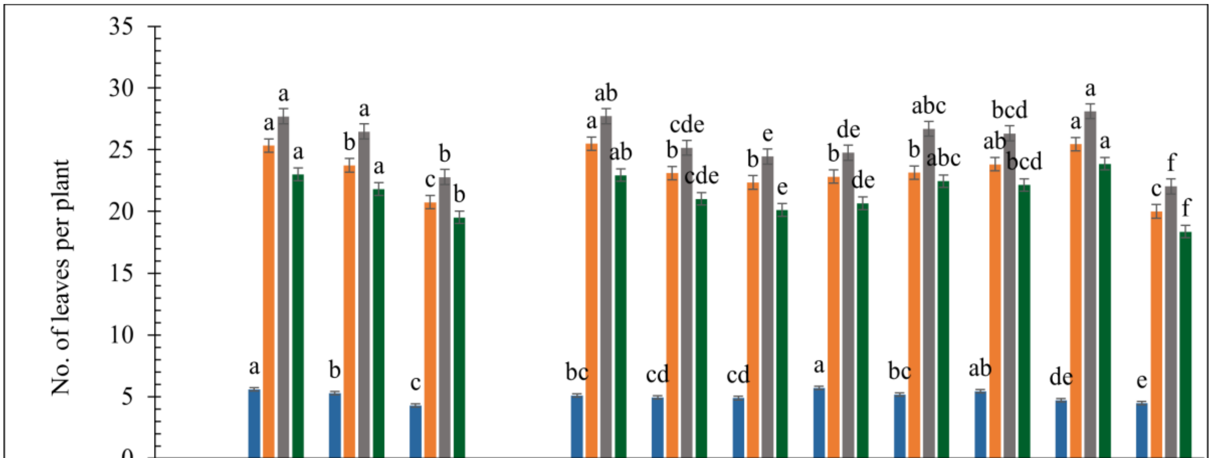
The variations in leaf count of Gobhi Sarson across different treatments can be ascribed to the synergistic influences of sulphur sources, salicylic acid (SA), and hydrogel on plant physiology and stress alleviation. Sulphur (S) is an essential macronutrient that is integral to chlorophyll production, protein synthesis, and overall plant metabolism. The utilization of various sulphur sources, including gypsum elemental sulphur and bentonite sulphur influences the accessibility of sulphate, the form of sulphur that plants rapidly assimilate. Gypsum (Calcium sulphate): Gypsum supplies sulphate in an accessible form, facilitating prompt absorption by plants. This leads to augmented chlorophyll synthesis and greater photosynthetic activity, thus elevating leaf output. Research indicates that gypsum administration markedly enhances seed output and root development in *Brassica napus* L., demonstrating its efficacy in fostering vegetative growth (Kadirimangalam *et al.,* 2024). Bentonite Sulphur source releases sulphate more gradually than gypsum. Although it may not yield an instant increase in sulphate availability, its gradual release facilitates a consistent supply of sulphur, advantageous for extended growth periods. Research demonstrates that bentonite sulphur significantly increases sulphur levels in plants, hence promoting growth and production (Kumar *et al.,* 2018). Elemental sulphur necessitates microbial oxidation to transform into plant-available sulphate, rendering it a slow-release source. This postponed availability may hinder initial sulphur absorption, perhaps constraining early foliar growth. Over time, it enhances the soil sulphur reservoir, promoting long-term crop nutrition. Further, as water supply is a crucial determinant of leaf development. The application of hydrogels and sodium alginate has been investigated to alleviate water stress and improve plant resistance. Hydrogel is a superabsorbent polymer and possesses the capacity to store significant quantities of water, which it subsequently releases gently to plants. This feature aids in preserving soil moisture, particularly under restricted irrigation, thereby facilitating continuous leaf growth. Field investigations have shown that the application of hydrogel enhances growth characteristics and yield in *Brassica juncea* L. under rainfed conditions (Malhi *et al.,* 2025). Salicylic Acid (SA) is a phytohormone that regulates plant responses to abiotic stressors, such as drought. The external administration of salicylic acid has demonstrated the ability to augment photosynthetic efficiency, stabilize chlorophyll levels, and boost gas exchange metrics under stress situations. In *Brassica napus*, the administration of salicylic acid alleviated the detrimental impacts of drought and salinity stress, resulting in enhanced leaf gas exchange properties. The combination of gypsum with hydrogel and SA treatments has shown a synergistic effect on leaf growth. Gypsum provides a quick source of sulphate, hydrogel preserves adequate soil moisture, and SA improves stress resilience and photosynthetic efficiency. This combination results in enhanced leaf production and postponed senescence, as evidenced in experiments where these inputs were concurrently applied. A study indicated that the synergistic application of gypsum, hydrogel, and SA markedly enhanced seed yield, root length, and dry weight in *Brassica napus* L., underscoring the efficacy of this integrated strategy in water-scarce environments (Ali *et al.,* 2023; Nazar *et al.,* 2011; Raza, 2021). The increased leaf production in Gobhi Sarson under particular treatments is attributable to the prompt and prolonged availability of sulphur from gypsum and bentonite sulphur, respectively, together with enhanced soil moisture retention from hydrogel and stress alleviation from salicylic acid. These elements combined enhance vigorous vegetative growth and resistance in diverse environmental conditions.

Table 4.1.5.1: Treatment influence on number of leaves per plant in rapeseed at periodic intervals in *rabi* 2021–22 and 2022–23

Treatments	Leaf number per plant (2021-2022)				Leaf number per plant (2022-2023)			
Intervals	30 DAS	60 DAS	90 DAS	120 DAS	30 DAS	60 DAS	90 DAS	120 DAS
Sulphur sources								
S1: Gypsum	5.58^{a}	25.34^{a}	27.70^{a}	23.00^{a}	5.62^{a}	25.01^{a}	27.84^{a}	23.12^{a}
S2: Bentonite Sulphur	5.26^{b}	23.73^{b}	26.47^{a}	21.81^{a}	5.35^{b}	24.44^{a}	26.59^{a}	22.31^{a}
S3: Elemental Sulphur	4.27^{c}	20.74^{c}	22.79^{b}	19.51^{b}	4.55^{c}	21.36^{b}	23.03^{b}	19.79^{b}
CV (Sulphur Sources)	6.28	6.48	8.78	10.92	6.13	9.18	8.97	11.65
CD @5% (Sulphur Sources)	0.25	1.21	1.81	1.88	0.25	1.74	1.86	2.03
Agrochemical								
A0: Control (Irrigation as per requirement)	5.09^{bc}	25.48^{a}	27.72^{ab}	22.93^{ab}	6.02^{a}	27.32^{a}	27.65^{ab}	23.59^{ab}
A1: Hydrogel (2.5 kg/ha) as basal application	4.91^{cd}	23.10^{b}	25.16^{cde}	21.01^{cde}	4.96^{c}	23.12^{bc}	25.36^{cde}	21.20^{cde}
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	4.87^{cd}	22.35^{b}	24.45^{e}	20.12^{e}	4.88^{c}	22.55^{c}	24.51^{e}	20.51^{e}
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	5.70^{a}	22.82^{b}	24.75^{de}	20.66^{de}	4.95^{c}	22.69^{c}	24.96^{de}	20.86^{de}
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	5.17^{bc}	23.15^{b}	26.69^{abc}	22.45^{abc}	5.32^{b}	24.41^{b}	26.77^{bc}	22.56^{abc}
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	5.42^{ab}	23.82^{ab}	26.32^{bcd}	22.15^{bcd}	4.92^{c}	24.10^{bc}	26.45^{bcd}	22.35^{bcd}
A6: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at both 50% flowering and 50% pod formation stage	4.70^{de}	25.45^{a}	28.12^{a}	23.86^{a}	5.51^{b}	23.95^{bc}	28.39^{a}	24.01^{a}
A7: Control (Restricted irrigation)	4.45^{e}	20.00^{c}	22.02^{f}	18.35^{f}	4.81^{c}	20.69^{d}	22.45^{f}	18.85^{f}
CD @5% (Agrochemical)	0.34	1.7	1.59	1.56	0.34	1.7	1.56	1.58
CV (Sulphur Sources and agrochemical)	7.04	7.67	6.53	7.67	6.98	7.26	6.36	7.65

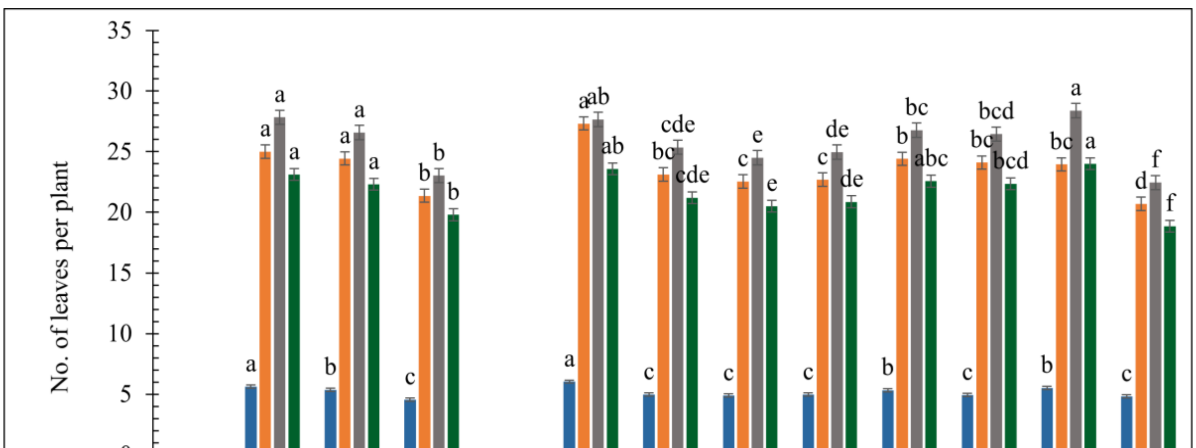
Table 4.1.5.2: Interaction effect of treatments on leaf number per plant in rapeseed during *rabi* 2021–22 and 2022–23

Treatments	Leaf number per plant (2021-2022)				Leaf number per plant (2022-2023)			
Intervals	**30 DAS**	**60 DAS**	**90 DAS**	**120 DAS**	**30 DAS**	**60 DAS**	**90 DAS**	**120 DAS**
S1A0	6.29±0.80	28.10±0.85	29.76±1.35	24.74±1.35	6.34±0.90	26.45±3.77	29.96±1.53	24.63±0.70
S1A1	5.45±0.17	25.31±0.17	27.20±0.17	22.52±0.17	5.48±0.10	25.36±0.17	27.32±0.17	22.61±0.17
S1A2	5.35±0.26	24.49±3.25	26.43±3.25	21.56±3.25	5.39±0.09	24.74±3.25	26.41±3.25	21.87±3.25
S1A3	5.38±0.65	25.31±0.17	26.75±0.65	22.14±0.65	5.42±0.65	24.89±0.65	26.89±0.65	22.24±0.65
S1A4	5.13±0.26	24.82±0.65	28.85±2.86	24.06±2.86	5.17±0.26	26.44±2.27	28.84±3.66	24.06±3.66
S1A5	6.01±0.26	26.10±2.27	28.45±2.27	23.74±2.27	6.02±0.26	26.44±2.27	28.50±2.27	23.83±2.27
S1A6	6.09±0.30	26.68±2.86	30.39±0.85	25.57±0.85	6.13±0.30	23.07±0.03	30.59±0.85	25.60±0.85
S1A7	4.94±0.16	21.91±0.16	23.80±0.16	19.67±0.16	4.98±0.16	22.70±0.16	24.19±0.16	20.10±0.16
S2A0	4.95±0.03	25.05±2.35	28.87±1.12	23.00±1.29	6.65±0.85	28.54±0.85	28.12±0.54	23.37±1.92
S2A1	5.19±0.12	23.76±0.12	25.92±0.12	21.42±0.12	5.23±0.12	23.50±0.12	26.17±0.12	21.87±0.12
S2A2	5.10±0.26	22.99±0.26	25.19±0.26	20.51±0.26	5.14±0.26	22.92±0.26	25.29±0.26	21.16±0.26
S2A3	6.60±0.85	23.30±2.25	25.50±2.25	21.06±2.25	5.31±0.18	23.06±2.25	25.75±2.25	21.52±2.25
S2A4	5.81±0.36	23.30±2.25	27.50±2.35	22.89±2.35	5.85±0.36	25.00±2.35	27.62±2.35	23.28±2.35
S2A5	5.73±0.26	24.50±0.26	27.12±0.26	22.58±0.26	4.16±0.14	24.50±0.26	27.29±0.26	23.06±0.26
S2A6	4.01±0.12	26.38±3.77	28.97±3.77	24.33±3.77	5.74±0.26	26.97±2.86	29.29±3.77	24.77±3.77
S2A7	4.71±0.26	20.57±2.96	22.69±3.67	18.71±3.67	4.75±0.10	21.03±2.76	23.16±2.76	19.45±1.82
S3A0	4.04±0.49	23.30±2.25	24.53±0.52	21.06±0.80	5.07±0.03	26.97±2.86	24.88±0.27	22.76±2.26
S3A1	4.09±0.09	20.23±0.09	22.36±0.09	19.09±0.09	4.18±0.09	20.50±0.09	22.59±0.09	19.12±0.09
S3A2	4.16±0.14	19.57±0.12	21.73±0.12	18.28±0.12	4.11±0.12	19.99±0.12	21.83±0.12	18.50±0.12
S3A3	5.12±0.23	19.84±0.49	22.00±0.49	18.77±0.49	4.13±0.19	20.12±0.49	22.23±0.49	18.81±0.49
S3A4	4.57±0.50	21.32±0.50	23.72±0.50	20.40±0.50	4.95±0.03	21.80±0.50	23.85±0.50	20.35±0.50
S3A5	4.51±0.09	20.86±2.09	23.39±2.09	20.13±1.09	4.59±0.09	21.37±2.09	23.56±2.09	20.16±2.09
S3A6	4.01±0.12	23.30±2.25	24.99±0.03	21.68±0.03	4.67±0.50	21.80±0.50	25.29±0.03	21.65±0.03
S3A7	3.70±0.03	17.51±0.03	19.57±0.03	16.68±0.03	4.71±0.26	18.34±0.03	20.00±0.03	17.00±0.03
CV	7.04	7.67	6.53	7.67	6.98	7.26	6.36	7.65
CD @5%	0.60	2.99	NS	NS	0.61	3.13	3.11	NS



	Main Plots	S1	S2	S3	Sub Plots	A0	A1	A2	A3	A4	A5	A6	A7
30 DAS		5.58	5.26	4.27		5.09	4.91	4.87	5.70	5.17	5.42	4.70	4.45
60 DAS		25.34	23.73	20.74		25.48	23.10	22.35	22.82	23.15	23.82	25.45	20.00
90 DAS		27.70	26.47	22.79		27.72	25.16	24.45	24.75	26.69	26.32	28.12	22.02
120 DAS		23.00	21.81	19.51		22.93	21.01	20.12	20.66	22.45	22.15	23.86	18.35

Fig. 4 .1.5.1 (a) Treatment influence on number of leaves per plant in rapeseed at periodic intervals in *rabi* 2021–22



	Main Plots	S1	S2	S3	Sub Plots	A0	A1	A2	A3	A4	A5	A6	A7
30 DAS		5.62	5.35	4.55		6.02	4.96	4.88	4.95	5.32	4.92	5.51	4.81
60 DAS		25.01	24.44	21.36		27.32	23.12	22.55	22.69	24.41	24.10	23.95	20.69
90 DAS		27.84	26.59	23.03		27.65	25.36	24.51	24.96	26.77	26.45	28.39	22.45
120 DAS		23.12	22.31	19.79		23.59	21.20	20.51	20.86	22.56	22.35	24.01	18.85

Fig. 4 .1.5.2 (b) Treatment influence on number of leaves per plant in rapeseed at periodic intervals in *rabi* 2022–23

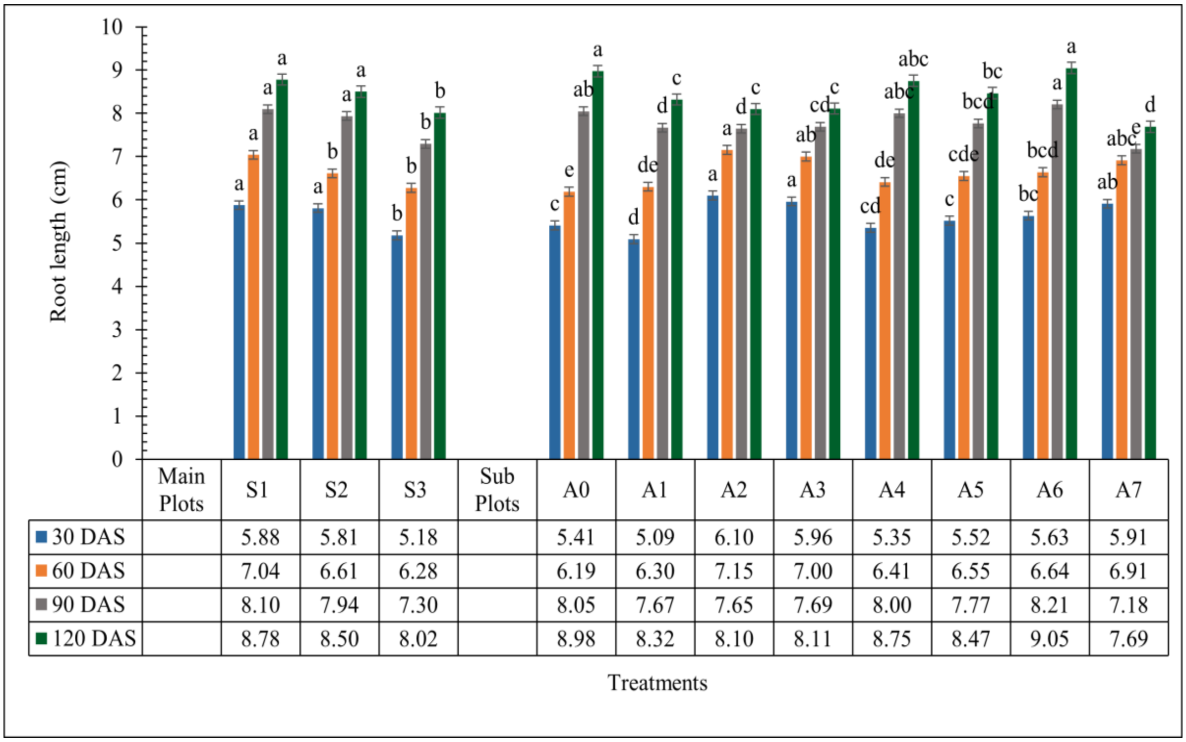
4.1.6 Root length (cm): The data in the Table 4.1.6.1, 4.1.6.2 and Figure 4.1.6.1(a) and 4.1.6.2(b) demonstrate the impact of various sulphur sources along with agrochemical treatments on the root length (cm) of Gobhi Sarson at distinct growth stages (30, 60, 90, and 120 DAS). In the year 2021-2022, the root length of Gobhi Sarson was markedly affected by various sulphur sources and agrochemical treatments during all growth stages. Among the sulphur sources, gypsum (S1) exhibited the greatest root length at all intervals viz., 5.88 cm at 30 DAS, 7.04 cm at 60 DAS, 8.10 cm at 90 DAS, and 8.78 cm at 120 DAS demonstrating significant superiority over elemental sulphur (S3), which recorded the lowest root length with values of 5.18 cm, 6.28 cm, 7.30 cm, and 8.02 cm, respectively. Gypsum produced root lengths that were 13.5%, 12.1%, 11.0%, and 9.5% greater than those of elemental sulphur at 30, 60, 90, and 120 days after sowing, respectively. The disparity between gypsum (S1) and bentonite sulphur (S2) was not significant at 30 days after sowing (DAS), but was significant at 60, 90, and 120 DAS. Among agrochemical treatments, A2 (salicylic acid at 150 ppm during 50% flowering) exhibited the highest root length at 30 DAS (6.10 cm) and 60 DAS (7.15 cm). This was followed by A3 (salicylic acid at pod formation) and A6 (hydrogel + salicylic acid during flowering and pod formation), which were statistically comparable to A2 but significantly superior to the other treatments. At 90 DAS, A6 had the maximum root length (8.21 cm), but A0 (control with irrigation) and A4 (hydrogel + salicylic acid at flowering) were statistically comparable; nevertheless, all three treatments significantly outperformed A1 (hydrogel alone) and A7 (limited irrigation). At 120 DAS, A6 exhibited the longest root length (9.05 cm), which was statistically comparable to A0 (8.98 cm) and A4 (8.75 cm), while significantly surpassing A1 (8.32 cm), A2 (8.10 cm), A3 (8.11 cm), A5 (8.47 cm), and A7 (7.69 cm). The root length of minimum was recorded in A1 at 30 DAS (5.09 cm) and A7 at 120 DAS (7.69 cm). A6 exhibited a 17.7% enhancement in root length at 120 DAS compared to A7, and a 0.78% increase relative to A0, signifying a minor advantage under ideal irrigation and a significant improvement under water-stress conditions. The results indicate that gypsum is the most effective sulphur source, whereas A6 (the combination application of hydrogel and salicylic acid) is the most efficient agrochemical treatment for increasing root development in Gobhi Sarson. The interaction of several treatments on root length (cm) at 30, 60, 90, and 120 days after sowing revealed distinct variations in treatment effectiveness with time. At 30 DAS, the maximum root length was observed in treatment S1A6 (5.74 cm), closely followed by S1A3 (6.21 cm), whilst the minimum root length was documented in S3A1 (4.69 cm). The preliminary results indicate that treatments with S1A6 and S1A3 were more efficacious in stimulating root growth during the early developmental stages than S3A1, which exhibited the least growth. At 60 DAS, S1A6 retained its preeminent status with the greatest root length (6.88 cm), exhibiting a modest yet substantial growth of 1.3% relative to 30 DAS (5.74 cm). The augmentation in root length from 30 DAS to 60 DAS signifies a favorable growth tendency, which was statistically significant. Simultaneously, S3A1 persisted at the lowest position, exhibiting the shortest root length (6.07 cm) and maintaining its trend of suboptimal growth. At 90 DAS, S1A6 consistently surpassed all other treatments, attaining the maximum root length of 8.62 cm, reflecting a significant increase of 20.2% over the 6.88 cm observed at 60 DAS. This signifies robust, sustained root development under the influence of S1A6, demonstrating its efficacy in enhancing root growth. Conversely, S3A7, which had exhibited average performance until now, recorded the lowest root length of 6.70 cm at 90 DAS, reflecting an 11.3% decrease compared to 60 DAS, underscoring its diminished capacity for root extension. At 120 days after sowing, S1A6 sustained the maximum root length of 9.48 cm, reflecting a 7.9% growth over the 8.62 cm recorded at 90 days after sowing. This signifies persistent, substantial root growth during the trial duration, underscoring the ongoing advantageous benefits of treatment S1A6. Conversely, S3A7 demonstrated the shortest root length at 7.28 cm, representing a 9.6% reduction from 90 DAS, indicating a stall or deceleration in root growth relative to other treatments. S1A6 consistently exhibited the longest root lengths at all different growth stages, with statistically significant increases observed at 60, 90, and 120 DAS. This indicates that S1A6 was the most efficacious treatment in facilitating root elongation during the growth period. Conversely, S3A1 and S3A7 consistently demonstrated the shortest root lengths, with significant reductions from previous observation points, suggesting that these treatments were less efficacious in promoting root development. This pattern highlights the enhanced efficacy of treatments incorporating S1A6, indicating that alternative treatments, particularly those utilizing S3A1 and S3A7, may be less advantageous for promoting root growth in Gobhi Sarson (*Brassica napus* L.) the observations about root length for the consecutive year 2022-23 reveal that the root length of Gobhi Sarson was markedly affected by both Sources of sulphur and agrochemical applications throughout all growth phases. Gypsum (S1) consistently had the longest root length among the sulphur sources measuring 5.95 cm at 30 DAS, 7.06 cm at 60 DAS, 8.13 cm at 90 DAS, and 8.87 cm at 120 DAS, all significantly surpassing the values recorded for elemental sulphur (S3), which were 5.20 cm, 6.34 cm, 7.29 cm, and 8.07 cm, respectively. Gypsum (S1) produced increases in root length of 13.27%, 11.35%, 11.55%, and 10.02% compared to elemental sulphur (S3) at 30, 60, 90, and 120 days after sowing (DAS), respectively. The disparity between gypsum (S1) and bentonite sulphur (S2) was not significant at 30 days after sowing (DAS), but was significant at 60, 90, and 120 DAS, with gypsum exhibiting greater root length. A6 (hydrogel + salicylic acid during flowering and pod development) had the greatest root length, measuring 5.75 cm at 30 DAS, 6.72 cm at 60 DAS, 8.26 cm at 90 DAS, and 9.15 cm at 120 DAS, greatly surpassing all other treatments at 120 DAS. At 30, 60, and 90 days after sowing, A6 exhibited significantly greater root length in comparison to treatments A0 (irrigation as required) and A1 (hydrogel alone). A7 (limited irrigation) exhibited the minimal root length of 5.82 cm at 30 DAS, 7.08 cm at 60 DAS, 7.23 cm at 90 DAS, and 7.77 cm at 120 DAS. A6 had a 17.56% enhancement in root length at 120 DAS compared to A7. A4 (hydrogel + salicylic acid during flowering) and A5 (hydrogel + salicylic acid during pod development) exhibited comparable root lengths and were statistically equivalent to A6 at all phases, except at 120 DAS, where A6 showed considerable superiority. A2 (salicylic acid during blooming) and A3 (salicylic acid during pod development) demonstrated efficacy, although they were less effective than the combination treatments of hydrogel and salicylic acid. The minimum root length at 120 DAS was observed in A7 (limited irrigation). The interaction impact of several treatments on root length (cm) at 30, 60, 90, and 120 days after sowing demonstrates considerable variance during the growth stages. At 30 DAS, the maximum root length was observed in treatment S1A6 (6.06 cm), closely followed by S1A3 (6.30 cm), whilst the minimum root length was recorded in S3A0 (4.74 cm). The preliminary results indicate that treatments with S1A6 and S1A3 were more efficacious in facilitating early root growth, whereas S3A0 demonstrated the least root elongation. At 60 days after sowing, S1A6 had the greatest root length of 6.94 cm, reflecting a modest growth of 14.6% from the original value of 6.06 cm at 30 days after sowing. Conversely, S3A0 exhibited a marginal rise, attaining 5.72 cm, and stayed at the lowest position, indicating its comparatively slower root development. This phase experienced moderate growth across all treatments, with S1A6 demonstrating consistent performance once more. At 90 days after sowing, S1A6 consistently surpassed all other treatments, achieving a root length of 8.67 cm, reflecting a 24.9% increase from 60 days after sowing (6.94 cm). This robust growth trend illustrates the treatment's efficacy in facilitating sustained root elongation. S3A7 had the shortest root length at 6.73 cm, reflecting an 8.7% decrease from 60 DAS (6.74 cm), signifying a plateau in root development under this treatment. At 120 days after sowing, S1A6 demonstrated the greatest root length of 9.57 cm, reflecting a 10.4% increase from 90 days after sowing (8.67 cm), thus affirming its dominance in facilitating root growth throughout time. In contrast, S3A7 had the shortest root length, measuring at 7.35 cm, which represents a 9.6% reduction from the last value at 90 DAS (6.73 cm). This indicates a deceleration or stabilization of root development under S3A7. S1A6 had the longest root lengths at all growth stages, with statistically significant increases observed from 30 to 120 days after sowing (DAS). This treatment had the highest efficacy in promoting root elongation over the trial period. Conversely, treatments S3A0 and S3A7 consistently demonstrated the shortest root lengths, with significant reductions in growth from earlier stages, showing their limited efficacy in fostering vigorous root development. Non-significant (NS) variations in root length were seen at 30 DAS in both years, as well as at 60, 90, and 120 DAS in 2022–2023. This suggests that root elongation during these stages was not considerably impacted by the hydrogel treatments, salicylic acid, or external sulphur sources. The crop's innate genetic root growth potential, which seems to predominate in early root development, could be the cause of the NS effect. Furthermore, consistent soil moisture and regulated irrigation probably reduced treatment variations, enabling roots to grow at a comparable rate in every plot. As a result, interventions were insufficient to create statistically significant variation in root length at these stages, even though they might have had minor numerical effects. Root development in Gobhi Sarson (*Brassica napus* L.) under various treatments is influenced by intricate physiological and biochemical processes that control cell proliferation, elongation, and differentiation. The changes in root length at distinct growth stages (30, 60, 90, and 120 days after sowing) are principally driven by water availability, nutrition supply, hormone signaling, and environmental stress responses. During the initial phases (30 and 60 DAS), plants experiencing restricted irrigation (A7) had greater root lengths than those receiving an adequate water supply. This is a traditional drought adaptation method in which plants prioritize root elongation over shoot development to access deeper soil moisture. The primary mechanism underlying this reaction is hydrotropism, wherein roots detect and grow toward moisture gradients. This process is facilitated by the redistribution of auxin, a plant hormone that concentrates in the elongation zone, stimulating cell expansion towards water. Moreover, water stress elevates abscisic acid (ABA) levels, which suppresses lateral root development while promoting primary root elongation. Ethylene levels are significant, as their suppression during water-deficient situations alleviates limitations on root extension, enabling roots to extend deeper into the soil. Sulphur sources markedly affected root development, as sulphur is crucial for amino acid synthesis, coenzyme function, and energy metabolism (Antoni *et al.,* 2016; Dietrich, 2018; Gangadhar & Brar, 2021; Krieger *et al.,* 2016; Kumar *et al.,* 2020; Lynch *et al.,* 2021; Nakajima *et al.,* 2017; Strock & Schneider, 2022; Sun *et al.,* 2014). Out of the three sulphur sources, gypsum (S1) produced the greatest root length at all growth stages, achieving a maximum of 8.87 cm at 120 DAS. Gypsum supplies readily accessible sulphate (SO_4^{2-}), which is directly assimilated by plants for protein synthesis, enzyme activation, and ATP production— essential components in root elongation. Bentonite sulphur (S2) exhibited a moderate impact, necessitating microbial oxidation to liberate sulphate, resulting in a consistent albeit delayed availability of sulphur. Conversely, elemental sulphur (S3) yielded the least root development, especially in the initial phases, owing to the slow microbial conversion process that restricts immediate sulphur availability. At later phases (90 and 120 DAS), oxidation advances, enabling elemental sulphur to aid in root growth, though less effectively than gypsum. The use of hydrogel (A1, A4, A5, A6) significantly facilitated root growth by augmenting soil moisture retention. Hydrogel collects water and subsequently releases it gradually, ensuring a consistent water supply for root absorption. During the initial phases (30-60 DAS), hydrogel-treated plants displayed marginally shorter roots than water- stressed plants (A7), since they did not necessitate significant elongation to seek moisture. By 90 and 120 days after sowing, hydrogel substantially enhanced root development, alleviating metabolic stress and guaranteeing consistent water availability (Agtuca *et al.,* 2014; Armengot *et al.,* 2014; Narjary *et al.,* 2013; Pasternak *et al.,* 2019). The maximum root length of 9.15 cm was seen in A6 (Hydrogel + Salicylic Acid applied during flowering and pod development), suggesting a synergistic interaction between moisture retention and hormonal modulation. Salicylic acid (A2, A3, A4, A5, A6) further influenced root elongation by promoting cell division, enhancing stress tolerance, and improving nutrient uptake efficiency. It enhances root meristem activity, accelerating cell division and elongation, notably observed in A2 (applied at 50% flowering) and A3 (applied at 50% pod formation). Salicylic acid also increases antioxidant enzyme activity, mitigating oxidative stress in root cells and preserving membrane integrity, so promoting continuous growth.

Table 4.1.6.1: Treatment effect on root length (cm) of rapeseed at periodic intervals in *Rabi* 2021–22 and 2022–23

Treatments	Root length (cm) 2021-2022				Root length (cm) 2022-2023			
Intervals	**30 DAS**	**60 DAS**	**90 DAS**	**120 DAS**	**30 DAS**	**60 DAS**	**90 DAS**	**120 DAS**
Sulphur sources								
S1: Gypsum	5.88^{a}	7.04^{a}	8.10^{a}	8.78^{a}	5.95^{a}	7.06^{a}	8.13^{a}	8.87^{a}
S2: Bentonite Sulphur	5.81^{a}	6.61^{b}	7.94^{a}	8.50^{a}	5.78^{a}	6.74^{ab}	7.97^{a}	8.52^{ab}
S3: Elemental Sulphur	5.18^{b}	6.28^{b}	7.30^{b}	8.02^{b}	5.20^{b}	6.34^{b}	7.29^{b}	8.07^{b}
CV (Sulphur Sources)	9.12	6.71	6.1	6.8	8.88	10.73	10.86	10.81
CD @5% (Sulphur Sources)	0.41	0.36	0.38	0.46	0.40	0.58	0.68	0.74
Agrochemical								
A0: Control (Irrigation as per requirement)	5.41^{c}	6.19^{e}	8.05^{ab}	8.98^{a}	5.25^{e}	6.23^{d}	7.88^{abc}	8.69^{abc}
A1: Hydrogel (2.5 kg/ha) as basal application	5.09^{d}	6.30^{de}	7.67^{d}	8.32^{c}	5.34^{de}	6.36^{cd}	7.69^{bcd}	8.36^{bcd}
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	6.10^{a}	7.15^{a}	7.65^{d}	8.10^{c}	6.06^{a}	7.23^{a}	7.57^{cd}	8.16^{de}
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	5.96^{a}	7.00^{ab}	7.69^{cd}	8.11^{c}	5.96^{ab}	7.07^{ab}	7.66^{bcd}	8.22^{cde}
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	5.35^{cd}	6.41^{de}	8.00^{abc}	8.75^{ab}	5.39^{de}	6.46^{cd}	8.06^{ab}	8.81^{ab}
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	5.52^{c}	6.55^{cde}	7.77^{bcd}	8.47^{bc}	5.59^{cd}	6.55^{cd}	8.05^{ab}	8.75^{ab}
A6: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at both 50% flowering and 50% pod formation stage	5.63^{bc}	6.64^{bcd}	8.21^{a}	9.05^{a}	5.75^{bc}	6.72^{bc}	8.26^{a}	9.15^{a}
A7: Control (Restricted irrigation)	5.91^{ab}	6.91^{abc}	7.18^{e}	7.69^{d}	5.82^{abc}	7.08^{ab}	7.23^{d}	7.77^{e}
CD @5% (Agrochemical)	0.29	0.36	0.32	0.39	0.29	0.45	0.46	0.48
CV (Sulphur Sources and agrochemical)	5.39	5.76	4.29	4.82	5.39	7.06	6.21	5.95

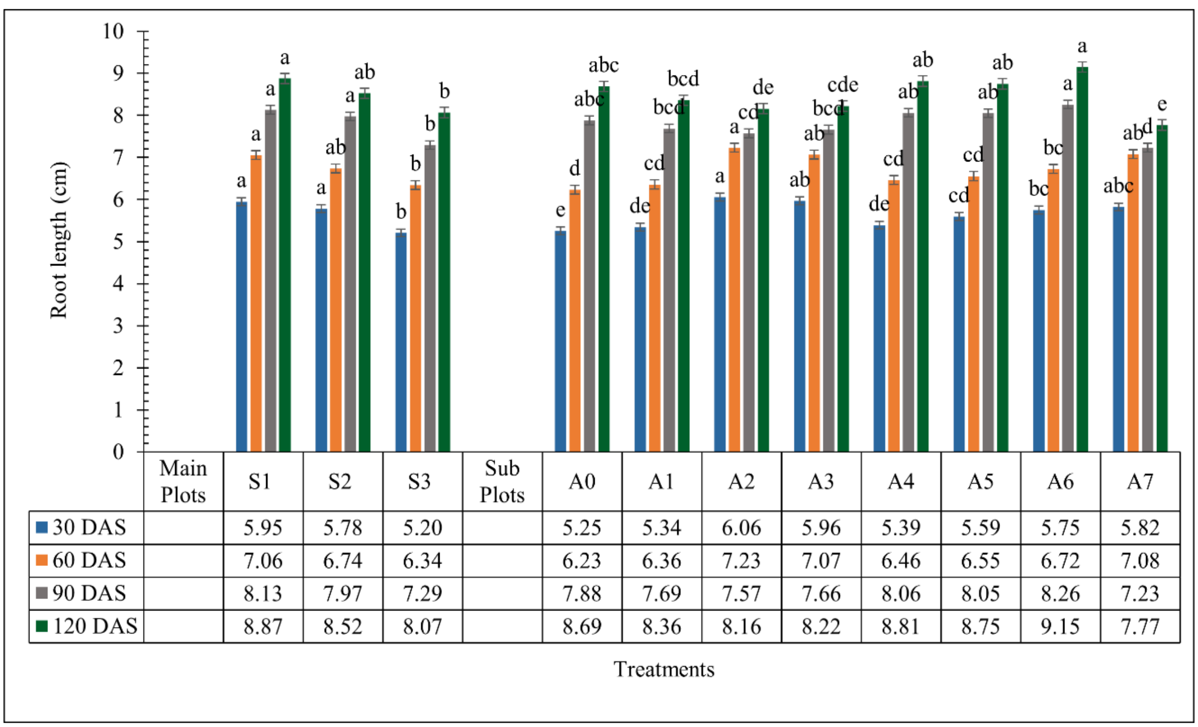
Table 4.1.6.2: Interaction effect of treatments on root length (cm) of rapeseed at periodic intervals during *rabi* 2021–22 and 2022–23

Treatments	Root length (cm) 2021-2022				Root length (cm) 2022-2023			
Intervals	30 DAS	60 DAS	90 DAS	120 DAS	30 DAS	60 DAS	90 DAS	120 DAS
S1A0	5.69±0.07	6.86±0.06	8.36±0.57	9.39±0.65	5.43±0.16	6.92±0.06	7.81±1.68	9.04±1.13
S1A1	5.35±0.16	6.44±0.16	8.06±0.50	8.72±0.50	5.73±0.06	6.46±0.16	8.07±0.50	8.75±0.50
S1A2	6.38±0.69	7.62±0.66	8.03±0.50	8.49±0.50	6.37±0.62	7.68±1.66	7.95±0.44	8.54±0.44
S1A3	6.21±0.65	7.48±0.65	8.08±0.07	8.50±0.06	6.30±0.66	7.41±1.54	8.04±0.06	8.60±0.06
S1A4	5.62±0.50	6.83±0.50	8.40±0.51	9.17±0.51	5.68±0.44	6.87±0.45	8.46±0.51	9.22±0.51
S1A5	5.80±0.50	6.98±0.50	7.68±1.12	8.44±1.22	5.89±0.50	6.86±0.29	8.45±0.83	9.15±0.83
S1A6	5.74±0.96	6.88±1.35	8.62±0.67	9.48±0.66	6.06±0.83	6.94±0.43	8.67±1.48	9.57±1.48
S1A7	6.22±0.32	7.25±0.51	7.54±0.16	8.06±0.16	6.13±0.51	7.31±0.51	7.59±0.16	8.13±0.16
S2A0	5.56±0.04	6.01±0.72	8.21±0.17	9.01±0.20	5.58±0.04	6.06±0.72	8.26±0.64	8.52±0.90
S2A1	5.23±0.72	6.39±0.04	7.79±0.04	8.36±0.04	5.28±0.72	6.48±0.04	7.83±0.04	8.42±0.04
S2A2	6.37±0.17	7.10±0.14	7.77±0.03	8.14±0.03	6.22±0.50	7.19±0.50	7.71±0.03	8.22±0.03
S2A3	6.07±0.11	6.99±0.19	7.81±0.05	8.15±0.04	6.07±0.47	7.17±0.43	7.80±0.04	8.28±0.04
S2A4	5.50±0.03	6.36±0.03	8.13±0.04	8.79±0.04	5.53±0.03	6.43±0.03	8.21±0.04	8.88±0.04
S2A5	5.67±0.04	6.50±0.04	8.14±0.03	8.73±0.90	5.73±0.04	6.58±0.04	8.20±0.03	8.82±0.03
S2A6	5.88±0.03	6.72±0.03	8.34±0.14	9.10±0.14	5.89±0.03	6.80±0.03	8.41±0.50	9.22±1.32
S2A7	6.17±0.22	6.83±0.10	7.30±0.72	7.73±0.72	5.97±0.04	7.18±0.54	7.36±0.72	7.83±0.72
S3A0	4.98±0.04	5.70±0.03	7.58±0.06	8.53±0.02	4.74±0.03	5.72±0.03	7.58±0.03	8.50±0.03
S3A1	4.69±0.03	6.07±0.04	7.16±0.03	7.88±0.03	5.01±0.04	6.13±0.04	7.16±0.03	7.91±0.03
S3A2	5.55±0.03	6.74±0.03	7.14±0.04	7.67±0.04	5.59±0.03	6.82±0.06	7.05±0.04	7.72±0.04
S3A3	5.60±0.24	6.53±0.02	7.18±0.04	7.68±0.04	5.52±0.03	6.62±0.08	7.13±0.04	7.78±0.04
S3A4	4.93±0.04	6.04±0.04	7.47±0.05	8.29±0.05	4.96±0.04	6.08±0.04	7.51±0.05	8.34±0.05
S3A5	5.08±0.03	6.17±0.03	7.48±0.03	8.23±0.03	5.15±0.03	6.22±0.03	7.50±0.03	8.28±0.03
S3A6	5.27±0.03	6.31±0.11	7.66±0.03	8.57±0.03	5.30±0.03	6.43±0.03	7.69±0.03	8.66±0.03
S3A7	5.33±0.05	6.65±0.21	6.70±0.03	7.28±0.03	5.36±0.05	6.74±0.19	6.73±0.03	7.35±0.03
CV	5.39	5.76	4.29	4.82	5.39	7.06	6.21	5.95
CD @5%	NS	0.68	0.63	0.77	NS	NS	NS	NS



	Main Plots	S1	S2	S3	Sub Plots	A0	A1	A2	A3	A4	A5	A6	A7
30 DAS		5.88	5.81	5.18		5.41	5.09	6.10	5.96	5.35	5.52	5.63	5.91
60 DAS		7.04	6.61	6.28		6.19	6.30	7.15	7.00	6.41	6.55	6.64	6.91
90 DAS		8.10	7.94	7.30		8.05	7.67	7.65	7.69	8.00	7.77	8.21	7.18
120 DAS		8.78	8.50	8.02		8.98	8.32	8.10	8.11	8.75	8.47	9.05	7.69

Fig. 4 .1.6.1 (a) Treatment effect on root length (cm) of rapeseed at periodic intervals in *rabi* 2021–22



	Main Plots	S1	S2	S3	Sub Plots	A0	A1	A2	A3	A4	A5	A6	A7
30 DAS		5.95	5.78	5.20		5.25	5.34	6.06	5.96	5.39	5.59	5.75	5.82
60 DAS		7.06	6.74	6.34		6.23	6.36	7.23	7.07	6.46	6.55	6.72	7.08
90 DAS		8.13	7.97	7.29		7.88	7.69	7.57	7.66	8.06	8.05	8.26	7.23
120 DAS		8.87	8.52	8.07		8.69	8.36	8.16	8.22	8.81	8.75	9.15	7.77

Fig. 4 .1.6.2 (b) Treatment effect on root length (cm) of rapeseed at periodic intervals in *rabi* 2022–23

4.1.7 Root Volume (cm^3): The investigation on the effects of various sulphur sources and agrochemicals applications on the root volume (cm^3) of rapeseed (Gobhi Sarson, GSC 7) at 30, 60, 90, and 120 days after sowing during the *rabi* season of 2021-22 demonstrated notable differences across treatments as shown in Table 4.1.7.1 and Figure 4.1.7.1(a). Among sulphur sources, Gypsum (S1) had the greatest root volume at all growth stages, with values of 2.63, 3.28, 3.27, and 3.34 cm^3 at 30, 60, 90, and 120 DAS, respectively. Bentonite Sulphur (S2) exhibited marginally lower albeit statistically comparable values at 30 DAS (2.54 cm^3; non-significant), whereas significant variations emerged at subsequent stages with values of 3.04, 3.02, and 3 cm^3 at 60, 90, and 120 DAS, respectively. Elemental Sulphur (S3) consistently exhibited the lowest root volume at all phases, with values of 2.30, 2.60, 2.61, and 2.72 cm^3. The augmentation in root volume with Gypsum compared to Elemental sulphur was 14.35%, 26.15%, 25.29%, and 22.79% at 30, 60, 90, and 120 DAS. The disparities across sulphur sources were statistically significant at all phases except 30 DAS, where S1 and S2 were comparable. For agrochemical treatments, A6 exhibited the highest root volume at all intervals, measuring 2.64, 3.16, 3.29, and 3.36 cm^3 at 30, 60, 90, and 120 days after sowing, respectively. This was statistically equivalent to A0, A1, A4, and A5 at early stages (30 and 60 DAS), but was significantly superior to all other treatments at 90 and 120 DAS. The root volume was recorded minimum in A7 (Control with limited irrigation) at 2.27, 2.66, 2.49, and 2.55 cm^3 during the four stages. At 120 DAS, the root volume under A6 increased by 31.76% compared to A7, and by 19.57% compared to A2 (2.81 cm^3). Treatments A2 and A3 exhibited markedly reduced values, particularly at 90 and 120 DAS, whereas A4 and A5 shown moderate performance. A6 was identified as the superior agrochemical treatment, whereas Gypsum (S1) proved to be the most efficacious source of sulphur for enhancing root volume in Gobhi Sarson. The analysis of various treatments on root volume (cm^3) at 30, 60, 90, and 120 days after sowing has shown that treatment S1A6 consistently exceeded all others, achieving the highest root volumes at 90 DAS (3.64 cm^3) and 120 DAS (3.70 cm^3), signifying robust and exceptional root growth. At 30 DAS, S1A4 had the greatest root volume (2.83 cm^3), closely followed by S1A6 and S1A1 (2.80 cm^3 each), whilst the lowest volume was recorded in S3A2 (2.07 cm^3). At 60 DAS, S1A4 maintained the lead with 3.51 cm^3, while S1A6 closely followed at 3.49 cm^3, and S3A2 recorded the lowest volume at 2.32 cm^3. At 90 DAS, S1A6 exhibited the highest value (3.64 cm^3), but S3A7 declined to the lowest (2.19 cm^3). At 120 DAS, S1A6 retained the highest volume at 3.70 cm^3, whereas S3A7 recorded the lowest at 2.30 cm^3. S1A6 was the most efficacious treatment for augmenting root volume during the crop growth period, whereas S3A2 and S3A7 were the least efficacious.

In the 2022-23 period, at 30 days after sowing, gypsum (S1) exhibited the largest root volume (2.71 cm^3), greatly surpassing elemental sulphur (S3) (2.33 cm^3) and being statistically comparable to bentonite sulphur (S2) (2.59 cm^3). At 60 DAS, the pattern remained same with S1 (3.31 cm^3) markedly exceeding both S2 (3 cm^3) and S3 (2.65 cm^3). At 90 DAS and 120 DAS, gypsum (S1) consistently outperformed elemental sulphur (S3), recording volumes of 3.36 cm^3 and 3.37 cm^3, respectively, whereas S3 exhibited the lowest values of 2.66 cm^3 and 2.76 cm^3 over these intervals. Root volume under S1 increased by 16.3% at 30 DAS, 24.9% at 60 DAS, 26.3% at 90 DAS, and 22.1% at 120 DAS compared to S3. Consequently, gypsum (S1) was identified as the optimal sulphur source for augmenting root volume. The highest root volume among the agrochemical treatments was continuously observed under A6, measuring 2.68 cm^3, 3.19 cm^3, 3.37 cm^3, and 3.41 cm^3 at 30, 60, 90, and 120 days after sowing, respectively. At 30 DAS, it was statistically comparable to A0, A1, A4, and A5, but significantly superior to A2, A3, and A7. The trend persisted in subsequent stages, with A6 demonstrating marked superiority over A7 (limited irrigation), which exhibited the lowest root volumes of 2.31 cm^3, 2.63 cm^3, 2.61 cm^3, and 2.62 cm^3 at the respective phases. A6 demonstrated a 30.1% enhancement compared to A7 at 120 DAS. A6 exhibited a 20.5% greater root volume at 120 DAS compared to A2 (2.83 cm^3), with this difference being statistically significant (CD @5% = 0.12). A6 was determined to be the most efficacious agrochemical treatment for augmenting root volume. Sulphur treatments demonstrated statistically significant differences at all growth phases, with gypsum (S1) consistently outperforming others. Agrochemical treatments have shown notable differences at every stage; A6 surpassed all other treatments with statistical significance at 60, 90, and 120 days after sowing (DAS). The root volume (cm^3) of Gobhi Sarson at various growth stages was dramatically affected with the synergistic application of sulphur sources and agrochemicals. At 30 DAS, the highest root volume (2.88 cm^3) was observed in treatment S1A1, closely followed by S1A5 (2.87 cm^3), whilst the minimum value (2.09 cm^3) was reported in S3A2 and S3A7. At 60 days after sowing, S1A5 exhibited the greatest root volume (3.59 cm^3), markedly surpassing other treatments, whereas S2A3 recorded 2.59 cm^3, the lowest volume. At 90 DAS, the maximum root volume was seen in S1A6 (3.72 cm^3), followed by S1A0 (3.67 cm^3), whilst S3A7 (2.29 cm^3) exhibited the minimum. At 120 DAS, S1A6 (3.76 cm^3) continued to be the top performer, whereas S3A7 (2.36 cm^3) exhibited the lowest root volume. Treatment S1A6 (Sulphur source S1 + Salicylic acid and Hydrogel) consistently exhibited the largest root volume at all phases, demonstrating its efficacy in promoting root development under controlled irrigation conditions. There were non-significant (NS) variations in root volume across treatments at particular growth stages, specifically 120 DAS in 2021–2022 and 90 DAS in 2022–2023. These findings suggest that natural plant variability and consistent environmental circumstances were more important factors than the applied sulphur sources, salicylic acid, and hydrogel treatments, which had no discernible effect on root growth at these periods.

During the initial phases of plant development, hydrogel coatings frequently yield consistent growth across treatments owing to their capacity to uniformly improve soil moisture retention. Hydrogels are cross-linked polymers capable of absorbing and retaining significant quantities of water, which they release gradually to plant roots. The regular availability of moisture facilitates uniform seed germination and seedling establishment, as all plants have equitable access to the requisite water supply. A study indicated that hydrogel seed coatings markedly enhanced early growth parameters, resulting in a 50% increase in fresh sprout weight and a fourfold increase in root length relative to uncoated seeds (Kaur *et al.,* 2023; Rahul Kumar *et al.,* 2020; Skrzypczak *et al.,* 2021). As plants advance to subsequent growth phases, their need for water and nutrients intensifies, and root systems penetrate more into the earth. The original hydrogel application may now be inadequate to satisfy the varied requirements of individual plants, resulting in inconsistent growth responses. Differential root penetration, localized soil nutrient availability, and varied rates of hydrogel decomposition contribute to this heterogeneity.

Studies demonstrate that although hydrogels significantly improve soil moisture retention, their structural integrity may deteriorate with time, particularly under environmental stressors such as UV radiation and microbial activity, hence diminishing their long-term effectiveness. (Li & Zhang, 2023; Narjary *et al.,* 2013; Peyrusson, 2021). Furthermore, the efficacy of hydrogels might be affected by soil composition and environmental factors. Research indicates that hydrogel additions can markedly enhance water retention in sandy soils, therefore facilitating plant development under constrained irrigation conditions. In soils with elevated clay content, the advantages may be diminished owing to the soil's intrinsic water retention capability. Furthermore, the progressive deterioration of hydrogels over time may result in diminished water-retention capacity, hence affecting the consistency of plant growth in subsequent phases. (Al Tamimi & Abbas, 2024; Alghamdi *et al.,* 2024; Palanivelu *et al.,* 2022).

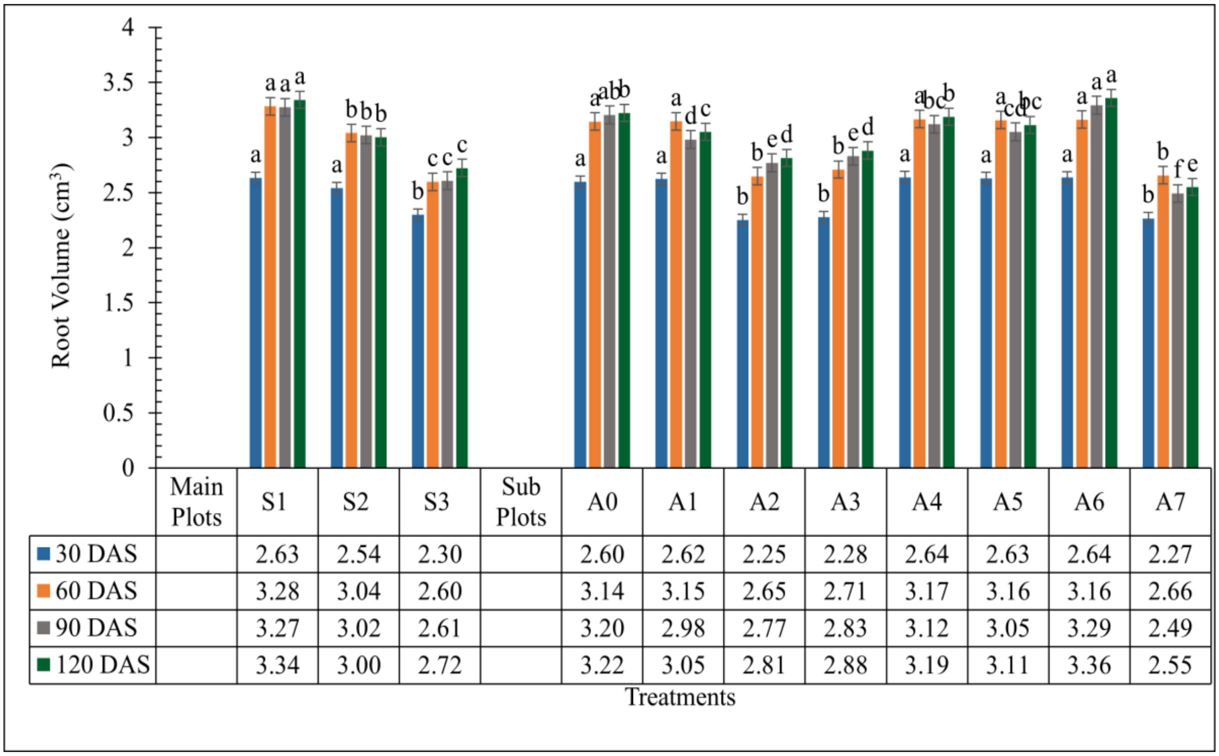
In conclusion, although hydrogel applications offer consistent advantages in the initial phases of plant development by maintaining uniform moisture levels, their declining efficacy over time, along with heightened plant requirements and environmental influences, may result in inconsistencies in subsequent growth stages. Current research seeks to improve the durability and efficacy of hydrogels to facilitate prolonged plant growth.

Table 4.1.7.1: Effect of treatments on root volume (cm^3) of rapeseed at periodic intervals in *Rabi* 2021–22 and 2022–23

Treatments	Root volume (cm^3) (2021-2022)				Root volume (cm^3) (2022-2023)			
Intervals	30 DAS	60 DAS	90 DAS	120 DAS	30 DAS	60 DAS	90 DAS	120 DAS
Sulphur sources								
S1: Gypsum	2.63^{a}	3.28^{a}	3.27^{a}	3.34^{a}	2.71^{a}	3.31^{a}	3.36^{a}	3.37^{a}
S2: Bentonite Sulphur	2.54^{a}	3.04^{b}	3.02^{b}	3.00^{b}	2.59^{b}	3.00^{b}	3.09^{b}	3.05^{b}
S3: Elemental Sulphur	2.30^{b}	2.60^{c}	2.61^{c}	2.72^{c}	2.33^{c}	2.65^{c}	2.66^{c}	2.76^{c}
CV (Sulphur Sources)	5.69	6.12	4.24	4.98	2.88	4.35	5.75	4.76
CD @5% (Sulphur Sources)	0.11	0.15	0.10	0.12	0.06	0.10	0.14	0.12
Agrochemical								
A0: Control (Irrigation as per requirement)	2.60^{a}	3.14^{a}	3.20^{ab}	3.22^{b}	2.68^{a}	3.17^{a}	3.29^{ab}	3.26^{b}
A1: Hydrogel (2.5 kg/ha) as basal application	2.62^{a}	3.15^{a}	2.98^{d}	3.05^{c}	2.69^{a}	3.16^{a}	3.01^{d}	3.08^{c}
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	2.25^{b}	2.65^{b}	2.77^{e}	2.81^{d}	2.29^{b}	2.71^{b}	2.82^{e}	2.83^{d}
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	2.28^{b}	2.71^{b}	2.83^{e}	2.88^{d}	2.34^{b}	2.65^{b}	2.88^{e}	2.91^{d}
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	2.64^{a}	3.17^{a}	3.12^{bc}	3.19^{b}	2.68^{a}	3.18^{a}	3.18^{bc}	3.22^{b}
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	2.63^{a}	3.16^{a}	3.05^{cd}	3.11^{bc}	2.68^{a}	3.18^{a}	3.14^{c}	3.15^{bc}
A6: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at both 50% flowering and 50% pod formation stage	2.64^{a}	3.16^{a}	3.29^{a}	3.36^{a}	2.68^{a}	3.19^{a}	3.37^{a}	3.41^{a}
A7: Control (Restricted irrigation)	2.27^{b}	2.66^{b}	2.49^{f}	2.55^{e}	2.31^{b}	2.63^{b}	2.61^{f}	2.62^{e}
CD @5% (Agrochemical)	0.08	0.09	0.12	0.11	0.07	0.13	0.13	0.12
CV (Sulphur Sources and agrochemical)	3.31	3.2	4.38	3.96	2.76	4.74	4.35	4.18

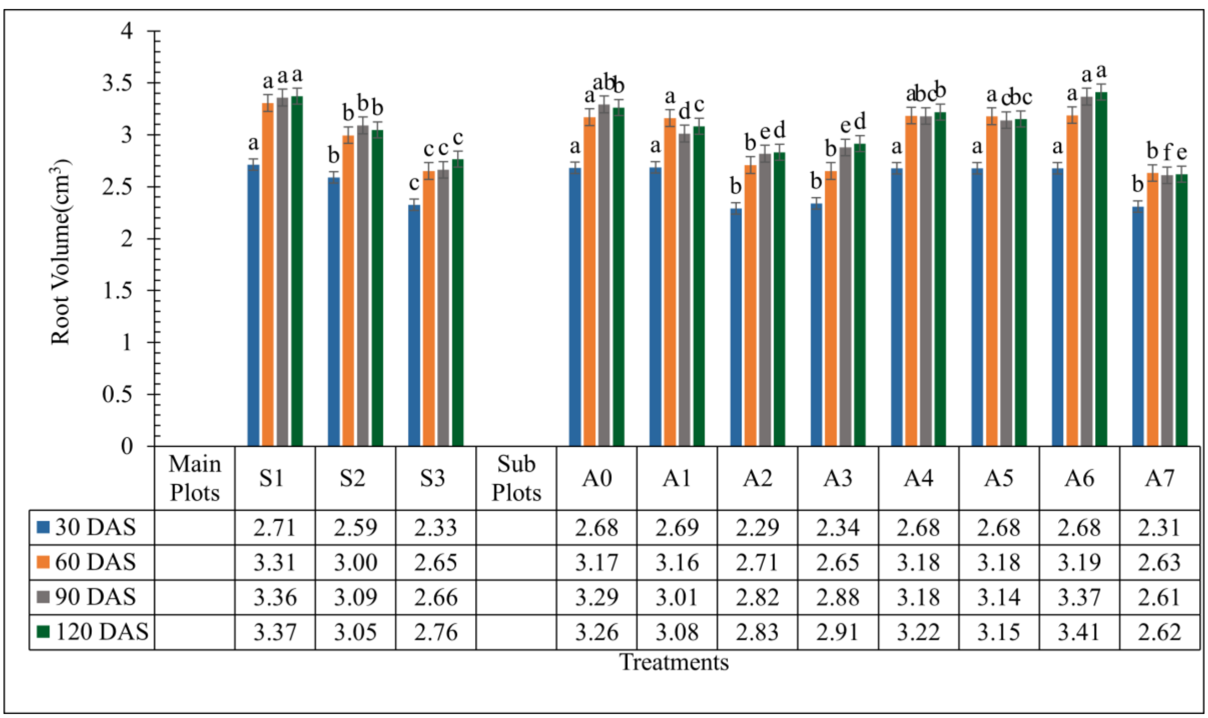
Table 4.1.7.2: Interaction effect of treatments on root volume (cm^3) of rapeseed at periodic intervals during *rabi* 2021–22 and 2022–23

Treatments	Root volume (cm^3) (2021-2022)				Root volume (cm^3) (2022-2023)			
Intervals	**30 DAS**	**60 DAS**	**90 DAS**	**120 DAS**	**30 DAS**	**60 DAS**	**90 DAS**	**120 DAS**
S1A0	2.73±0.12	3.47±0.05	3.50±0.16	3.65±0.12	2.85±0.05	3.51±0.11	3.67±0.13	3.58±0.09
S1A1	2.80±0.07	3.49±0.06	3.29±0.02	3.36±0.02	2.88±0.04	3.51±0.03	3.32±0.02	3.40±0.02
S1A2	2.37±0.04	2.92±0.04	3.06±0.04	3.10±0.04	2.44±0.04	2.99±0.22	3.11±0.07	3.12±0.07
S1A3	2.39±0.04	2.99±0.06	3.13±0.06	3.17±0.06	2.50±0.06	2.93±0.17	3.18±0.06	3.21±0.06
S1A4	2.83±0.05	3.51±0.24	3.45±0.21	3.51±0.21	2.85±0.03	3.56±0.11	3.51±0.31	3.55±0.31
S1A5	2.78±0.14	3.46±0.25	3.37±0.43	3.43±0.33	2.87±0.30	3.59±0.32	3.47±0.47	3.47±0.42
S1A6	2.80±0.24	3.49±0.13	3.64±0.13	3.70±0.13	2.86±0.10	3.54±0.16	3.72±0.16	3.76±0.16
S1A7	2.35±0.10	2.92±0.17	2.75±0.16	2.81±0.16	2.46±0.06	2.81±0.13	2.88±0.16	2.89±0.16
S2A0	2.67±0.03	3.23±0.08	3.29±0.20	3.14±0.30	2.71±0.03	3.19±0.06	3.32±0.05	3.24±0.13
S2A1	2.64±0.03	3.20±0.01	3.03±0.04	3.04±0.04	2.72±0.02	3.23±0.04	3.07±0.04	3.07±0.04
S2A2	2.31±0.03	2.70±0.03	2.82±0.03	2.80±0.03	2.34±0.03	2.76±0.03	2.87±0.03	2.82±0.03
S2A3	2.36±0.04	2.76±0.04	2.88±0.04	2.87±0.04	2.40±0.04	2.59±0.35	2.93±0.04	2.90±0.04
S2A4	2.69±0.02	3.25±0.08	3.17±0.04	3.17±0.04	2.72±0.05	3.18±0.08	3.24±0.21	3.21±0.21
S2A5	2.64±0.15	3.24±0.14	3.10±0.03	3.10±0.03	2.72±0.04	3.11±0.13	3.20±0.03	3.14±0.03
S2A6	2.67±0.07	3.22±0.02	3.35±0.19	3.34±0.19	2.71±0.03	3.21±0.05	3.43±0.02	3.39±0.02
S2A7	2.34±0.03	2.71±0.02	2.53±0.22	2.54±0.22	2.38±0.03	2.71±0.13	2.66±0.04	2.61±0.04
S3A0	2.39±0.07	2.73±0.08	2.82±0.04	2.87±0.07	2.48±0.01	2.82±0.07	2.89±0.02	2.97±0.05
S3A1	2.42±0.19	2.75±0.18	2.62±0.03	2.75±0.03	2.46±0.02	2.74±0.19	2.64±0.03	2.78±0.03
S3A2	2.07±0.04	2.32±0.04	2.43±0.04	2.54±0.04	2.09±0.04	2.38±0.04	2.47±0.04	2.55±0.04
S3A3	2.08±0.02	2.37±0.04	2.48±0.04	2.60±0.04	2.12±0.01	2.43±0.04	2.52±0.04	2.63±0.04
S3A4	2.40±0.03	2.73±0.02	2.74±0.05	2.88±0.05	2.46±0.03	2.81±0.07	2.79±0.05	2.90±0.05
S3A5	2.47±0.01	2.77±0.05	2.68±0.03	2.81±0.03	2.44±0.04	2.83±0.03	2.75±0.03	2.84±0.03
S3A6	2.44±0.03	2.77±0.03	2.89±0.03	3.03±0.03	2.46±0.03	2.82±0.03	2.95±0.03	3.08±0.03
S3A7	2.11±0.04	2.33±0.03	2.19±0.03	2.30±0.03	2.09±0.03	2.38±0.15	2.29±0.03	2.36±0.03
CV	3.31	3.2	4.38	3.96	2.76	4.74	4.35	4.18
CD @5%	0.17	0.20	0.22	NS	0.12	0.24	NS	0.23



	Main Plots	S1	S2	S3	Sub Plots	A0	A1	A2	A3	A4	A5	A6	A7
30 DAS		2.63	2.54	2.30		2.60	2.62	2.25	2.28	2.64	2.63	2.64	2.27
60 DAS		3.28	3.04	2.60		3.14	3.15	2.65	2.71	3.17	3.16	3.16	2.66
90 DAS		3.27	3.02	2.61		3.20	2.98	2.77	2.83	3.12	3.05	3.29	2.49
120 DAS		3.34	3.00	2.72		3.22	3.05	2.81	2.88	3.19	3.11	3.36	2.55

Fig. 4 .1.7.1 (a) Effect of treatments on root volume (cm³) of rapeseed at periodic intervals in *rabi* 2021–22



	Main Plots	S1	S2	S3	Sub Plots	A0	A1	A2	A3	A4	A5	A6	A7
30 DAS		2.71	2.59	2.33		2.68	2.69	2.29	2.34	2.68	2.68	2.68	2.31
60 DAS		3.31	3.00	2.65		3.17	3.16	2.71	2.65	3.18	3.18	3.19	2.63
90 DAS		3.36	3.09	2.66		3.29	3.01	2.82	2.88	3.18	3.14	3.37	2.61
120 DAS		3.37	3.05	2.76		3.26	3.08	2.83	2.91	3.22	3.15	3.41	2.62

Fig. 4 .1.7.2 (b) Effect of treatments on root volume (cm³) of rapeseed at periodic intervals in *rabi* 2022–23

4.1.8 Root Dry Weight (gm): The findings shown in Tables 4.1.8.1, 4.1.8.2, and Figures 4.1.8.1(a), 4.1.8.2(b) demonstrated substantial variations in dry weight of root across the treatments at all growth stages that are 30, 60, 90, and 120 days after sowing. During the year 2021-2022, at 30 days after sowing, gypsum (S1) had the highest root dry weight (23.52 g), greatly surpassing elemental sulphur (S3) (18.17 g) and being statistically comparable to bentonite sulphur (S2) (22.50 g). This pattern persisted at 60 DAS, with S1 (36.52 g) significantly outperforming S3 (29.64 g). At 90 DAS, gypsum (S1) had the greatest root dry weight of 62.36 g, greatly surpassing elemental sulphur (S3) at 51.95 g and bentonite sulphur (S2) at 60.30 g. At 120 days after sowing, gypsum (S1) exhibited the highest root dry weight at 62.39 g, greatly surpassing both bentonite sulphur (S2) at 60.16 g and elemental sulphur (S3) at 52.29 g. The root dry weight percentage increase for gypsum (S1) relative to elemental sulphur (S3) was 29.2% at 30 DAS, 23.3% at 60 DAS, 20% at 90 DAS, and 19.3% at 120 DAS. Gypsum (S1) was the optimal sulphur source for augmenting root dry weight. A6 (Hydrogel @ 2.5 kg/ha + Salicylic acid @ 150 ppm at 50% flowering and pod formation) exhibited the highest root dry weight at 30 DAS (22.32 g), 60 DAS (35.31 g), 90 DAS (64.67 g), and 120 DAS (66.16 g) among the agrochemical treatments. This treatment was markedly superior to A7 (limited irrigation), which consistently exhibited the lowest values at all stages. At 120 DAS, A6 exhibited a root dry weight of 66.16 g, whereas A7 recorded 50.99 g, indicating a 29.8% rise. Among various treatments, A0 (Control, irrigation as required) demonstrated notable efficacy with a root dry weight of 65.13 g at 120 DAS, comparable to A6, and statistically superior to A1 (Hydrogel at basal dose), A2 (Salicylic acid at 50% flowering), and A3 (Salicylic acid at 50% pod formation), which exhibited lower root dry weights of 55.92 g, 53.81 g, and 53.96 g, respectively, at 120 DAS. A6 had the highest efficacy as an agrochemical treatment for enhancing root dry weight. Sources of sulphur exhibited notable variations at every stage, with gypsum (S1) consistently yielding the highest root dry weight. Agrochemical treatments exhibited notable variations, with A6 (Hydrogel + Salicylic acid) demonstrating the highest root dry weight at all stages, surpassing A7 (limited irrigation), which yielded the lowest values.

The interaction impact of treatments on root dry weight (g) at various growth stages of Gobhi Sarson exhibited notable disparities among treatments. At 30 DAS, the maximum root dry weight was observed in S1A5 (24.91 g), whilst the minimum was documented in S3A2 (16.89

g). At 60 DAS, S1A6 exhibited the highest root dry weight at 39.69 g, whilst S3A2 recorded the lowest at 26.47 g. At 90 days after sowing, S1A6 exhibited the highest root dry weight at 69.18 g, while S3A7 recorded the lowest at 44.37 g. At 120 days after sowing, the highest root dry weight was recorded in S1A6 (70.82 g), whereas the lowest was in S3A7 (45.78 g). The root dry weight (g) of Gobhi Sarson in the 2022–23 *rabi* season was significantly affected by sulphur sources and agrochemical treatments at every growth stage. Among the sources of sulphur, gypsum (S1) consistently yielded the highest root dry weight, measuring 23.40 g at 30 DAS, 37.30 g at 60 DAS, 62.78 g at 90 DAS, and 63.94 g at 120 DAS. Conversely, elemental sulphur (S3) exhibited the lowest values at each interval (18.20, 29.21, 52.26, and 53.59 g, respectively), while gypsum produced approximately 28.6% greater dry weight at 30 DAS, 27.7% higher at 60 DAS, 20.1% superior at 90 DAS, and 19.3% increased at 120 DAS in comparison to elemental sulphur. Bentonite sulphur (S2) exhibited intermediate performance, being statistically inferior to gypsum at 30 and 60 days after sowing (DAS) and comparable to gypsum at 120 DAS, but significantly surpassing elemental sulphur. The control with full irrigation (A0) and the combination application of hydrogel with salicylic acid at both 50% flowering and pod formation (A6) yielded the greatest root dry weights in agrochemical treatments. A0 recorded 22.22 g, 35.24 g, 63.46 g, and 65.11 g at 30, 60, 90, and 120 days after sowing (DAS), respectively, whereas A6 attained marginally superior values of 22.30 g, 35.61 g, 64.95 g, and 66 g at the same intervals. Treatments utilizing hydrogel alone (A1), salicylic acid alone at both growth stages (A2 and A3), and the combined treatments A4 and A5 yielded modest root dry weights, consistently lower than those observed in A0 and A6. Significantly, restricted irrigation (A7) markedly diminished root dry weight, yielding the lowest values of 19.68 g, 29 g, 49.97 g, and 51.96 g from 30 to 120 DAS. At 120 DAS, A6 had a 27% enhancement in root dry weight compared to A7. These results demonstrate that gypsum is the most efficacious sulphur source for augmenting root dry weight, whereas the synergistic application of hydrogel and salicylic acid at both critical growth stages (A6) and optimal irrigation (A0) represents the most advantageous agrochemical strategies for enhancing root development in Gobhi Sarson during the 2022–23 season. The interaction impact of treatments on root dry weight (g) at various growth stages of Gobhi Sarson exhibited significant disparities among treatments. At 30 DAS, the maximum root dry weight was observed in S1A5 (24.59 g), whilst the minimum was reported in S3A7 (16.24 g). At 60 DAS, S1A1 demonstrated the greatest root dry weight (39.97 g), whilst S3A7 exhibited the least (25.44 g). At 90 days after sowing, the maximum root dry weight was observed in S1A6 (69.63 g), whereas the minimum was recorded in S3A7 (44.67 g). At 120 DAS, S1A6 exhibited the greatest root dry weight (70.64 g), whilst S3A7 recorded the lowest (47.45 g). S1A6 was the most effective treatment at all growth stages, demonstrating the highest root dry weight, whereas S3A7 consistently yielded the lowest values. The applied treatments had little effect on root dry weight; in 2022–2023, non-significant (NS) changes were noted at 60 and 120 DAS. This suggests that hydrogel, salicylic acid, and sulphur sources had no apparent impact on root biomass throughout these phases. The findings imply that root dry weight was more significantly influenced by uniform growing circumstances under regulated irrigation and natural plant variability than by the treatments that were used.

The variations in root dry weight among the treatments indicate the complex interaction of nutrition availability, moisture retention, and stress alleviation strategies affecting root development in rapeseed. In the initial growth phases, root development is mostly determined by genetic potential and soil conditions, while sulphur supplies and agrochemical applications have less impact. Sulphur is an essential ingredient for protein synthesis, and its significance in root development intensifies as plants progress to advanced developmental stages. Gypsum and bentonite sulphur, which supply easily available sulphate, promoted increased root biomass by enhancing metabolic activities, including amino acid synthesis and energy transfer via sulphur-containing coenzymes. In contrast, elemental sulphur needs microbial oxidation to transform into a plant-accessible form, resulting in postponed advantages for root development due to the protracted conversion process, particularly under situations of reduced microbial activity, such as water scarcity or cold temperatures. Agrochemical applications additionally influenced root development dynamics. Hydrogel enhanced soil water retention, establishing a more advantageous moisture environment in the root zone and diminishing the energy expenditure of roots in their pursuit of water in deeper soil strata. This enabled the plant to dedicate additional resources to the formation of a denser and more fibrous root system, essential for efficient nutrient absorption. Salicylic acid, utilized as a foliar application, indirectly affected root development by augmenting the plant's stress response systems. It enhances root architecture by regulating hormonal pathways, particularly auxin signaling, which is essential for lateral root development and elongation.

Treatments combining hydrogel and salicylic acid demonstrated a synergistic effect, improving water availability and stress tolerance, hence increasing root biomass. Root development is crucial for rapeseed during the flowering and pod formation stages, as a robust root system facilitates the effective absorption of water and essential nutrients, including sulphur and nitrogen, required for reproductive growth and seed production. Limited irrigation markedly impeded root development by diminishing the accessibility of water and nutrients, resulting in decreased root dry weight. This underscores the significance of treatments in alleviating water stress and enhancing root functionality. Roots serve to anchor the plant and function as a dynamic interface for the acquisition of nutrients and water, rendering their growth and health essential for maximizing yields in oilseed crops. (Balliu *et al.,* 2021; Gao *et al.,* 2024; Kumar *et al.,* 2020; Lynch *et al.,* 2021; Mann *et al.,* 2023a, 2023b; Shoaib *et al.,* 2022; Strock & Schneider, 2022).

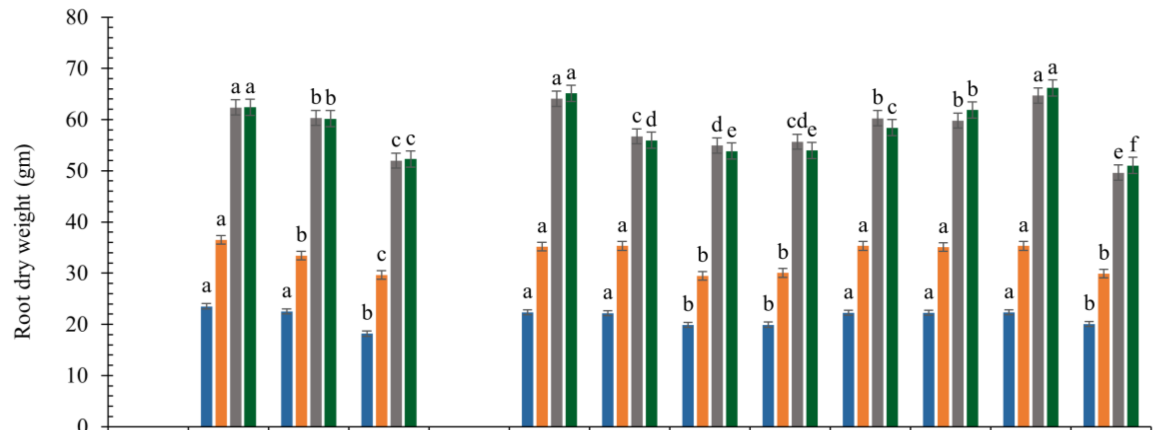
These findings correspond with research indicating that sulphur supplementation promotes root growth by enhancing cell division and expansion, while hydrogel and salicylic acid mitigate water stress and oxidative damage, facilitating improved resource allocation for root development. Collectively, these treatments enhance the rhizosphere environment, fostering vigorous root systems that facilitate increased shoot growth and production under diverse environmental conditions.

Table 4.1.8.1: Treatment influence on root dry weight (gm) of rapeseed at periodic intervals in *rabi* 2021–22 and 2022–23

Treatments	Root dry weight (gm) (2021-2022)				Root dry weight (gm) (2022-2023)			
Intervals	30 DAS	60 DAS	90 DAS	120 DAS	30 DAS	60 DAS	90 DAS	120 DAS
Sulphur sources								
S1: Gypsum	23.52^{a}	36.52^{a}	62.36^{a}	62.39^{a}	23.40^{a}	37.30^{a}	62.78^{a}	63.94^{a}
S2: Bentonite Sulphur	22.50^{a}	33.42^{b}	60.30^{b}	60.16^{b}	22.31^{b}	33.37^{b}	60.48^{b}	61.41^{a}
S3: Elemental Sulphur	18.17^{b}	29.64^{c}	51.95^{c}	52.29^{c}	18.20^{c}	29.21^{c}	52.26^{c}	53.59^{b}
CV (Sulphur Sources)	6.65	4.2	3.83	2.38	4.21	12.19	3.84	5.87
CD @5% (Sulphur Sources)	1.14	1.12	1.79	1.11	0.72	3.25	1.80	2.81
Agrochemical								
A0: Control (Irrigation as per requirement)	22.37^{a}	35.16^{a}	64.05^{a}	65.13^{a}	22.22^{a}	35.24^{a}	63.46^{a}	65.11^{a}
A1: Hydrogel (2.5 kg/ha) as basal application	22.19^{a}	35.30^{a}	56.69^{c}	55.92^{d}	22.12^{a}	35.00^{a}	56.99^{c}	57.86^{c}
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	19.85^{b}	29.47^{b}	54.92^{d}	53.81^{e}	19.85^{b}	30.44^{b}	55.49^{c}	55.98^{c}
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	19.91^{b}	30.03^{b}	55.66^{cd}	53.96^{e}	19.78^{b}	30.67^{b}	55.96^{c}	56.99^{c}
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	22.25^{a}	35.30^{a}	60.25^{b}	58.39^{c}	22.19^{a}	35.13^{a}	60.87^{b}	61.82^{b}
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	22.24^{a}	35.08^{a}	59.77^{b}	61.85^{b}	22.30^{a}	35.27^{a}	60.34^{b}	61.45^{b}
A6: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at both 50% flowering and 50% pod formation stage	22.32^{a}	35.31^{a}	64.67^{a}	66.16^{a}	22.30^{a}	35.61^{a}	64.95^{a}	66.00^{a}
A7: Control (Restricted irrigation)	20.02^{b}	29.90^{b}	49.62^{e}	50.99^{f}	19.68^{b}	29.00^{b}	49.97^{d}	51.96^{d}
CD @5% (Agrochemical)	1.14	1.41	1.56	1.58	0.97	1.82	1.76	2.03
CV (Sulphur Sources and agrochemical)	5.59	4.47	2.81	2.85	4.81	5.76	3.16	3.57

Table 4.1.8.2: Interaction effect of treatments on root dry weight (gm) of rapeseed at periodic intervals during *rabi* 2021–22 and 2022–23.

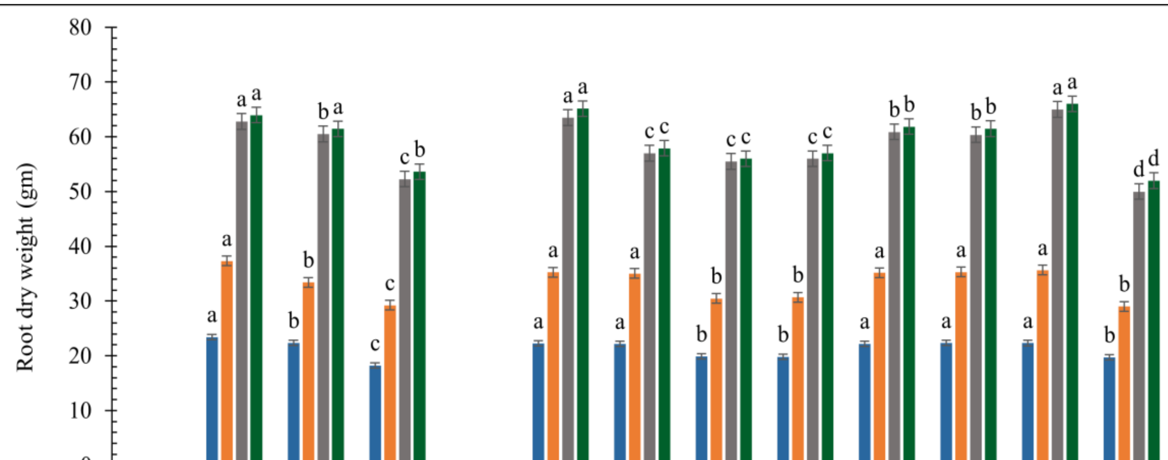
Treatments	Root dry weight (gm) (2021-2022)				Root dry weight (gm) (2022-2023)			
Intervals	30 DAS	60 DAS	90 DAS	120 DAS	30 DAS	60 DAS	90 DAS	120 DAS
S1A0	24.44±0.63	39.68±0.71	68.24±0.40	69.90±0.14	24.07±0.85	39.55±0.71	68.54±0.40	69.46±0.14
S1A1	24.52±1.79	39.49±1.13	60.81±0.50	59.83±0.50	24.20±0.30	39.97±1.13	61.08±0.50	61.93±0.50
S1A2	21.85±0.50	31.93±2.19	58.91±0.50	57.57±0.50	21.91±0.50	34.17±2.19	59.47±0.50	59.91±0.50
S1A3	21.76±5.52	31.58±1.57	59.70±0.06	57.73±0.06	21.90±0.65	34.84±1.57	59.98±0.06	61.00±0.06
S1A4	24.37±0.89	38.62±0.55	64.63±0.51	62.47±0.51	24.14±0.74	38.98±0.55	65.24±0.51	66.17±0.51
S1A5	24.91±0.11	39.41±1.14	64.19±0.83	66.21±0.83	24.59±0.81	39.95±1.14	64.67±0.83	65.77±0.83
S1A6	24.57±0.66	39.69±0.49	69.18±0.66	70.82±0.66	24.40±0.66	39.87±0.49	69.63±0.66	70.64±0.66
S1A7	21.71±0.37	31.74±0.24	53.22±0.16	54.56±0.16	22.02±0.40	31.08±0.24	53.61±0.16	56.68±0.16
S2A0	23.74±1.24	35.01±1.09	67.30±5.99	67.35±6.33	23.35±0.55	35.13±1.09	65.12±5.99	67.29±6.33
S2A1	23.47±1.62	35.28±1.49	58.57±0.04	57.72±0.04	23.24±0.27	34.01±1.49	59.00±0.04	59.81±0.04
S2A2	20.80±0.03	30.02±0.03	56.74±0.03	55.55±0.03	20.87±0.71	30.40±0.03	57.44±0.03	57.87±0.03
S2A3	20.96±3.04	31.10±3.04	57.50±3.04	55.70±3.04	20.63±2.55	31.54±3.04	57.93±3.04	58.91±3.04
S2A4	23.30±0.78	35.58±0.60	62.24±0.04	60.27±0.04	23.36±0.31	35.08±0.60	63.01±4.04	63.90±0.04
S2A5	23.37±0.44	34.89±0.90	61.61±0.32	63.79±0.50	23.20±1.19	34.56±0.90	62.47±0.32	63.52±0.50
S2A6	23.39±3.10	35.17±1.77	67.17±5.20	68.22±3.62	23.02±2.60	35.76±1.77	67.20±5.20	68.22±3.62
S2A7	20.94±2.47	30.32±1.44	51.27±0.71	52.64±0.72	20.79±1.51	30.46±1.44	51.64±0.71	51.74±0.72
S3A0	18.92±0.05	30.78±0.20	56.59±0.50	58.14±0.18	19.24±0.21	31.04±0.20	56.74±0.50	58.58±0.18
S3A1	18.57±0.34	31.13±0.70	50.69±0.03	50.21±0.03	18.93±1.07	31.01±0.70	50.89±0.03	51.84±0.03
S3A2	16.89±0.04	26.47±0.04	49.11±0.04	48.31±0.04	16.76±0.60	26.76±0.04	49.55±0.04	50.16±0.04
S3A3	17.02±0.04	27.42±0.04	49.77±0.04	48.45±0.04	16.82±1.15	25.64±0.04	49.97±0.04	51.06±0.04
S3A4	19.07±0.16	31.69±3.89	53.88±0.05	52.42±0.05	19.06±0.55	31.31±3.89	54.36±0.05	55.39±0.05
S3A5	18.44±1.13	30.93±2.12	53.51±0.03	55.56±0.03	19.10±0.76	31.29±2.12	53.88±0.03	55.06±0.03
S3A6	19.00±0.03	31.08±0.03	57.67±0.03	59.43±0.03	19.47±0.03	31.22±0.03	58.02±0.03	59.14±0.03
S3A7	17.42±0.33	27.63±0.28	44.37±0.03	45.78±0.03	16.24±0.03	25.44±0.28	44.67±0.03	47.45±0.03
CV	5.59	4.47	2.81	2.85	4.81	5.76	3.16	3.57
CD @5%	2.15	2.53	3.06	2.77	1.72	NS	3.34	NS



	Main Plots	S1	S2	S3	Sub Plots	A0	A1	A2	A3	A4	A5	A6	A7
30 DAS		23.52	22.50	18.17		22.37	22.19	19.85	19.91	22.25	22.24	22.32	20.02
60 DAS		36.52	33.42	29.64		35.16	35.30	29.47	30.03	35.30	35.08	35.31	29.90
90 DAS		62.36	60.30	51.95		64.05	56.69	54.92	55.66	60.25	59.77	64.67	49.62
120 DAS		62.39	60.16	52.29		65.13	55.92	53.81	53.96	58.39	61.85	66.16	50.99

Treatments

Fig. 4 .1.8.1 (a) Treatment influence on root dry weight (gm) of rapeseed at periodic intervals in *rabi* 2021–22



	Main Plots	S1	S2	S3	Sub Plots	A0	A1	A2	A3	A4	A5	A6	A7
30 DAS		23.40	22.31	18.20		22.22	22.12	19.85	19.78	22.19	22.30	22.30	19.68
60 DAS		37.30	33.37	29.21		35.24	35.00	30.44	30.67	35.13	35.27	35.61	29.00
90 DAS		62.78	60.48	52.26		63.46	56.99	55.49	55.96	60.87	60.34	64.95	49.97
120 DAS		63.94	61.41	53.59		65.11	57.86	55.98	56.99	61.82	61.45	66.00	51.96

Treatments

Fig. 4 .1.8.2 (b) Treatment influence on root dry weight (gm) of rapeseed at periodic intervals in *rabi* 2022–23

4.2 Attributes of Yield:

4.2.1 No. of siliqua per plant: The quantity of siliqua per plant in Gobhi Sarson (*Brassica napus* L.) was shown in Table 4.2.1.1 and Figure 4.2.1.1(a) and 4.2.1.2(b) markedly affected by various sulphur sources and agrochemical applications across both farming seasons (2021-22 and 2022-23). The maximum quantity of siliqua per plant was noted in Gypsum-treated plots (S1), whilst the minimum was found in Elemental Sulphur (S3). Likewise, among the agrochemical treatments, the combination of Hydrogel and Salicylic Acid administered during both flowering and pod formation stages (A6) yielded the highest siliqua count, whereas the lowest values were seen under restricted irrigation (A7). The use of sulphur has a substantial impact on siliqua development. Gypsum (S1) exhibited the largest yield of siliqua per plant (353.71 in 2021-22 and 351.22 in 2022-23), markedly surpassing Bentonite Sulphur (S2) and Elemental Sulphur (S3). The utilization of Gypsum resulted in increases of 7.63% and 5.32% relative to Bentonite Sulphur, and 33.65% and 28.51% in comparison to Elemental Sulphur for the years 2021-22 and 2022-23, respectively. Bentonite Sulphur (S2) demonstrated notable enhancement compared to Elemental Sulphur, although it was still inferior to Gypsum owing to its slower oxidation and postponed sulphate release. The lowest siliqua count was noted in Elemental Sulphur (S3), which registered 264.59 in 2021-22 and 273.29 in 2022-23, signifying inadequate sulphur supply and diminished reproductive effectiveness under this treatment. A6 (Hydrogel + Salicylic Acid during flowering and pod formation) had the greatest siliqua count per plant (352.49 in 2021-22 and 355.64 in 2022-23), greatly surpassing all other treatments. This treatment produced a 2.09% and 0.86% enhancement compared to the well-irrigated control (A0) and a 32.72% and 30.51% enhancement relative to restricted irrigation (A7) in the years 2021-22 and 2022-23, respectively. Hydrogel alone (A1) and Salicylic Acid administered at various growth phases (A2 and A3) demonstrated a moderate enhancement compared to restricted irrigation (A7), underscoring the significance of moisture retention and stress alleviation. Nonetheless, their effects were markedly inferior to those of the combination treatments (A4, A5, and A6). The lowest number of siliquae per plant was observed in A7 (limited irrigation), with counts of 265.47 in 2021-22 and 272.45 in 2022-23, affirming water stress's adverse impact on reproductive structures.

The quantity of siliqua per plant in Gobhi Sarson (*Brassica napus* L.) during the *rabi* seasons of 2021–22 and 2022–23 was markedly affected by the interaction of various sulphur sources and agrochemical treatments shown in Table 4.2.1.2. Among all treatments, S1A6 exhibited the largest number of siliquae per plant, recording 394.90 in 2021–22 and 391.10 in 2022–23, closely followed by S1A0 with 391.98 and 388.06, respectively. Alternative treatments, including S2A6, indicated significantly increased siliqua counts, suggesting the advantageous effects of gypsum and bentonite sulphur, both with and without agrochemicals. Conversely, the minimum siliqua count was noted in treatment S3A7, which yielded 222.60 siliqua per plant in 2021–22 and 233.10 in 2022– 23, markedly lower than all other treatments. Treatments utilizing elemental sulphur (S3) consistently yielded less siliqua per plant than those employing gypsum (S1) and bentonite sulphur (S2). S1A6 was shown to be the most efficacious treatment for optimizing siliqua production, whereas S3A7 was the least efficacious.

The varying efficacy of the sulphur sources for siliqua generation can be ascribed to their sulphur availability, oxidation rate, and absorption efficiency. Gypsum (S1) yielded the greatest siliqua production owing to its accessible sulphate (SO_4^{2-}) form, which may be promptly assimilated by plants for protein synthesis, hormonal control, and improved glucose translocation to reproductive structures. Bentonite Sulphur (S2) exhibited limited efficacy, necessitating microbial oxidation to transform into the plant-available sulphate form. The gradual release characteristics of Bentonite Sulphur may have restricted sulphur availability during critical reproductive phases, thereby diminishing siliqua production in comparison to Gypsum. Elemental Sulphur (S3) had the lowest siliqua count due to the necessity for microbial oxidation to transform into plant-available sulphate, a process significantly influenced by soil temperature, microbial activity, and moisture content. The slow oxidation rate resulted in postponed sulphur availability, constraining its function in siliqua production. Sulphur shortage is recognized to diminish pollen viability, limit pod development, and decrease seed set. The diminished siliqua count in Elemental Sulphur (S3) corroborates this, as insufficient sulphur availability impairs carbohydrate distribution and hormonal communication, leading to a decrease in siliqua per plant. Water availability is a critical factor affecting reproductive success in Brassica crops, as it impacts nutrient delivery, photosynthesis, and hormonal equilibrium. Restricted irrigation (A7) markedly diminished siliqua counts due to water stress, which causes reduced cell expansion, impaired nutrient absorption, and hormonal abnormalities (namely ABA buildup), hence hindering reproductive development. Drought stress is recognized to diminish floral quantity, elevate flower abortion rates, and restrict siliqua development due to stomatal closure, decreased CO_2 absorption, and oxidative stress. Control with sufficient irrigation (A0) exhibited a markedly increased siliqua count, as consistent soil moisture guarantees optimal photosynthesis, maintenance of turgor pressure, and enhanced transfer of assimilates to growing siliques (Bellaloui et al., 2022; Beltrán et al., 2023; Khan et al., 2018; Mohammadi et al., 2025; Oyebamiji et al., 2023; Poethig, 2013; Shah et al., 2022; Zenda et al., 2021).

Hydrogel is a superabsorbent polymer that boosts soil moisture retention and increases the availability of water and nutrients to plants in water-deficient environments. The treatments utilizing Hydrogel (A1, A4, A5, and A6) consistently enhanced siliqua count relative to restricted irrigation (A7), hence affirming its efficacy in alleviating drought-induced stress. Hydrogel at 2.5 kg/ha (A1) enhanced siliqua development under limited irrigation by diminishing soil water evaporation and preserving soil moisture, hence assuring prolonged root-zone hydration. The utilization of Hydrogel and Salicylic Acid during flowering and development of pod (A6) yielded the highest siliqua count, illustrating the synergistic advantages of moisture retention and stress alleviation. Hydrogel increases sulphur availability by preserving soil moisture and enhancing sulphate solubility and absorption. Salicylic acid (SA) is a Phyto regulator that improves stress resilience, antioxidant defense, and reproductive efficacy in plants. In the current investigation, Salicylic Acid treatments (A2, A3, A4, A5, A6) markedly enhanced siliqua count relative to the untreated control (A0 and A7) as SA mitigates oxidative stress throughout reproductive phases, decreasing flower abortion and enhancing pod retention. SA improves photosynthetic efficiency and assimilate translocation, resulting in enhanced reproductive production. Application at flowering (A2) and pod development (A3) enhanced siliqua formation; however, A6 (SA at both phases with Hydrogel) yielded the most favorable outcomes, underscoring the synergistic effect of SA and moisture retention in augmenting siliqua formation under stress conditions (Bano et al., 2022; Chen et al., 2023; Moghadam et al., 2022; Ramzan et al., 2024).

The findings indicate that both sulphur feeding and agrochemical applications substantially affect siliqua yield in Gobhi Sarson. Gypsum (S1) yielded the highest siliqua count owing to its quick sulphur availability, whilst Hydrogel and Salicylic Acid proficiently alleviated moisture stress, enhancing reproductive success. The combination of Hydrogel and Salicylic Acid during flowering and pod development (A6) with Gypsum (S1) yielded the highest siliqua count, underscoring the significance of integrated nutrient and moisture management techniques in enhancing oilseed production in semi-arid environments. Recent research indicates that sulphur administration markedly improves the growth and productivity of oilseed crops, especially within the Brassica family. Nawaz et al., (2023) showed that the utilization of sulphur at 30 kg ha^{1}, particularly as ammonium sulphate, significantly enhanced plant height, branch count, siliquae quantity, seed production, and oil content in winter canola (*Brassica napus* L.). Similarly, Singh et al., (2023) utilised sulphur at 60 kg ha^{1} led to an increased number of siliquae per plant, enhanced seed output, and improved biological yield in mustard. These conclusions correspond with the actual data, suggesting that sulphur supplementation enhances siliqua production and overall crop performance. Prajapati et al. (2023) noted that elevating sulphur levels to 60 kg ha^{1} markedly improved plant height, branch quantity, leaf area index, siliquae count per plant, and dry matter accumulation in Indian mustard (*Brassica juncea* L.). These studies collectively affirm that sulphur fertilization is essential for maximizing the growth and yield of oilseed crops, validating the findings of the present experiment.

Table 4.2.1.1: The impact of treatments on no. of siliqua per plant of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	No. of siliqua per plant (2021-22)	No. of siliqua per plant (2022-23)
Sulphur sources		
S1: Gypsum	353.71[a]	351.22[a]
S2: Bentonite Sulphur	328.62[b]	333.51[b]
S3: Elemental Sulphur	264.59[c]	273.29[c]
CV (Sulphur Sources)	2.85	2.86
CD (Sulphur Sources)	12.73	12.74
Agrochemical		
A0: Control (Irrigation as per requirement)	349.21[b]	352.59[b]
A1: Hydrogel (2.5 kg/ha) as basal application	306.78[e]	309.42[e]
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	298.64[g]	301.52[g]
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	301.61[f]	305.67[f]
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	331.49[c]	335.61[c]
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	319.45[d]	321.82[d]
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	352.49[a]	355.64[a]
A7: Control (Restricted irrigation)	265.47[h]	272.45[h]
CD (Agrochemical)	12.79	12.85
CV (Sulphur Sources and agrochemical)	0.4	0.47

Table 4.2.1.2: The interaction impact of treatments on no. of siliqua per plant of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	No. of siliqua per plant (2021-22)	No. of siliqua per plant (2022-23)
S1A0	391.98±0.67	388.06±1.24
S1A1	343.69±0.88	340.27±0.88
S1A2	334.57±0.78	331.58±0.47
S1A3	337.9±0.06	336.15±0.06
S1A4	371.37±1.33	369.07±1.84
S1A5	357.88±0.83	353.91±0.83
S1A6	394.9±0.66	391.1±0.66
S1A7	297.41±0.16	299.62±0.16
S2A0	363.42±2.43	367.47±4.44
S2A1	319.41±0.04	323.26±0.04
S2A2	310.94±0.03	315.01±0.03
S2A3	314.03±0.04	319.34±0.04
S2A4	345.14±0.04	350.62±0.04
S2A5	332.6±2.96	336.22±3.68
S2A6	367±2.97	371.55±2.97
S2A7	276.4±3.41	284.64±3.41
S3A0	292.21±1.52	302.24±0.77
S3A1	257.24±0.03	264.73±0.03
S3A2	250.41±0.04	257.97±0.04
S3A3	252.9±0.04	261.52±0.04
S3A4	277.96±0.05	287.13±0.05
S3A5	267.86±0.03	275.34±0.03
S3A6	295.57±0.03	304.27±0.03
S3A7	222.6±0.03	233.1±0.03
CV	0.4	0.47
CD	2.43	2.92

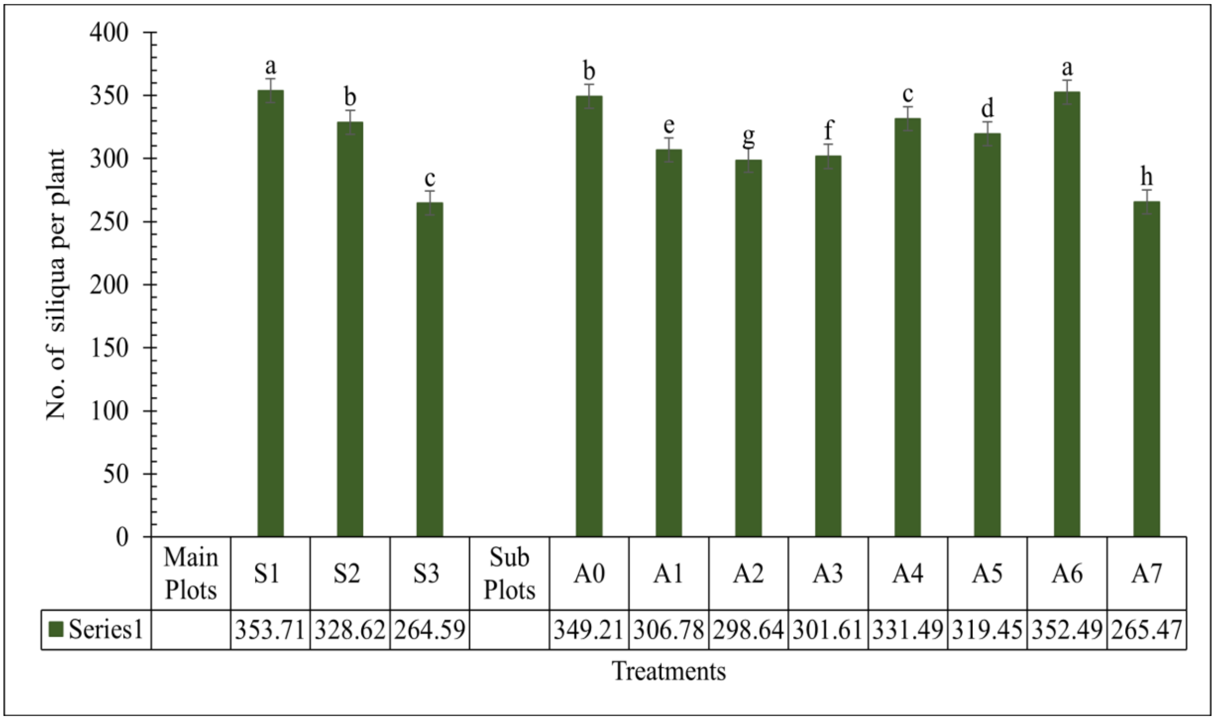


Fig:4.2.1.1. (a) The impact of various sulphur sources and agrochemical treatments on the number of siliqua per plant in the year 2021-2022

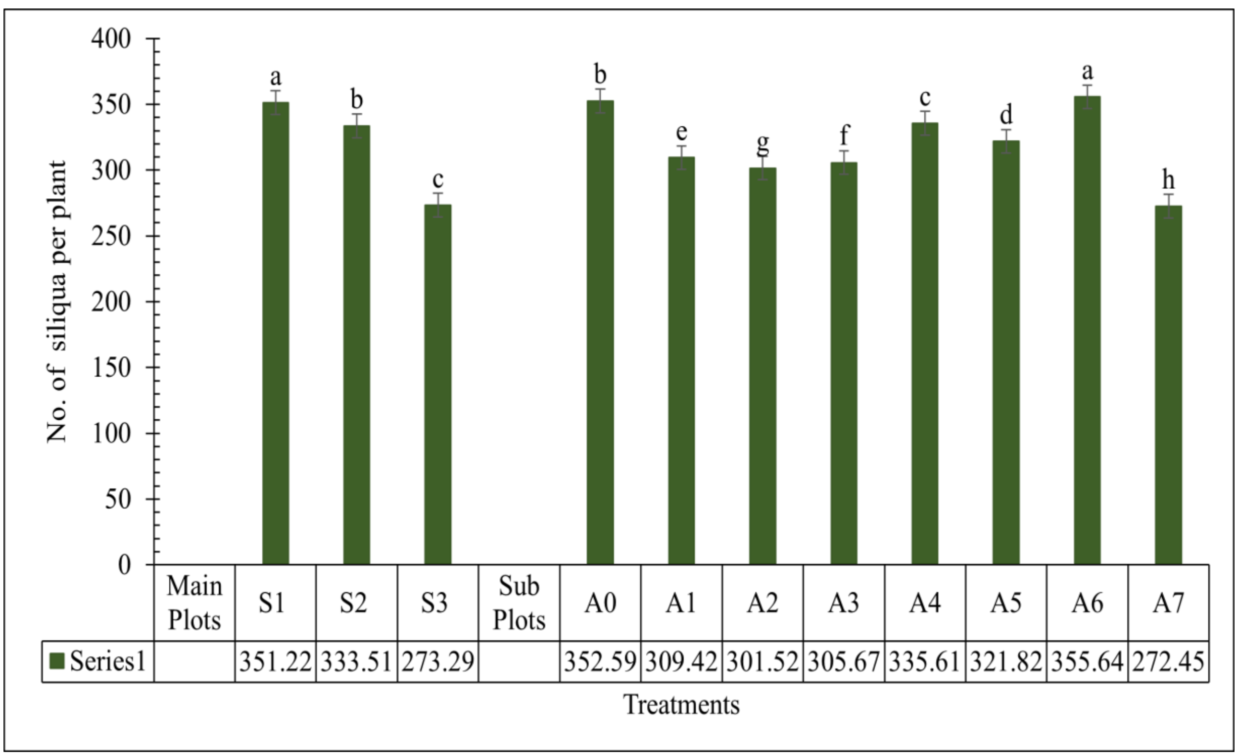


Fig. 4 .2.1.2 (b) The impact of various sulphur sources and agrochemical treatments on the number of siliqua per plant in the year 2022-2023

4.2.2 Number of seeds per siliqua: The quantity of seeds of each siliqua in *Brassica napus* L. variety GSC-7 was markedly affected by various sulphur sources and agrochemical applications throughout the 2021-22 and 2022-23 growth seasons, shown in Table 4.2.2.1 and Figure 4.2.2.1 (a) and 4.2.2.2 (b). Among the various sources of sulphur, Gypsum (S1) exhibited the greatest seed count per siliqua (13.3 in both years), greatly surpassing Bentonite Sulphur (S2) and Elemental Sulphur (S3). Bentonite Sulphur (S2) caused a 4.51% and 3.10% decline in seed count relative to Gypsum in the years 2021-22 and 2022- 23, respectively, whilst Elemental Sulphur (S3) exhibited a 15.04% and 14.29% decrease in the same years. The values for Gypsum and Bentonite Sulphur were markedly different, while Bentonite Sulphur and Elemental Sulphur were also statistically dissimilar, as demonstrated by the homogeneous subgroups. Likewise, agrochemical applications markedly influenced the seed count per siliqua. The maximum seed count was recorded in A6, yielding 13.6 and 13.7 seeds per siliqua in the years 2021-22 and 2022-23, respectively. This was markedly superior to all other treatments. In comparison to A0, A6 exhibited increases of 3.03% and 3.01% in the respective years, demonstrating the beneficial impact of the combined application of Hydrogel and Salicylic Acid. Among the different treatments, A4 yielded a seed count comparable to A0, with values of 12.8 and 12.9 seeds per siliqua in the corresponding years. Likewise, A5 demonstrated a similar pattern, yielding values of 12.7 in both years. The minimum seed count was recorded in A7 (Restricted Irrigation), with 11.0 and 11.2 seeds per siliqua, indicating a substantial decrease of 16.67% and 15.79% relative to A6.

The quantity of seeds per siliqua in Gobhi Sarson (*Brassica napus* L.) was markedly affected by the application of various sulphur sources and agrochemical treatments during the *rabi* seasons of 2021–22 and 2022–23 shown in Table 4.2.2.2. Among the treatments, S1A6 had the greatest seed count per siliqua, averaging 14.6 in both years, closely followed by S1A0 (Gypsum alone), which recorded 14.1 and 13.9 seeds per siliqua, respectively. Additional effective treatments comprised S2A6, yielding 13.9 and 14.1 seeds per siliqua, and S2A0, producing 13.6 and 13.8 seeds of each siliqua. The minimum seed count per siliqua was recorded in S3A7, with just 10.0 in 2021–22 and 10.2 in 2022–23. Treatments utilizing elemental sulphur exhibited suboptimal performance regarding seed set per siliqua, but gypsum-based treatments, particularly when integrated with hydrogel and salicylic acid, markedly improved seed development. In general, S1A6 had the most efficacy in maximizing seed quantity per siliqua, whereas S3A7 exhibited the lowest efficacy.

The quantity of seeds per siliqua in Gobhi Sarson (*Brassica napus* L.) was markedly affected by water availability, sulphur nutrition, and agrochemical applications. The results can be scientifically elucidated by comprehending the physiological, biochemical, and molecular mechanisms that regulate seed growth under diverse moisture and nutritional conditions. Water availability is crucial to reproductive development and seed production. Water stress, especially during the flowering and seed-setting phases, results in considerable decreases in seed quantity due to physiological and metabolic disturbances (Sehgal et al., 2018). Water stress triggers stomatal closure, leading to diminished CO_2 assimilation and photosynthetic performance. This results in a reduction of carbohydrate synthesis, which is crucial for ovule fertilization and embryo growth. As a result, a diminished quantity of assimilates is accessible for seed filling, leading to a reduction in the number of seeds of each siliqua (Fahad et al., 2017). Water scarcity elevates abscisic acid (ABA) levels, a stress hormone that suppresses cell division in reproductive tissues and causes premature abortion of flowers and pods. This hormonal imbalance diminishes pollination efficacy and decreases the ultimate seed yield per siliqua (Oyedoh et al., 2025). Water stress negatively impacts root function and nutrient transport, especially for mobile elements like sulphur, nitrogen, and potassium. Impaired nutrition absorption restricts amino acid synthesis, protein production, and enzyme function essential for optimal reproductive growth, hence jeopardizing seed development. The restricted irrigation treatment (A7) yielded the fewest seeds per siliqua, corroborating the negative impact of moisture stress on reproductive performance. (Ahanger et al., 2016).

Sulphur plays a vital role in plant metabolism, particularly in protein synthesis, activation of enzyme, and biosynthesis of oil in oilseed crops. The varying responses among sulphur sources can be ascribed to differences in sulphur availability and uptake efficiency. Gypsum ($CaSO_4 \cdot 2H_2O$) delivers readily accessible sulphate ions (SO_4^{2-}), guaranteeing a consistent supply of sulphur for protein and enzyme synthesis during vital reproductive phases. The maximum seed count recorded under S1 (Gypsum) treatments corroborates the benefit of accessible sulphur in improving seed set and pod development. Bentonite Sulphur requires microbial oxidation to convert into plant-available sulphate, leading to a slower release rate. The delayed availability of sulphur may have resulted in a slight decrease in seed quantity relative to Gypsum-treated plants. Elemental Sulphur undergoes a biological oxidation process, which is highly dependent on microbial activity, soil moisture, and temperature. The slow rate of oxidation may have resulted in poor sulphur availability during flowering and pod development, contributing to the lowest seed count among the sulphur sources (Sharma et al., 2024).

Agrochemical applications, having hydrogel and salicylic acid, were beneficial in alleviating water stress and improving seed yield. Hydrogel, a superabsorbent polymer, enhances the water retention capacity of soil and guarantees sustained water availability to plants, especially during periods of moisture stress. The Hydrogel-treated plants (A1, A4, A5, A6) showed improved seed count due to better water retention, which prevented drought-induced stress during flowering and seed formation. Salicylic acid (A2, A3) serves as a plant growth regulator that plays a role in stress tolerance. It increases the activity of antioxidant enzymes (e.g., catalase, peroxidase, and superoxide dismutase), mitigating oxidative damage induced by drought stress. Furthermore, Salicylic Acid regulates ethylene production, inhibiting premature senescence of flowers and pods while enhancing seed set. The combination of Hydrogel and Salicylic Acid applied at both flowering and pod formation (A6) resulted in the highest number of seeds per siliqua, indicating a synergistic effect on water retention, nutrient availability, and hormonal regulation. This combination-maintained cell turgidity, enhanced reproductive success, and improved seed filling (Vedovello et al., 2024; Zhu et al., 2024).

The study demonstrates that seed production in Gobhi Sarson is significantly influenced by water availability, sulphur nutrition, and agrochemical treatments. Water stress negatively affects seed count by reducing photosynthetic efficiency, disrupting hormonal balance, and limiting nutrient uptake. The application of Gypsum (S1) provided the highest seed count due to its readily available sulphur, while Elemental Sulphur (S3) resulted in the lowest due to its slow oxidation rate. The combined application of Hydrogel and Salicylic Acid (A6) provided the maximum benefit, suggesting that moisture conservation and stress mitigation strategies can significantly enhance reproductive success in oilseed crops. A 2018 study in BMC Plant Biology investigated the transgenerational impacts of drought stress on winter oilseed rape (*Brassica napus*). The researchers discovered that drought stress during seed development negatively impacted seed quality and output. Maternal drought stress specifically resulted in diminished seed quality, attributable to compromised nutrient allocation and hormonal abnormalities during seed development (Hatzig et al., 2018). Sulphur is essential for the synthesis of proteins and amino acids, which are necessary for plant growth and development. A research article in the Agricultural Reviews journal indicated that sulphur administration markedly enhances seed output in sunflower, an oilseed crops akin to *Brassica napus*. The review aggregated findings from multiple studies, demonstrating that sulphur fertilizer augments photosynthesis and carbohydrate metabolism, resulting in increased seed output (Ningthi et al., 2024). These studies corroborate the reported data, indicating that water stress adversely affects seed production by compromising seed quality and yield, whereas sulphur administration augments seed yield by enhancing critical physiological processes.

Table 4.2.2.1: The impact of treatments on no. of seeds per siliqua of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	No. of seeds per siliqua (2021-22)	No. of seeds per siliqua (2022-23)
Sulphur sources		
S1: Gypsum	13.3[a]	13.3[a]
S2: Bentonite Sulphur	12.7[b]	12.9[b]
S3: Elemental Sulphur	11.3[c]	11.4[c]
CV (Sulphur Sources)	0.75	0.58
CD (Sulphur Sources)	0.07	0.06
Agrochemical		
A0: Control (Irrigation as per requirement)	13.2[b]	13.3[b]
A1: Hydrogel (2.5 kg/ha) as basal application	12.2[e]	12.5[e]
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	11.9[g]	12.0[g]
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	12.0[f]	12.2[f]
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	12.8[c]	12.9[c]
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	12.7[d]	12.7[d]
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	13.6[a]	13.7[a]
A7: Control (Restricted irrigation)	11.0[h]	11.2[h]
CD (Agrochemical)	0.06	0.06
CV (Sulphur Sources and agrochemical)	0.55	0.54

Table 4.2.2.2: The interaction impact of treatments on no. of seeds per siliqua of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	No. of seeds per siliqua (2021-22)	No. of seeds per siliqua (2022-23)
S1A0	14.1±0.05	13.9±0.02
S1A1	13.1±0.02	13.3±0.02
S1A2	12.7±0.04	12.8±0.04
S1A3	12.9±0.06	12.9±0.06
S1A4	13.7±0.05	13.7±0.29
S1A5	13.5±0.30	13.5±0.03
S1A6	14.6±0.09	14.6±0.09
S1A7	11.8±0.09	11.9±0.09
S2A0	13.6±0.01	13.8±0.03
S2A1	12.5±0.04	12.8±0.04
S2A2	12.1±0.03	12.3±0.03
S2A3	12.3±0.04	12.5±0.04
S2A4	13.0±0.04	13.2±0.04
S2A5	12.9±0.03	13.0±0.03
S2A6	13.9±0.02	14.1±0.02
S2A7	11.2±0.05	11.5±0.05
S3A0	11.8±0.05	12.1±0.05
S3A1	11.1±0.03	11.4±0.03
S3A2	10.8±0.04	10.9±0.04
S3A3	11.0±0.04	11.1±0.04
S3A4	11.6±0.05	11.7±0.05
S3A5	11.5±0.03	11.6±0.03
S3A6	12.4±0.03	12.5±0.03
S3A7	10.0±0.03	10.2±0.03
CV	0.55	0.54
CD	0.13	0.12

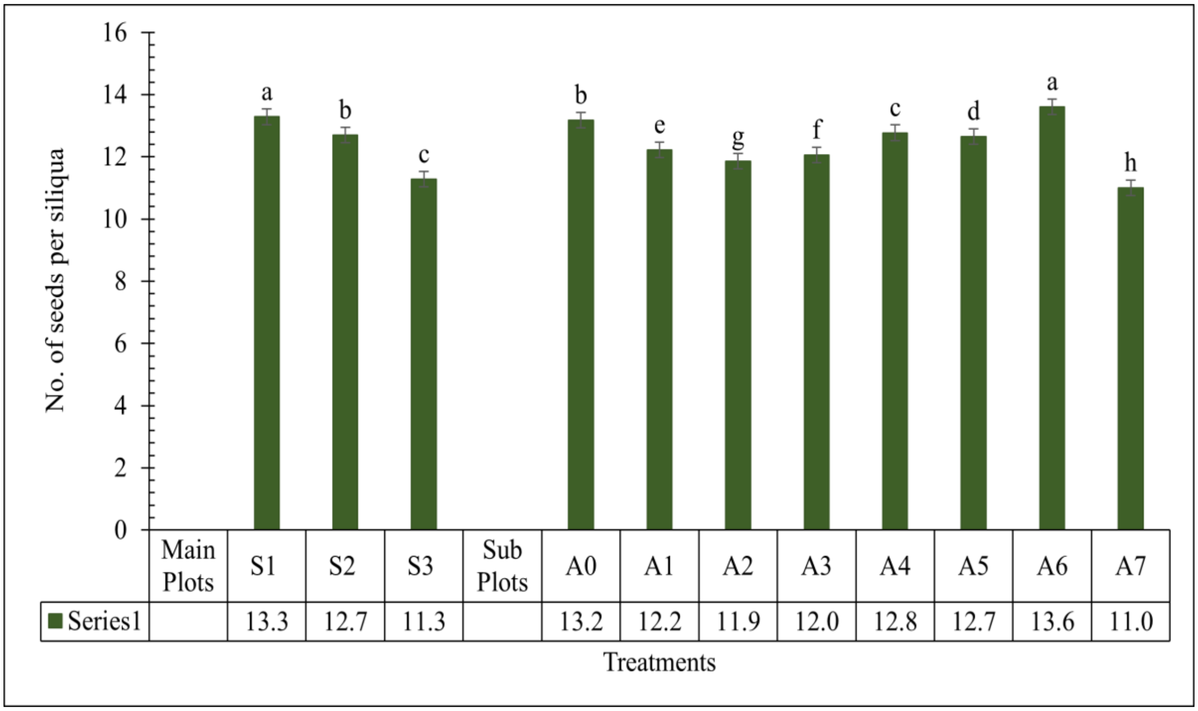


Fig. 4 .2.2.1 (a) The impact of sulphur sources and agrochemical treatments on the no. of seeds per siliqua in the year 2021-2022

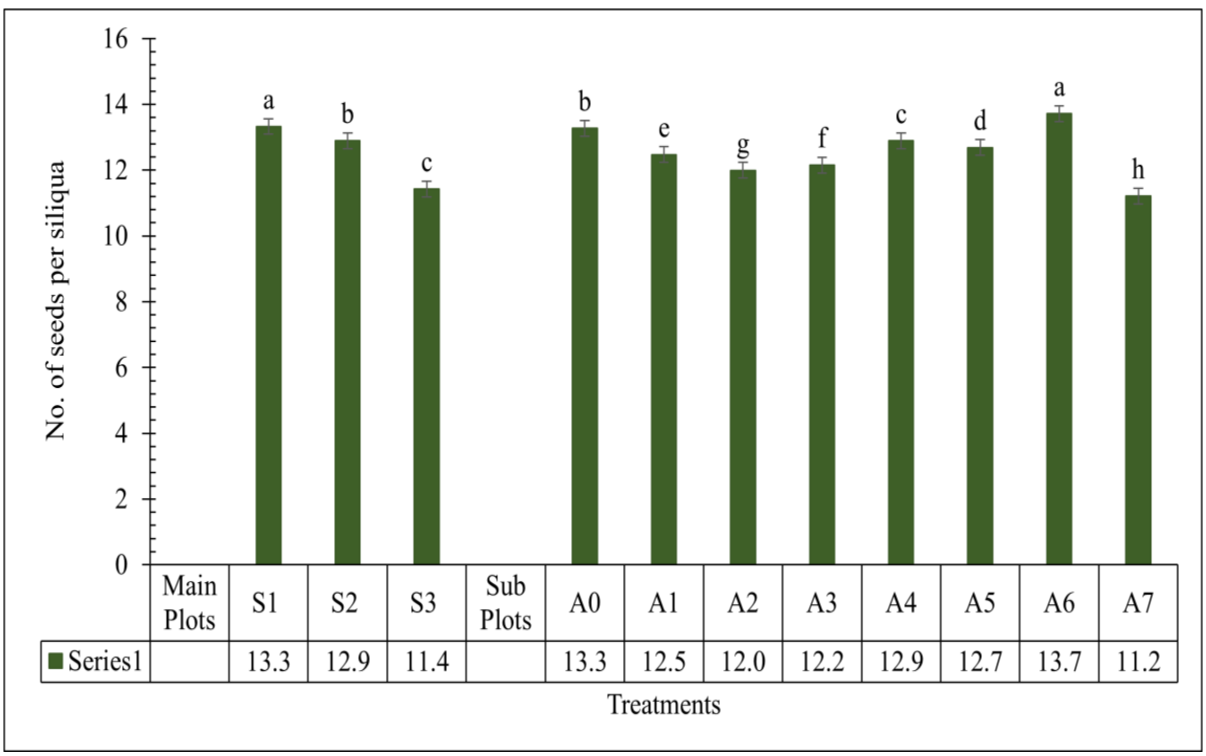


Fig. 4 .2.2.2 (b) The impact of sulphur sources and agrochemical treatments on no. of seeds per siliqua in the year 2022-2023

4.2.3 Length of Siliqua: Table 4.2.3.1 and Figure 4.2.3.1(a) & 4.2.3.2(b) illustrate the impact of various sulphur sources and agrochemical treatments on the siliqua length of Gobhi Sarson (*Brassica napus* L.) variety GSC-7 during the 2021-22 and 2022-23 growth seasons. A thorough analysis was performed to ascertain notable differences between treatments, compute percentage changes, and define homogeneous subsets utilizing crucial differences (CD) at a 5% significance standard. Gypsum (S1) consistently exhibited the longest siliqua length among sulphur sources in both growing seasons, measuring 5.37 cm in 2021-22 and 5.46 cm in 2022-23. This was markedly better than the lengths recorded for bentonite sulphur (S2) and elemental sulphur (S3), which measured 5.15 cm and 5.22 cm for S2, and 4.34 cm and 4.38 cm for S3 in the corresponding years. Gypsum (S1) demonstrated superiority over elemental sulphur (S3) with increases of 23.7% in 2021-22 and 24.6% in 2022-23. Bentonite sulphur (S2) demonstrated enhancements of 18.7% in 2021-22 and 19.1% in 2022-23 relative to elemental sulphur (S3). In case of agrochemicals, the findings indicated that the combination of Hydrogel at 2.5 kg/ha and Salicylic acid at 150 ppm during 50% flowering and pod formation (A6) yielded the greatest siliqua length among agrochemical treatments, measuring 5.39 cm and 5.44 cm in 2021-22 and 2022-23, respectively. This medication was markedly more effective than all other agrochemical treatments. In comparison to the control group under restricted irrigation (A7), which exhibited the smallest siliqua length (4.29 cm in 2021-22 and 4.35 cm in 2022-23), A6 demonstrated an increase of 25.7% in 2021-22 and 25.1% in 2022-23. The second most effective treatment was the control under optimal irrigation conditions (A0), yielding siliqua lengths of 5.21 cm and 5.26 cm in the years 2021-22 and 2022-23, respectively. This was succeeded by Hydrogel + Salicylic acid at 50% flowering (A4), which demonstrated lengths of 5.11 cm and 5.21 cm in the corresponding years, and Hydrogel + Salicylic acid at 50% pod formation (A5), with lengths of 5.05 cm and 5.11 cm. Individual administrations of Salicylic acid (A2 and A3) produced reduced siliqua lengths, measuring between 4.76 cm and 4.92 cm across the two seasons. During *rabi* seasons of 2021–22 as well as 2022–23, the interaction effect of different sources of sulphur and agrochemicals treatments on the length of siliqua in Gobhi Sarson (*Brassica napus* L.) exhibited substantial variability as shown in Table 4.2.3.2. The S1A6 treatment exhibited the greatest siliqua length, measuring 5.85 cm in 2021–22 and 5.91 cm in 2022–23, substantially surpassing the majority of other treatments. The minimum siliqua length was recorded at S3A7, measuring 3.76 cm in 2021–22 and 3.80 cm in 2022–23. Treatments S1A0, S1A4, S1A5, and S2A6 demonstrated markedly greater siliqua lengths than S3A7 in both years. Nonetheless, treatments such as S1A1, S1A2, S1A3, S2A0, S2A1, S2A2, S2A3, S2A4, S2A5, S3A0, S3A1, S3A2, S3A3, S3A4, S3A5, and S3A6, even being significantly superior to S3A7, exhibited no significant difference from it, suggesting a non-significant effect. The findings show the advantageous effect of integrating Gypsum with Hydrogel and Salicylic acid (S1A6) in promoting siliqua length, whereas the lack of these agrochemicals (S3A7) resulted in unsatisfactory performance.

The length of siliqua in Gobhi Sarson (*Brassica napus* L.) is significantly affected by the availability of sulphur and water, which are essential for physiological, biochemical, and structural processes throughout the reproductive stage of plant growth. Sulphur is a vital macronutrient which has a direct role in the production of proteins, enzymes, and sulphur-containing amino acids such as methionine and cysteine, which are crucial for cell division, elongation, and the development of reproductive organs. Accessible sulphur sources, like as gypsum, deliver sulphur in the plant-available sulphate form, guaranteeing a consistent supply during essential growth phases, including flowering and siliqua development. This results in excellent cell wall development, structural integrity, and prolonged elongation of the siliqua. Conversely, slowly oxidizing sulphur sources, such as bentonite sulphur and elemental sulphur, release sulphate more gradually via microbial oxidation, which may result in delayed sulphur availability during the reproductive phase and restrict cell proliferation in siliqua tissues. In addition to sulphur, water availability considerably influences siliqua length, as it sustains turgor pressure, aids in the delivery of nutrients (including sulphur) to developing siliqua, and underpins photosynthesis, which supplies the energy and carbohydrates essential for growth (Abdallah et al., 2010; Kumar et al., 2021; Rameeh et al., 2021; Shah et al., 2022; Sharma & Chopra, 2020).

Enough water supply facilitates cell expansion and elongation, ensuring the appropriate development of the siliqua. Nonetheless, under conditions of water stress, the development of siliqua is adversely affected by a series of physiological disturbances. Decreased water availability diminishes turgor pressure, impeding cell division and elongation, and restricts the transport of nutrients such as sulphur, hence intensifying shortages in protein and chlorophyll synthesis. Water stress induces stomatal closure to limit water loss, resulting in diminished carbon dioxide assimilation and compromised photosynthesis, which decreases carbohydrate availability and energy for reproductive growth. Furthermore, water stress triggers oxidative stress through the accumulation of reactive oxygen species (ROS), resulting in cellular damage and further impairing metabolic pathways essential for siliqua formation. The interplay of insufficient sulphur and water exacerbates these constraints, as the nutrient-water synergy is impaired; adequate water facilitates nutrient mobility, whereas sulphur fosters biochemical processes such as photosynthesis and enzyme activation. The absence of either resource results in inadequate siliqua development. The interaction between sulphur availability and water supply is essential for establishing siliqua length, with accessible sulphur supplies and effective irrigation management being vital for alleviating stress and enhancing reproductive success in oilseed crops such as Gobhi Sarson (Muhammad et al., 2024; Nour et al., 2024; Okan et al., 2024; Shah et al., 2022).

Table 4.2.3.1: The impact of treatments on length of siliqua of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	Length of siliqua (2021-22)	Length of siliqua (2022-23)
Sulphur sources		
S1: Gypsum	5.37[a]	5.46[a]
S2: Bentonite Sulphur	5.15[b]	5.22[b]
S3: Elemental Sulphur	4.34[c]	4.38[c]
CV (Sulphur Sources)	1.05	0.88
CD (Sulphur Sources)	0.04	0.03
Agrochemical		
A0: Control (Irrigation as per requirement)	5.21[b]	5.26[b]
A1: Hydrogel (2.5 kg/ha) as basal application	4.96[e]	5.01[e]
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	4.76[g]	4.88[g]
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	4.82[f]	4.92[f]
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	5.11[c]	5.21[c]
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	5.05[d]	5.11[d]
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	5.39[a]	5.44[a]
A7: Control (Restricted irrigation)	4.29[h]	4.35[h]
CD (Agrochemical)	0.04	0.04
CV (Sulphur Sources and agrochemical)	0.81	0.72

Table 4.2.3.2: The interaction impact of treatments on length of siliqua of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	Length of siliqua (2021-22)	Length of siliqua (2022-23)
S1A0	5.63±0.01	5.78±0.03
S1A1	5.38±0.02	5.44±0.02
S1A2	5.16±0.04	5.30±0.04
S1A3	5.23±0.06	5.34±0.06
S1A4	5.54±0.05	5.66±0.03
S1A5	5.48±0.10	5.55±0.03
S1A6	5.85±0.09	5.91±0.09
S1A7	4.65±0.09	4.72±0.09
S2A0	5.48±0.01	5.46±0.02
S2A1	5.15±0.04	5.21±0.04
S2A2	4.94±0.03	5.08±0.03
S2A3	5.00±0.04	5.12±0.04
S2A4	5.30±0.04	5.42±0.04
S2A5	5.24±0.03	5.31±0.03
S2A6	5.59±0.02	5.66±0.02
S2A7	4.45±0.05	4.52±0.05
S3A0	4.52±0.01	4.56±0.03
S3A1	4.35±0.03	4.38±0.03
S3A2	4.18±0.04	4.26±0.04
S3A3	4.23±0.04	4.30±0.04
S3A4	4.48±0.05	4.55±0.05
S3A5	4.43±0.03	4.46±0.03
S3A6	4.73±0.03	4.75±0.03
S3A7	3.76±0.03	3.80±0.03
CV	0.81	0.72
CD	0.07	0.07

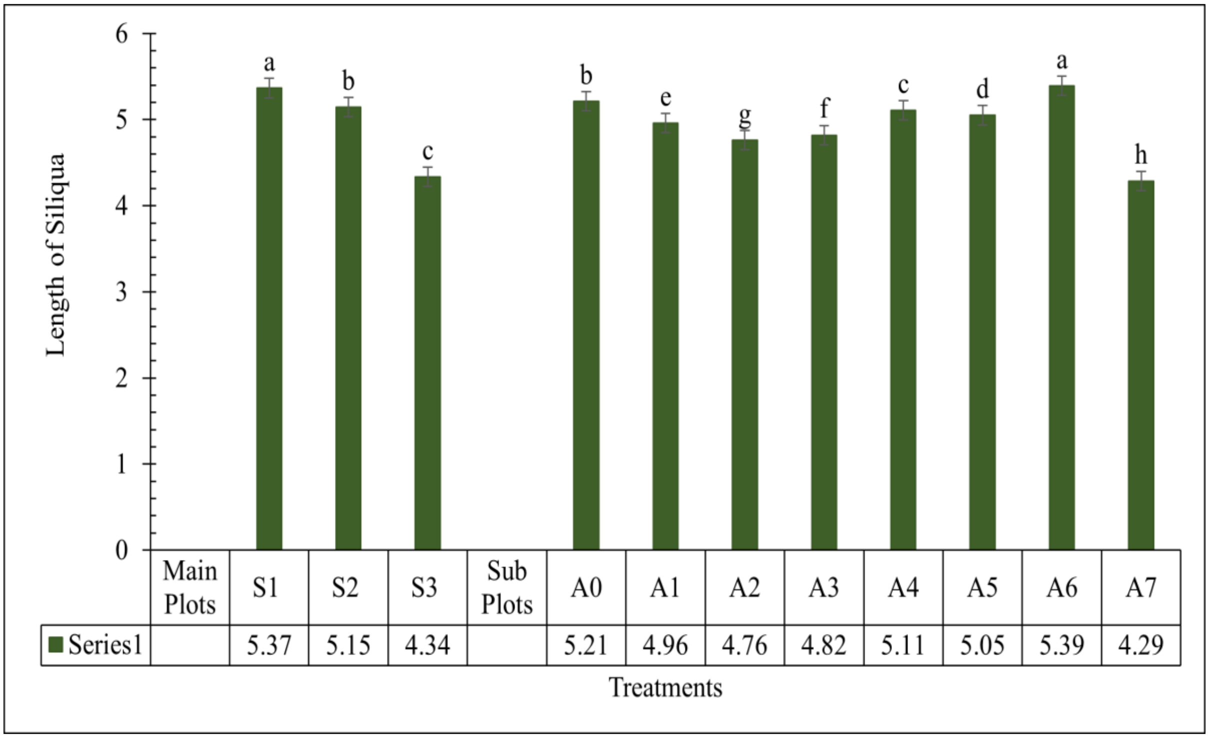


Fig. 4 .2.3.1 (a) The impact of sulphur sources and agrochemical treatments on the length of siliqua in the year 2021-2022

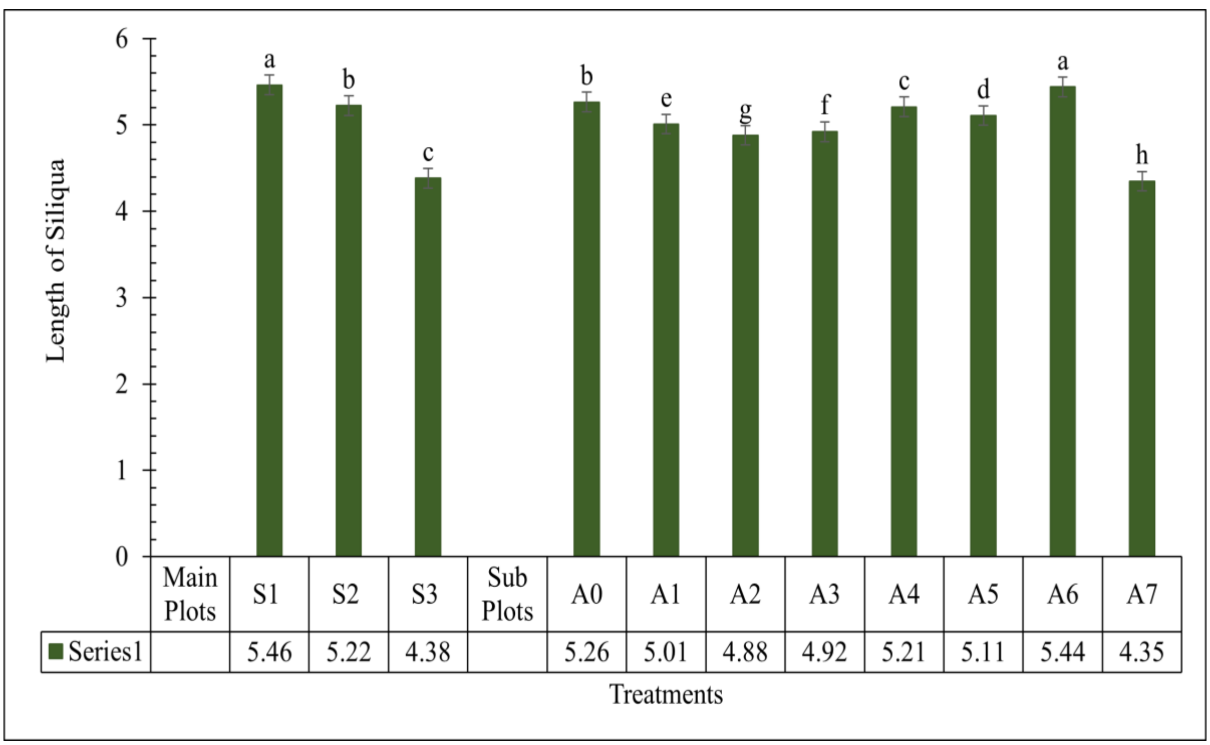


Fig. 4 .2.3.2 (b) The impact of sulphur sources and agrochemical treatments on the length of siliqua in the year 2022-2023

4.2.4 1000-Seed Weight (g): The 1000-seed weight of *Brassica napus* L. var. GSC-7 was significantly affected by sulphur sources and agrochemical treatments in both years of the study, as shown in Table 4.2.4.1 and Figure 4.2.4.1(a) and 4.2.4.2(b). Gypsum (S1) exhibited the greatest 1000-seed weight among the sulphur sources, measuring 4.33 g in 2021-22 and 4.38 g in 2022-23, greatly exceeding bentonite sulphur (S2) and elemental sulphur (S3). In contrast to S2 and S3, gypsum reported rises of 3.84% and 14.87%, respectively, in 2021-22, and 3.79% and 14.06%, respectively, in 2022-23. Elemental sulphur consistently yielded the lowest 1000-seed weight. Agrochemical treatments strongly influenced results, with the maximum 1000-seed weight recorded, resulting in 4.36 g in 2021-22 and 4.41 g in 2022-23. This indicated an increase of 16.88% and 12.23%, respectively, compared to the control (A0, irrigation as required). Among the treatments utilizing salicylic acid only, A3 (150 ppm at 50% pod formation) exhibited a superior 1000-seed weight relative to A2 (150 ppm at 50% flowering), with enhancements of 2.02% and 1.99% in the years 2021-22 and 2022-23, respectively. The combined application of hydrogel and salicylic acid (A4, A5, and A6) consistently surpassed individual treatments, with A4 (Hydrogel at 2.5 kg/ha + Salicylic acid at 150 ppm during 50% flowering) achieving a 1000-seed weight of 4.22 g in 2021-22 and 4.26 g in 2022-23, reflecting increases of 13.14% and 11.59%, respectively, relative to A0. Restricted irrigation (A7) significantly diminished the 1000-seed weight, resulting in 3.85 g in 2021-22 and 3.93 g in 2022-23, which were 14.68% and 10.89% below, respectively, the recommended treatment (A6). The interaction effect (in Table 4.2.4.2) of various sulphur sources and agrochemical treatments on the 1000-seed weight of Gobhi Sarson (*Brassica napus* L.) during the *rabi* seasons of 2021–22 and 2022–23 showed significant differences among treatments. The highest 1000-seed weight was recorded in treatment S1A6 (Gypsum + Hydrogel at 2.5 kg/ha + Salicylic acid at 1.0 mm), measuring 4.60 g in 2021–22 and 4.63 g in 2022–23, substantially surpassing numerous other treatments. The minimum 1000-seed weight was observed in S3A0, measuring 3.52 g in 2021–22 and 3.68 g in 2022–23. Treatments S1A4, S1A5, and S2A6 had much higher seed weights than S3A0 in both years, demonstrating the beneficial effects of gypsum and agrochemical application. Nonetheless, treatments such as S1A0, S1A1, S1A2, S1A3, S1A7, S2A0, S2A1, S2A2, S2A3, S2A4, S2A5, S2A7, S3A1, S3A2, S3A3, S3A4, S3A5, S3A6, and S3A7 shown no significant differences from S3A0, indicating non-significant alterations. The results indicate that S1A6 was the most efficacious treatment for increasing 1000-seed weight, whereas the least effective performance occurred without agrochemicals and with elemental sulphur alone (S3A0). Sulphur is an essential nutrient in oilseed crops, crucial for protein synthesis, chlorophyll production, and enzyme functions. Gypsum supplied accessible sulphate ions, which improved nutrient absorption and photosynthesis, resulting in increased seed weight. Bentonite sulphur necessitated an extended duration for oxidation, while elemental sulphur, characterized by its slow-release properties, postponed sulphur availability, hence constraining its influence on seed weight during vital growth phases. The hydrogel enhanced the soil's water retention capacity, providing a consistent water supply throughout the growth period. This probably boosted nutrient delivery and cellular functions, especially under restricted irrigation conditions, leading to increased seed weight. Salicylic acid functions as a signaling molecule that alleviates stress by improving antioxidant defense mechanisms and modulating stomatal conductance. Its treatment during the flowering and pod formation stages, crucial for seed development, likely enhanced metabolic efficiency and stress tolerance, leading to increased seed weight. The enhancement of seed weight resulting from scientific treatments in research is ascribed to several physiological, biochemical, and molecular mechanisms that increase plant growth, nutrient absorption, stress resilience, and metabolic processes. Water availability, enhanced by the use of superabsorbent polymers (hydrogel), is a significant factor affecting seed weight. Hydrogels enhance soil moisture retention by absorbing and gradually releasing water to the plant root zone, so guaranteeing a consistent water supply during crucial growth phases, especially during seed filling. This mitigates moisture stress, diminishes transpiration losses, and improves nutrient solubilization, thereby fostering superior seed development and increased seed weight. Furthermore, the application of hydrogel markedly influences root architecture by enhancing root length, surface area, and root hair proliferation, resulting in higher efficiency of water and nutrient absorption (Abdallah, 2019; Abdelghafar et al., 2024; Beiranvandi et al., 2025; Paravar et al., 2023). The management of nutrients, especially the administration of sulphur (S) from various sources, is essential for improving seed weight. Sulphur is a vital macronutrient that aids in the synthesis of amino acids (methionine and cysteine), which serve as precursors for protein biosynthesis. It is a crucial element of glutathione, a significant antioxidant that safeguards cellular structures from oxidative damage during stressful situations. Additionally, sulphur is essential for the synthesis of coenzymes and secondary metabolites, including glucosinolates, which enhance plant defense mechanisms. The presence of sulphur affects nitrogen metabolism by enhancing nitrogen assimilation and protein synthesis, ultimately resulting in higher seed weight due to enhanced seed filling. Furthermore, sulphur promotes oil biosynthesis in oilseed crops by modulating lipid metabolism, which directly influences dry matter accumulation in seeds. The function of plant growth regulators (PGRs), especially salicylic acid (SA), in enhancing seed weight is an essential mechanism. Salicylic acid acts as a signaling molecule that modulates physiological and biochemical processes, including as photosynthesis, transpiration, and enzyme activity. It is essential in alleviating oxidative stress by augmenting the function of antioxidant enzymes, including superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), which neutralize reactive oxygen species (ROS) and avert cellular damage. This protection is crucial for preserving membrane integrity, ensuring chlorophyll stability, and promoting overall plant health throughout seed development. Furthermore, salicylic acid affects the translocation of assimilates from source tissues (leaves) to sink tissues (seeds) by regulating the function of sugar transporters and sucrose-metabolizing enzymes. The augmented translocation of photo assimilates (sucrose, starch, and proteins) to the growing seeds improves seed weight and quality. At the molecular level, these treatments jointly modulate gene expression associated with seed formation. The hydrogel-induced water retention stimulates aquaporin genes that facilitate water transport across membranes, hence assuring proper cell growth and turgidity in seed tissues. Sulphur metabolism activates genes associated with nitrogen assimilation pathways, including nitrate reductase (NR) and glutamine synthetase (GS), which promote protein buildup in seeds. Salicylic acid signaling induces the expression of genes associated with stress tolerance (NPR1, PR1, and WRKY transcription factors), hence augmenting the plant's capacity to endure environmental variations and sustain a consistent metabolic rate during seed maturation (Alam et al., 2023; Burmistrova et al., 2009; Elsisi et al., 2024; Li et al., 2022; McIntyre et al., 2021; ul Haq et al., 2022).

The combination of hydrogel, sulphur nutrition, and salicylic acid application produces a synergistic effect that enhances plant water balance, nutrient absorption, stress resilience, and assimilate translocation, all essential for increasing seed weight in Gobhi Sarson (*Brassica napus* L.) and other oilseed crops. When scientifically tested and implemented in field situations, these processes promote sustainable agriculture practices and improve crop output. The combined application of gypsum, hydrogel, and salicylic acid was the most efficient method for enhancing 1000-seed weight, underscoring the need to optimize nutrient and water management strategies in *Brassica napus* production.

Table 4.2.4.1: The impact of treatments on 1000-Seed weight of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	1000-Seed weight (2021-22)	1000-Seed weight (2022-23)
Sulphur sources		
S1: Gypsum	4.33^{a}	4.38^{a}
S2: Bentonite Sulphur	4.17^{b}	4.22^{b}
S3: Elemental Sulphur	3.77^{c}	3.84^{c}
CV (Sulphur Sources)	3.55	5.25
CD (Sulphur Sources)	0.12	0.17
Agrochemical		
A0: Control (Irrigation as per requirement)	3.73^{f}	4.09^{cde}
A1: Hydrogel (2.5 kg/ha) as basal application	4.11^{bc}	4.16^{bcd}
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	3.97^{de}	4.02^{de}
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	4.05^{cd}	4.10^{bcd}
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	4.22^{b}	4.26^{ab}
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	4.18^{bc}	4.21^{bc}
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	4.36^{a}	4.41^{a}
A7: Control (Restricted irrigation)	3.85^{ef}	3.93^{e}
CD (Agrochemical)	0.13	0.17
CV (Sulphur Sources and agrochemical)	3.44	4.19

Table 4.2.4.2: The interaction impact of treatments on 1000-Seed weight of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	1000-Seed weight (2021-22)	1000-Seed weight (2022-23)
S1A0	4.33±0.17	4.46±0.16
S1A1	4.34±0.02	4.37±0.02
S1A2	4.19±0.18	4.22±0.73
S1A3	4.27±0.09	4.30±0.28
S1A4	4.46±0.05	4.47±0.05
S1A5	4.41±0.30	4.42±0.30
S1A6	4.60±0.09	4.63±0.09
S1A7	4.06±0.09	4.13±0.09
S2A0	3.36±0.18	4.14±0.12
S2A1	4.18±0.04	4.24±0.04
S2A2	4.04±0.03	4.10±0.03
S2A3	4.12±0.04	4.18±0.04
S2A4	4.29±0.04	4.34±0.04
S2A5	4.25±0.03	4.29±0.03
S2A6	4.43±0.51	4.49±0.02
S2A7	3.92±0.05	4.01±0.05
S3A0	3.52±0.14	3.68±0.12
S3A1	3.81±0.03	3.87±0.03
S3A2	3.68±0.04	3.74±0.04
S3A3	3.76±0.04	3.81±0.04
S3A4	3.91±0.05	3.96±0.05
S3A5	3.88±0.03	3.92±0.03
S3A6	4.04±0.03	4.10±0.03
S3A7	3.57±0.03	3.66±0.03
CV	3.44	4.19
CD	0.24	0.32

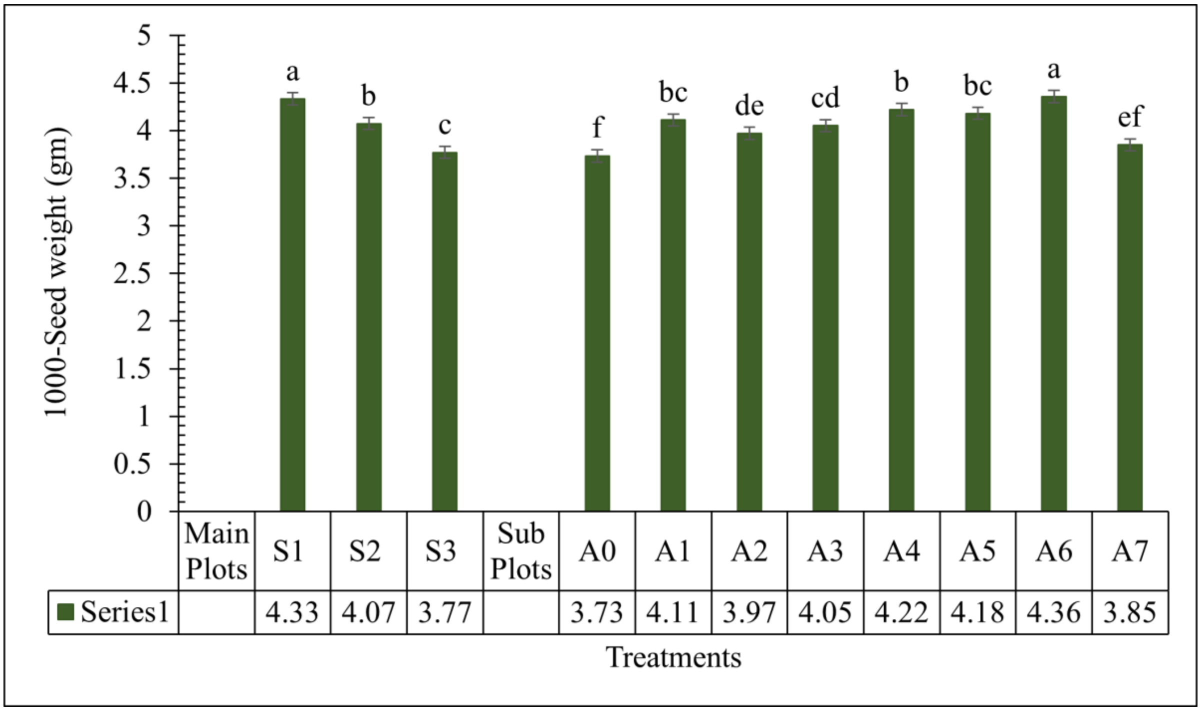


Fig 4.2.4.1(a): The impact of sulphur sources and agrochemical treatments on 1000-seed weight in the year 2021-2022

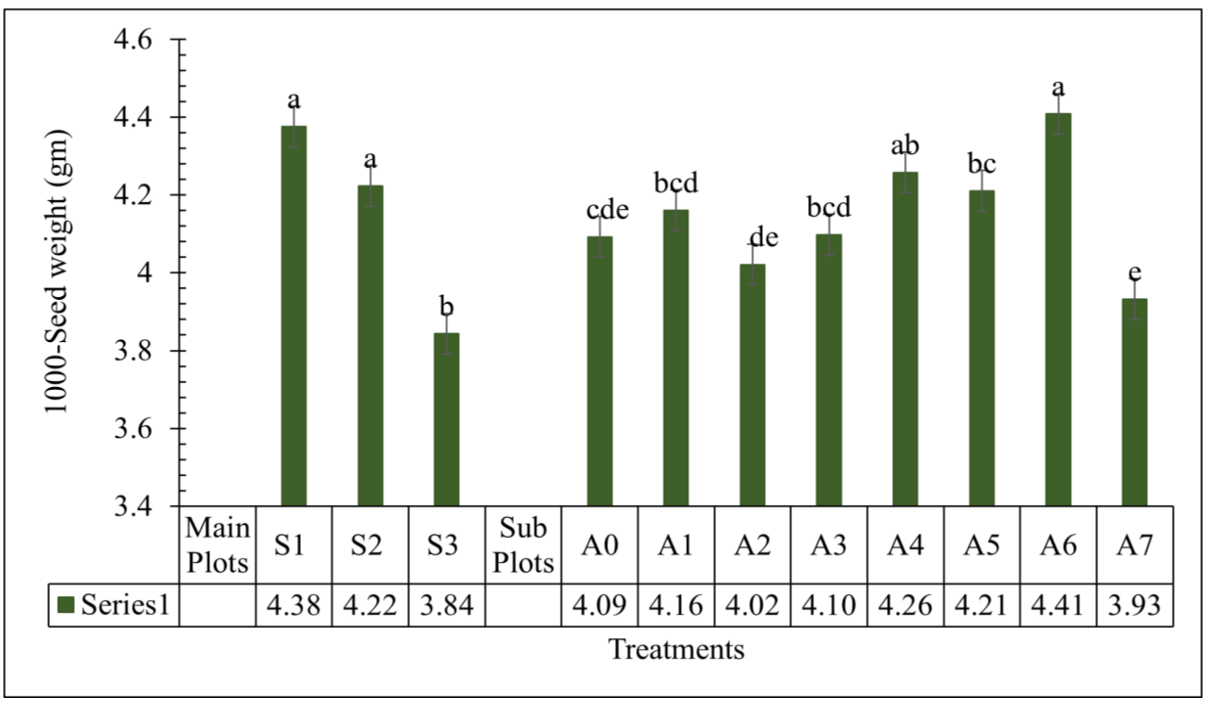


Fig 4.2.4.2(b): The impact of sulphur sources and agrochemical treatments on 1000-seed weight in the year 2022-2023

4.2.5 Seed Yield (q/ha): The data analysis for yield of seed for the year 2021-22 and 2022- 23 across various sulphur sources and agrochemical treatments demonstrated considerable variation as shown in Table 4.2.5.1 and Figure 4.2.5.1(a) and 4.2.5.2(b). Among sulphur sources, Gypsum (S1) consistently yielded the greatest results, with values of 19.92 q/ha and 20.26 q/ha, indicating a 1.71% increase in seed yield from 2021-22 to 2022-23. Bentonite Sulphur (S2) yielded 17.96 and 18.23, reflecting a 1.51% increase. The minimum yield was observed for Elemental Sulphur (S3), at 14.09 q/ha and 14.18 q/ha, indicating a slight 0.64% increase. Statistically, S1 (Gypsum) and S2 (Bentonite Sulphur) were comparable; however, S3 (Elemental Sulphur) exhibited major variations. In terms of agrochemical treatments, Hydrogel + Salicylic Acid applied during both flowering and pod formation (A6) yielded the highest results, with values of 20.16 q/ha and 20.48 q/ha, reflecting a 1.58% increase from 2021-22 to 2022-23. The Control (A0) treatment, with irrigation administered as required, yielded 19.09 q/ha and 19.59 q/ha, indicating a 2.62% increase. Alternative agrochemical treatments, including Hydrogel (A1) and Salicylic Acid during Flowering (A2), resulted in diminished yields, with enhancements of 1.44% and 1.75%, respectively. The Control (Restricted Irrigation, A7) exhibited a 1.94% rise. The most productive treatments, A6 (Hydrogel + Salicylic Acid during both flowering and pod formation) and A0 (Control, irrigation as required), yielded comparably, but treatments such as Hydrogel (A1) and Salicylic Acid at pod formation (A3) exhibited diminished yields. In summary, Gypsum (S1) and Hydrogel + Salicylic Acid (A6) regularly surpassed other treatments in seed yield, while S3 (Elemental Sulphur) and A1 (Hydrogel) exhibited the lowest yields. The findings reveal a little enhancement in seed yield across the majority of treatments from 2021-22 to 2022-23, with Gypsum (S1) and Hydrogel + Salicylic Acid (A6) having the most superior performance. Table 4.2.5.2 shows the interaction effect of various sulphur sources and agrochemical treatments on seed production of Gobhi Sarson (Brassica napus L.) during the *Rabi* seasons of 2021–22 and 2022–23, exhibiting substantial differences across the treatments. The maximum seed yield was seen in treatment S1A6, with yields of 23.18 q/ha in 2021–22 and 23.68 q/ha in 2022–23, greatly surpassing the majority of other treatments. The minimum yield was recorded in S3A7, measuring 11.27 q/ha in 2021–22 and 11.44 q/ha in 2022–23. The results indicate that the combined application of gypsum, hydrogel, and salicylic acid (S1A6) was the most effective in enhancing the seed yield of Gobhi Sarson under regulated irrigation, whereas the lowest yield was recorded in the presence of agrochemicals with elemental sulphur (S3A7). The variations in seed production resulting from different sulphur sources and agrochemical treatments can be ascribed to multiple scientific aspects concerning nutrient absorption, plant physiology, and the influence of agrochemicals on plant growth and development. Gypsum is a highly soluble source of sulphur that supplies both sulphur and calcium to plants. Sulphur is essential for the production of amino acids, proteins, and enzymes critical for plant growth, whereas calcium is important for cell wall integrity and the maintenance of optimal plant cell function. Gypsum, as a source of calcium sulphate, strengthens the structural integrity of plant cells and improves nutrient uptake efficiency, hence increasing seed yield. Bentonite is a clay-derived substance that disseminates sulphur into the soil at a slower rate than gypsum. The slower release rate of sulphur may restrict its immediate availability for plant absorption, thus diminishing growth efficiency and yield, particularly under high- demand conditions. Elemental Sulphur (S3) exhibited the lowest yields, presumably attributable to its limited solubility in the soil. Microbial oxidation is required to transform elemental sulphur into a sulphate form that is accessible to plants. The conversion process is slow and may exhibit inconsistency, particularly in environments where microbial activity is suboptimal, such as in chilly or arid soils. The delayed availability of sulphur for plant absorption diminishes its efficacy in promoting growth, resulting in reduced seed yields (Bello et al., 2021; Khan et al., 2018; Mishra et al., 2023; Singh & Singh, 2007). A study in the Agricultural Reviews journal indicates that gypsum, a moderately soluble sulphur source, can stimulate plant growth and improve soil characteristics, resulting in improved seed output. Furthermore, studies in the Agricultural Science Digest demonstrate that gypsum is markedly more effective than other sulphur sources for enhancing seed, stover, and oil yields, along with sulphur absorption (Abbas et al., 2023; Rashmi et al., 2018). The combination of hydrogel and salicylic acid during both flowering and pod formation (A6) resulted in the maximum seed output. The amalgamation of hydrogel with salicylic acid yields several advantageous impacts on flora. Hydrogel functions as a superabsorbent polymer that enhances soil water retention, especially advantageous during arid periods. This results in enhanced hydration and less stress on plants, especially during vital growth stages such as flowering and pod development. Salicylic acid, a phytohormone, augments stress resilience, boosts nutrient absorption, and activates the plant's defensive systems. Collectively, these agrochemicals enhance plants' resilience to environmental challenges, resulting in improved photosynthesis, enhanced growth, and increased seed harvests. The Control (A0) treatment, which utilized irrigation as required, demonstrated elevated seed output, underscoring the importance of effective water management for maximum plant growth. A reliable and sufficient water supply guarantees the efficient functioning of the plant's physiological functions, including nutrient absorption and enzyme activity. The 2.62% increase in seed output indicates that irrigation is crucial for sustaining an optimal growing environment for the plants. Hydrogel (A1) exhibited inferior seed yields when used in isolation compared to its combination with salicylic acid. Although hydrogel enhances water retention, it does not directly affect plant metabolism or stress resilience. Consequently, the impact of hydrogel alone may be limited in enhancing yield, as it fails to address the hormonal regulation of growth and stress management, which are critical throughout the flowering and pod formation phases. Salicylic Acid (A2 and A3) demonstrated moderate enhancements in seed yield, however, it was less effective than the hydrogel-salicylate combination. Salicylic acid contributes to plant growth by modulating activities such as stomatal conductance, photosynthesis, and nutrient absorption, especially under stress conditions. Nonetheless, its efficacy may diminish if administered solely during a single growth stage (either flowering or pod formation), as the plant necessitates ongoing hormonal regulation throughout its life cycle for optimal development. The diminished increase noted in A2 and A3 relative to A6 indicates that the timing and combination of treatments are essential for optimizing yield. The Control (Restricted Irrigation, A7) exhibited the lowest yield, as anticipated. Water stress during essential growth phases, especially during flowering and pod development, can significantly hinder plant growth, nutrient absorption, and metabolic functions, resulting in diminished seed output. Plants experiencing limited irrigation encounter restricted water supply, resulting in drought stress, diminished cell development, decreased photosynthetic efficiency, and eventually, reduced seed yield. A study on Indian mustard in rainfed settings revealed that the combination of hydrogel and salicylic acid markedly enhanced plant height, dry matter per plant, and seed output. Moreover, a study published in the International Journal of Current Microbiology and Applied Sciences indicated that the use of hydrogel and salicylic acid enhanced plant growth and seed output in mustard crops under limited irrigation conditions. These investigations collectively affirm that gypsum serves as a sulphur source, and the amalgamation of hydrogel with salicylic acid as an agrochemical treatment can augment seed output by enhancing nutrient availability and water retention (Mahto et al., 2023). The variations in seed production among treatments result from the synergistic influences of nutrient availability (sulphur), water management (hydrogel), and the modulation of plant growth via hormonal treatments (salicylic acid). Gypsum (S1) offers prompt and effective sulphur accessibility, promoting growth, whilst Hydrogel + Salicylic Acid (A6) maximizes water availability and stress resilience, resulting in increased yields. Conversely, slower-releasing sulphur sources such as Bentonite Sulphur (S2) and Elemental Sulphur (S3), together with isolated treatments like Hydrogel (A1) or Salicylic Acid (A2 and A3), lack comparable synergy, leading to diminished yields. Limited irrigation and insufficient sulphur or hormonal interventions intensify stress conditions, resulting in significant decreases in production. Recent studies have provided insights into the effects of hydrogel use and foliar sprays of nutrients on the yield attributes, seed, and stover yield of chickpea crops. A field experiment at the Instructional Cum Research Farm of IGKV, Raipur (Chhattisgarh) during the *Rabi* seasons of 2018-19 and 2019-20 examined the effects of hydrogel and foliar nutrition sprays on chickpea (Banjara et al., 2021). The research demonstrated that the application of hydrogel at 5.0 kg/ha prior to seeding markedly enhanced the number of pods per plant, seeds per pod, 1000-seed weight, and the yield of seeds throughout both years. Seed yield jumped to 1680.05 kg/ha and 1716.91 kg/ha in the corresponding years, relative to the control. The foliar spraying of 2% urea during flower initiation and pod development phases significantly enhanced yield characteristics and seed yield, comparable to thiourea at 500 ppm. These findings suggest that hydrogel applications enhance soil moisture retention, thereby improving nutrient uptake and utilization, leading to increased nitrogen content in seeds and straw. Similarly, foliar nutrition sprays, particularly urea, provide an immediate nitrogen source during critical growth stages, enhancing nitrogen assimilation and overall yield (Ahmed Bakry, 2015; Ali & Abdelaal, 2021; Kamanakeri & Deshpande, 2023; Nahar & Gretzmacher, 2002; Soto-Gonzales et al., 2024). A separate study on lentil yield in Rajasthan indicated that the use of hydrogel and foliar nutrition application enhanced the yield of grains and harvest index.

Table 4.2.5.1: The impact of treatments on no. of Seed yield (q/ha) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	Seed yield (q/ha) (2021-22)	Seed yield (q/ha) (2022-23)
Sulphur sources		
S1: Gypsum	19.92^{a}	20.26^{a}
S2: Bentonite Sulphur	17.96^{b}	18.23^{b}
S3: Elemental Sulphur	14.09^{c}	14.18^{c}
CV (Sulphur Sources)	3.12	3.31
CD (Sulphur Sources)	0.43	0.47
Agrochemical		
A0: Control (Irrigation as per requirement)	19.09^{b}	19.59^{b}
A1: Hydrogel (2.5 kg/ha) as basal application	16.62^{d}	16.86^{e}
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	15.45^{f}	15.72^{g}
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	16.10^{e}	16.19^{f}
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	18.32^{c}	18.48^{d}
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	18.95^{b}	19.00^{c}
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	20.16^{a}	20.48^{a}
A7: Control (Restricted irrigation)	13.88^{g}	14.15^{h}
CD (Agrochemical)	0.41	0.42
CV (Sulphur Sources and agrochemical)	2.51	2.54

Table 4.2.5.2: The interaction impact of treatments on Seed yield (q/ha) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	Seed yield (q/ha) (2021-22)	Seed yield (q/ha) (2022-23)
S1A0	21.94±0.51	22.32±0.47
S1A1	19.11±0.02	19.50±0.02
S1A2	17.77±1.23	18.18±1.23
S1A3	18.51±1.35	18.72±1.78
S1A4	21.07±0.04	21.37±0.04
S1A5	21.79±0.06	21.97±0.06
S1A6	23.18±0.09	23.68±0.09
S1A7	15.96±0.09	16.36±0.09
S2A0	19.64±0.76	20.74±0.32
S2A1	17.26±0.04	17.45±0.04
S2A2	16.04±0.03	16.27±0.03
S2A3	16.72±0.05	16.75±0.04
S2A4	19.02±0.04	19.12±0.04
S2A5	19.67±0.03	19.66±0.03
S2A6	20.93±0.51	21.19±0.02
S2A7	14.41±0.05	14.64±0.05
S3A0	15.71±0.40	15.70±0.28
S3A1	13.49±0.03	13.64±0.03
S3A2	12.54±0.04	12.71±0.04
S3A3	13.07±0.04	13.09±0.04
S3A4	14.87±0.05	14.95±0.05
S3A5	15.38±0.03	15.37±0.03
S3A6	16.37±0.03	16.56±0.03
S3A7	11.27±0.03	11.44±0.03
CV	2.51	2.54
CD	0.79	0.82

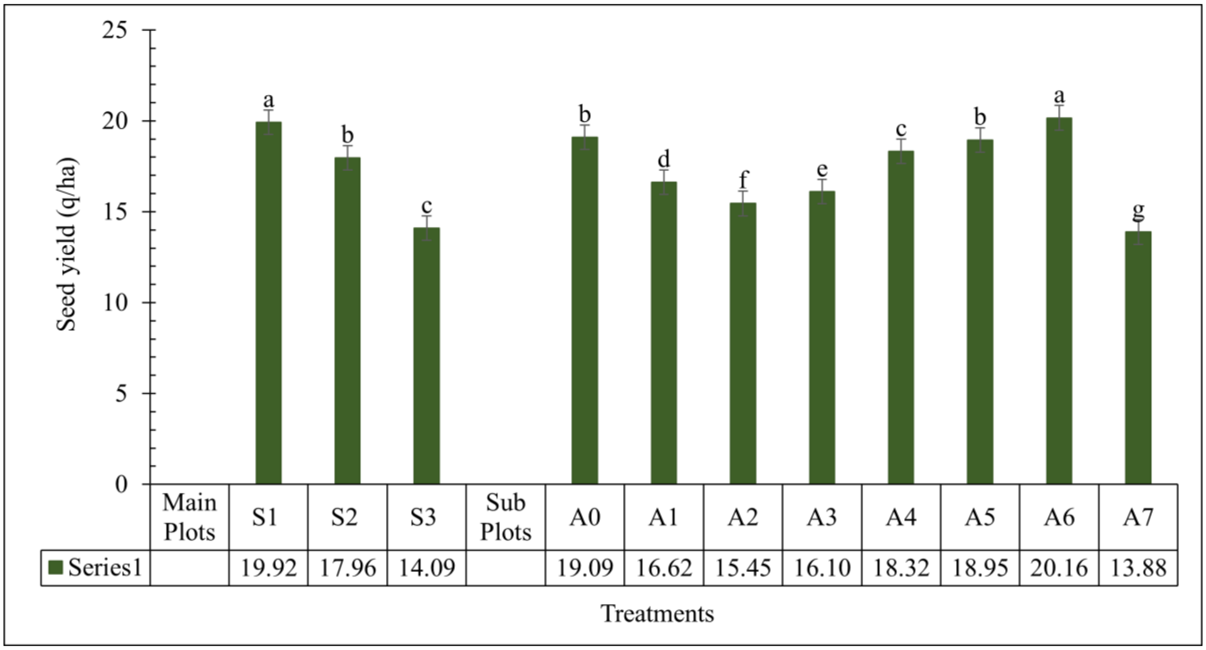


Fig. 4 .2.5.1 (a) The impact of various sulphur sources and agrochemical treatments on yield of seeds (q/ha) in the year 2021-2022

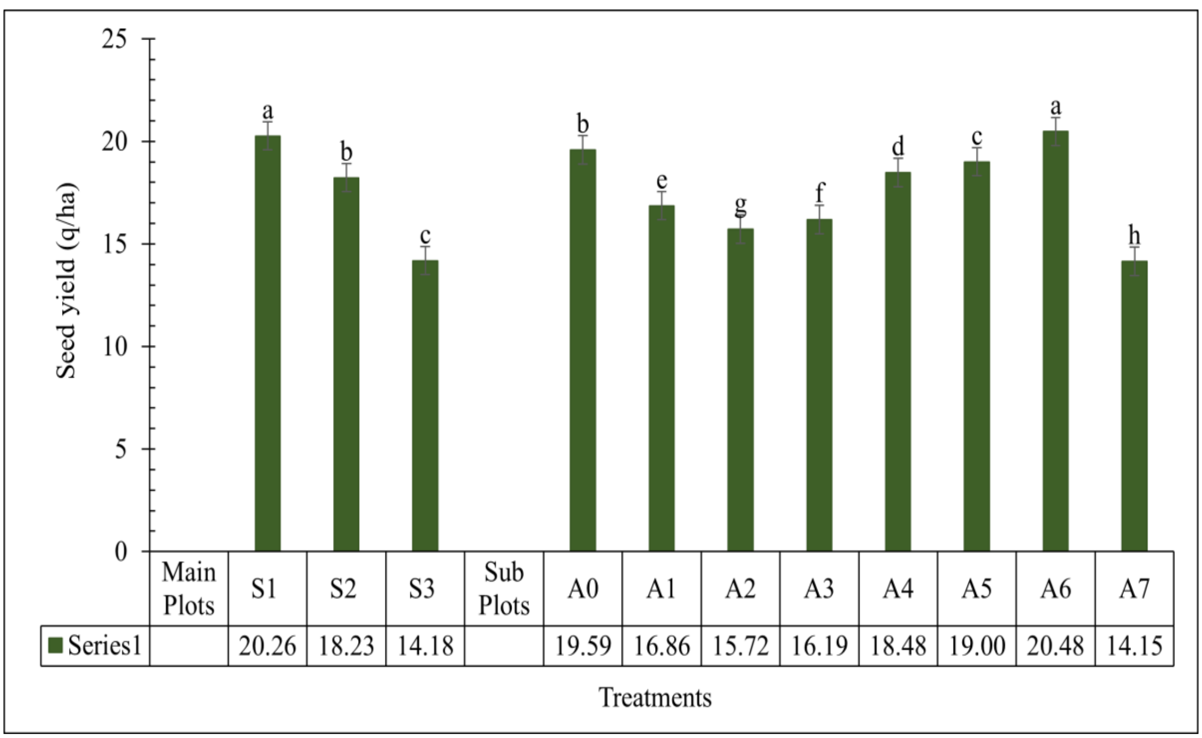


Fig. 4 .2.5.2 (b) The impact of various sulphur sources and agrochemical treatments on seed yield of seeds (q/ha) in the year 2022-2023

4.2.6 Straw yield (q/ha): The impact of various sulphur sources and agrochemical treatments on the straw yield (q/ha) Brassica napus L. during the *rabi* seasons of 2021-22 and 2022-23 is shown in Table 4.2.6.1 and Figure 4.2.6.1(a),4.2.6.2(b). The results demonstrate notable differences among treatments, with gypsum (S1) consistently yielding the largest straw output, succeeded by bentonite sulphur (S2) and elemental sulphur (S3). In the 2021-22 period, gypsum application produced a straw yield of 36.65 q/ha, surpassing bentonite sulphur by 12.77% (32.50 q/ha) and elemental sulphur by 46.34% (25.04 q/ha). In 2022-23, gypsum yielded 37.57 q/ha, which was 13.74% greater than bentonite sulphur at 33.03 q/ha and 45.74% higher than elemental sulphur at 25.79 q/ha. The maximum straw yield among agrochemical treatments was observed in A6, yielding 36.17 q/ha in the year 2021-22 and 37.51 q/ha in the year 2022-23. This was 2.98% greater than the control with irrigation as required (A0) in 2021-22 and 2.01% greater in 2022-23. The minimal straw output was noted in the restricted irrigation control (A7), with the value of 25.10 q/ha in the year 2021-22 and 26.19 q/ha in the year 2022-23, representing a decrease of 42.12% compared to A6 in 2021-22 and 30.22% in 2022-23. The utilization of hydrogel alone (A1) led to a decrease in straw yield of 14.44% in 2021-22 and 15.27% in 2022-23 relative to the irrigation control (A0). Likewise, the treatment of salicylic acid at 50% flowering (A2) and at 50% pod formation (A3) resulted in markedly reduced yields, with declines of 19.20% and 18.63% in 2021-22, and 19.83% and 18.46% in 2022-23, respectively, in comparison to A0. The effect of interaction with various sources of sulphur and agrochemical treatments on the straw yield of Gobhi Sarson (*Brassica napus* L.) during the *rabi* seasons of 2021–22 and 2022–23 showed significant variance among the treatments in Table 4.2.6.2. The maximum straw yield was recorded in treatment S1A6, achieving 42.16 q/ha in year 2021– 22 and 43.86 q/ha in year 2022–23, which was markedly superior to the majority of other treatments. The minimum straw yield was seen in S3A7, with 20.04 q/ha in 2021–22 and 20.99 q/ha in 2022–23. Treatments S1A0, S1A4, S1A5, and S2A6 yielded significantly greater straw outputs than S3A7 in both years, underscoring the advantageous effects of gypsum in conjunction with agrochemicals. Nonetheless, treatments S1A1, S1A2, S1A3, S1A7, S2A0, S2A1, S2A2, S2A3, S2A4, S2A5, S2A7, S3A0, S3A1, S3A2, S3A3, S3A4, S3A5, and S3A6 exhibited no significant differences compared to the lowest yielding treatment (S3A7), suggesting non-significant reactions. In summary, S1A6 proved to be the most efficacious treatment for increasing straw production under regulated irrigation settings, whereas the lowest yield occurred without agrochemicals and with sole application of elemental sulphur (S3A7).

The variations in straw yield of Gobhi Sarson (*Brassica napus* L.) across various treatments can be scientifically elucidated by the functions and effectiveness of sulphur sources and agrochemicals in plant growth. Gypsum (S1) exhibited the highest straw yield among sulphur sources owing to its rapidly available sulphate form, which is instantly accessible for plant absorption. Sulphur is crucial for the synthesis of amino acids and proteins, hence promoting vegetative growth and biomass buildup. Research indicates that gypsum treatment markedly enhances plant development and output by efficiently providing sulphur and enhancing soil structure and water retention (Jolly et al., 2025). Conversely, bentonite sulphur (S2) demonstrated a limited efficacy due to its composition of elemental sulphur combined with bentonite clay. Upon application to soil, bentonite expands and disperses tiny sulphur particles; nevertheless, the oxidation of elemental sulphur into plant-available sulphate occurs gradually, hindering its efficacy. (Sharma et al., 2024) indicate that bentonite sulphur requires time to liberate sulphate ions, rendering it less efficacious than gypsum during the first development phases. Elemental sulphur (S3) produced the lowest straw yield due to the necessity for microbial oxidation to become available to plants, a process that can be long and is highly contingent on soil microbial activity and environmental conditions (Malik et al., 2021). The interplay between agrochemicals and sulphur sources additionally affected the straw yield. The highest yield was recorded in the treatment combination of gypsum along with the combination of hydrogel and salicylic acid administered at 50% flowering and pod development (S1A6). Hydrogel, a superabsorbent polymer, enhances soil moisture retention, mitigates water stress, and promotes nutrient absorption, hence facilitating superior growth and increased straw production. Studies have shown that the application of hydrogel improves water-use efficiency and promotes root development, hence facilitating more effective nutrient acquisition by plants (Ali et al., 2024; Patra et al., 2022). Salicylic acid is essential for stress tolerance and metabolic control in plants. Its administration during crucial growth phases enhances physiological processes such antioxidant defense and nutrient translocation, resulting in increased biomass production (Hayat et al., 2025). The minimal straw production was seen under limited irrigation (S7) for all sulphur sources. Water stress diminishes nutrient solubility and absorption, impedes enzyme functions, and restricts photosynthetic efficacy, resulting in inhibited growth and reduced biomass accumulation. The findings correspond with prior research highlighting the significance of combining suitable sulphur sources with water-retention agents and growth enhancers to maximize plant growth. Research substantiates the superiority of gypsum compared to elemental sulphur and bentonite sulphur, as well as the advantageous function of hydrogel in enhancing soil moisture availability. The interaction effects further validate that the simultaneous application of hydrogel and salicylic acid during critical phenological phases markedly improves plant resistance and productivity. These findings highlight the necessity for accurate fertilizer and water management strategies to optimize production potential in oilseed crops under regulated irrigation conditions.

Table 4.2.6.1: The impact of treatments on Straw yield (q/ha) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	Straw yield (q/ha) (2021-22)	Straw yield (q/ha) (2022-23)
Sulphur sources		
S1: Gypsum	36.65[a]	37.57[a]
S2: Bentonite Sulphur	32.50[b]	33.03[b]
S3: Elemental Sulphur	25.04[c]	25.79[c]
CV (Sulphur Sources)	2.14	2.79
CD (Sulphur Sources)	0.54	0.72
Agrochemical		
A0: Control (Irrigation as per requirement)	35.81[a]	36.77[b]
A1: Hydrogel (2.5 kg/ha) as basal application	30.64[c]	31.15[d]
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	28.94[d]	29.47[e]
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	29.14[d]	29.96[e]
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	32.89[b]	33.11[c]
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	32.49[b]	32.89[c]
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	36.17[a]	37.51[a]
A7: Control (Restricted irrigation)	25.10[e]	26.19[f]
CD (Agrochemical)	0.69	0.58
CV (Sulphur Sources and agrochemical)	2.31	1.91

Table 4.2.6.2: The interaction impact of treatments on Straw yield (q/ha) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	Straw yield (q/ha) (2021-22)	Straw yield (q/ha) (2022-23)
S1A0	42.16±0.86	42.99±0.50
S1A1	35.72±0.02	36.42±0.02
S1A2	33.74±1.23	34.46±1.23
S1A3	33.97±1.36	35.03±1.78
S1A4	38.34±0.05	38.71±0.05
S1A5	37.87±0.06	38.46±0.06
S1A6	42.16±0.09	43.86±0.09
S1A7	29.26±0.09	30.62±0.09
S2A0	36.94±0.31	37.56±0.49
S2A1	31.73±0.04	32.06±0.04
S2A2	29.97±0.03	30.33±0.03
S2A3	30.18±0.04	30.83±2.04
S2A4	34.07±2.04	34.08±0.04
S2A5	33.65±2.03	33.85±0.03
S2A6	37.46±0.51	38.60±0.02
S2A7	26.00±0.05	26.95±0.05
S3A0	28.32±0.30	29.75±0.38
S3A1	24.47±0.03	24.97±0.03
S3A2	23.11±0.04	23.62±0.04
S3A3	23.27±0.04	24.02±0.04
S3A4	26.26±0.05	26.54±0.05
S3A5	25.94±0.03	26.36±0.03
S3A6	28.88±0.03	30.07±0.03
S3A7	20.04±0.03	20.99±0.03
CV	2.31	1.91
CD	1.23	1.17

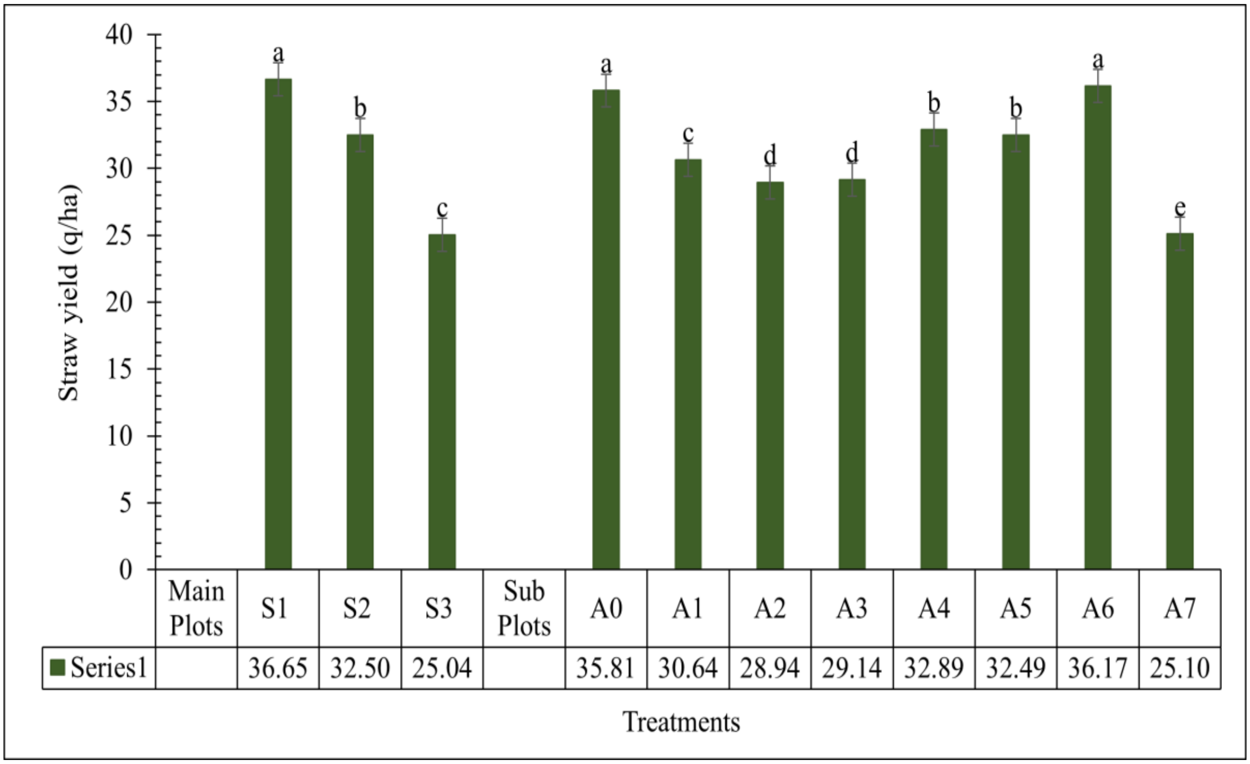


Fig. 4 .2.6.1 (a) The impact of various sources of sulphur and agrochemical treatments on straw yield of straw (q/ha) in year 2021-2022

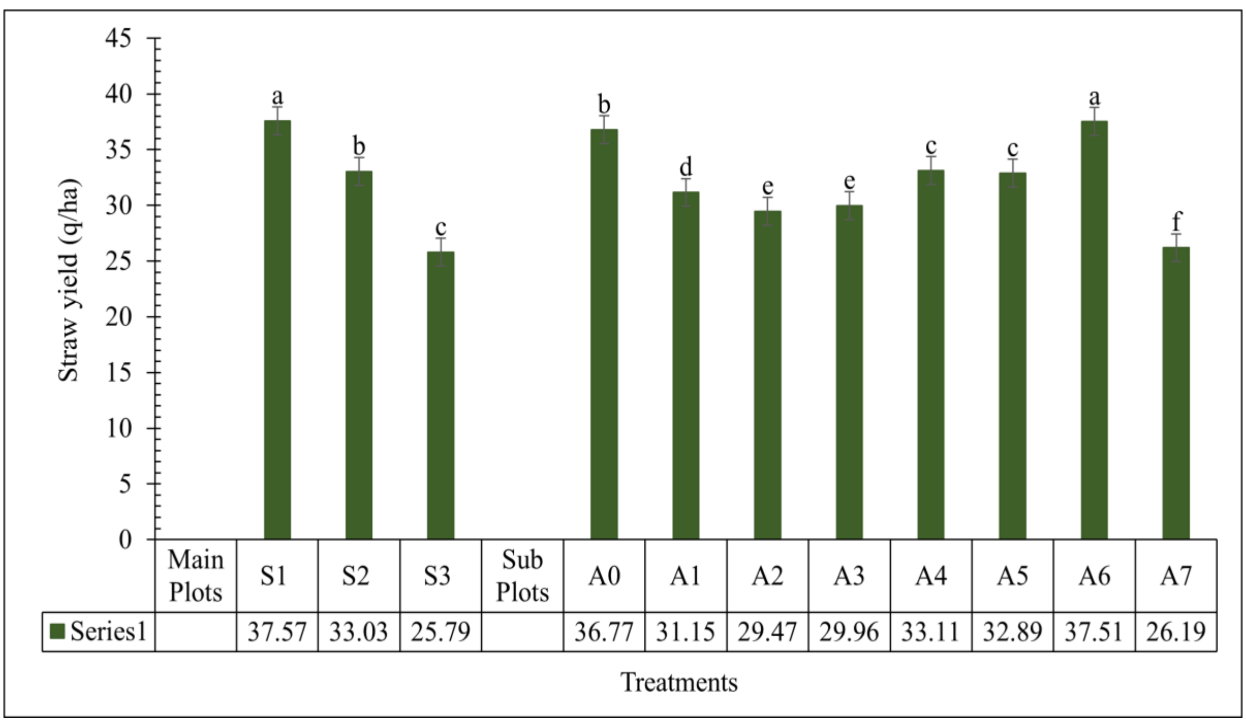


Fig:4.2.6.2(b) The impact of various sources of sulphur and agrochemical treatments on straw yield of straw (q/ha) in year 2022-2023

4.2.7 Biological yield (q/ha): The biological yield of Gobhi Sarson (*Brassica napus* L.) was dramatically affected by sulphur sources and agrochemicals treatments across the two years (2021-22 and 2022-23) as shown in Table 4.2.7.1 and Figure 4.2.7.1(a), 4.2.7.2 (b). Among the sulphur sources, S1 (Gypsum) had the highest biological yield in both years, with values of 56.58 q/ha and 57.83 q/ha, respectively. It was markedly superior to the alternative sulphur sources. S2 (Bentonite Sulphur) produced yields of 50.46 q/ha in the year 2021- 22 and 51.26 q/ha in the year 2022-23, which were statistically comparable to each other but considerably less than S1. S3 (Elemental Sulphur) exhibited the lowest yields of 39.13 q/ha and 39.98 q/ha in the two respective years, markedly lower than both S1 and S2. A6 yielded the highest biological output among agrochemical treatments, with values of 56.34 q/ha (2021-22) and 58.00 q/ha (2022-23) over both years. This treatment was markedly superior to all alternative treatments. The second-highest yields were recorded under A0 (Control with irrigation as required) at 54.89 q/ha and 56.36 q/ha, which were statistically comparable to A6 but greatly exceeded all other agrochemical treatments. Treatments A4 and A5 demonstrated intermediate biological yields, achieving 51.21 q/ha and 51.59 q/ha for A4, and 51.44 q/ha and 51.91 q/ha for A5, across the respective years. These treatments were statistically equivalent to one another and considerably superior to A1, A2, A3, and A7. Conversely, treatments A1, A2, and A3 exhibited diminished biological yields, varying from 44.39 to 47.99 q/ha during the two years. The minimal biological yield was recorded in A7 (Control with restricted irrigation) at 38.99 q/ha and 40.36 q/ha, much lower than all other treatments.

The effect of interaction with various sulphur sources and agrochemical treatments on the biological yield of Gobhi Sarson (*Brassica napus* L.) during the *rabi* seasons of 2021–22 and 2022–23 demonstrated considerable disparities among treatments shown in Table 4.2.7.2. The maximum biological yield was seen in treatment S1A6, yielding 65.37 q/ha in 2021–22 and 67.57 q/ha in 2022–23, greatly exceeding the other treatments. The minimum biological yield was recorded in treatment S3A7 (Elemental sulphur + No hydrogel + No salicylic acid), at 31.33 q/ha in 2021–22 and 32.47 q/ha in 2022–23. Additional treatments that exhibited elevated biological yields were S1A0, S1A4, S1A5, and S2A6, signifying a beneficial effect of gypsum and agrochemical application. Conversely, treatments included S1A1, S1A2, S1A3, S1A7, S2A0, S2A1, S2A2, S2A3, S2A4, S2A5, S2A7, S3A0, S3A1, S3A2, S3A3, S3A4, S3A5, and S3A6 showed no substantial enhancements relative to the least effective treatment (S3A7). Treatment S1A6 had the highest efficacy in augmenting biological yield under regulated irrigation settings, whereas S3A7 exhibited the lowest biological productivity.

The substantial rise in biological output with gypsum (S1) is due to its effectiveness as a superior sulphur source that enhances soil fertility and boosts crop productivity. Gypsum supplies sulphate-S, the most accessible form of sulphur, which is essential for protein synthesis, chlorophyll production, and enzyme function, hence enhancing plant growth and biomass yield. Research conducted by Kumar et al. (2018) and Adkine et al. (2018) demonstrates that gypsum application markedly improves yield in Brassica species owing to its high solubility and prompt availability of sulphur. The superiority of bentonite sulphur (S2) over elemental sulphur (S3) can be attributed to the gradual oxidation of elemental sulphur into sulphate, which hinders its accessibility to plants. Bentonite sulphur, exhibiting superior efficiency compared to elemental sulphur, releases sulphur gradually, so ensuring sustained nutrient availability during the whole crop growth cycle. This corresponds with the findings of (Choudhary et al., 2024), who indicated superior yield performance in oilseed crops when utilizing bentonite sulphur as opposed to elemental forms. The increased biological yield observed in treatments with hydrogel (A6, A4, and A5) underscores the water retention capability of hydrogel, enhancing moisture availability, particularly under regulated irrigation conditions. Hydrogel mitigates water stress by improving soil water retention and facilitating steady nutrient absorption. The findings align with the research by Mishra et al. (2021), which indicated that hydrogel treatment enhanced yield by alleviating the negative impacts of restricted water availability. Salicylic acid enhances production primarily by functioning as a plant growth regulator that alleviates abiotic stress and optimizes physiological processes such as photosynthesis, enzyme activity, and nutrient translocation. Treatments utilizing salicylic acid during the 50% flowering and 50% pod formation stages (A6) significantly enhanced biological yield, as salicylic acid modulates stress responses and optimizes plant metabolism during crucial growth phases. Tanin et al. (2023) found analogous findings, noting substantial production enhancements in oilseed crops following the application of salicylic acid. The interaction effect (S1A6) illustrated the synergistic advantages of gypsum, hydrogel, and salicylic acid. Gypsum provided sufficient sulphur availability, hydrogel improved water retention, and salicylic acid optimized physiological functions, collectively yielding the highest biological output. This outcome aligns with the research of Kumar et al. (2024; Srivastava et al., 2024), which highlighted that the integration of effective nutrient sources, water management techniques, and growth regulators can optimize crop yield. Conversely, restricted irrigation (A7) with elemental sulphur (S3) produced the lowest biological output, mostly due to constrained nutrient availability and water stress that impeded plant growth. This discovery aligns with the research of Enamul & Moni (2025), which emphasized that sulphur availability and adequate irrigation are essential for optimizing oilseed crop yields.

Table 4.2.7.1: The impact of treatments on the biological yield of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	Biological yield (q/ha) (2021-22)	Biological yield (q/ha) (2022-23)
Sulphur sources		
S1: Gypsum	56.58[a]	57.83[a]
S2: Bentonite Sulphur	50.46[b]	51.26[b]
S3: Elemental Sulphur	39.13[c]	39.98[c]
CV (Sulphur Sources)	1.54	1.95
CD (Sulphur Sources)	0.60	1.11
Agrochemical		
A0: Control (Irrigation as per requirement)	54.89[b]	56.36[b]
A1: Hydrogel (2.5 kg/ha) as basal application	47.26[d]	47.99[d]
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	44.39[e]	45.17[f]
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	45.24[e]	46.14[e]
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	51.21[c]	51.59[c]
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	51.44[c]	51.91[c]
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	56.34[a]	58.00[a]
A7: Control (Restricted irrigation)	38.99[f]	40.36[g]
CD (Agrochemical)	1.01	0.92
CV (Sulphur Sources and agrochemical)	2.17	1.95

Table 4.2.7.2: The interaction impact of treatments on biological yield of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	Biological yield (q/ha) (2021-22)	Biological yield (q/ha) (2022-23)
S1A0	64.10±1.34	65.30±0.36
S1A1	54.80±0.03	55.90±0.03
S1A2	51.50±2.46	52.60±2.01
S1A3	52.50±2.71	53.77±2.91
S1A4	59.43±0.09	60.07±0.07
S1A5	59.67±0.12	60.43±0.10
S1A6	65.37±0.17	67.57±0.14
S1A7	45.23±0.17	47.00±0.14
S2A0	56.57±0.97	58.30±0.15
S2A1	49.00±0.07	49.50±0.06
S2A2	46.03±0.05	46.57±0.04
S2A3	46.90±0.09	47.57±1.70
S2A4	53.07±2.07	53.20±0.06
S2A5	53.33±2.05	53.53±0.04
S2A6	58.40±1.01	59.80±0.03
S2A7	40.40±0.09	41.60±0.08
S3A0	44.00±0.36	45.47±0.43
S3A1	37.97±0.05	38.57±0.04
S3A2	35.63±0.07	36.33±0.06
S3A3	36.33±0.09	37.10±0.07
S3A4	41.13±0.09	41.50±0.07
S3A5	41.33±0.05	41.77±0.04
S3A6	45.27±0.05	46.63±0.04
S3A7	31.33±0.05	32.47±0.04
CV	2.17	1.95
CD	1.73	1.84

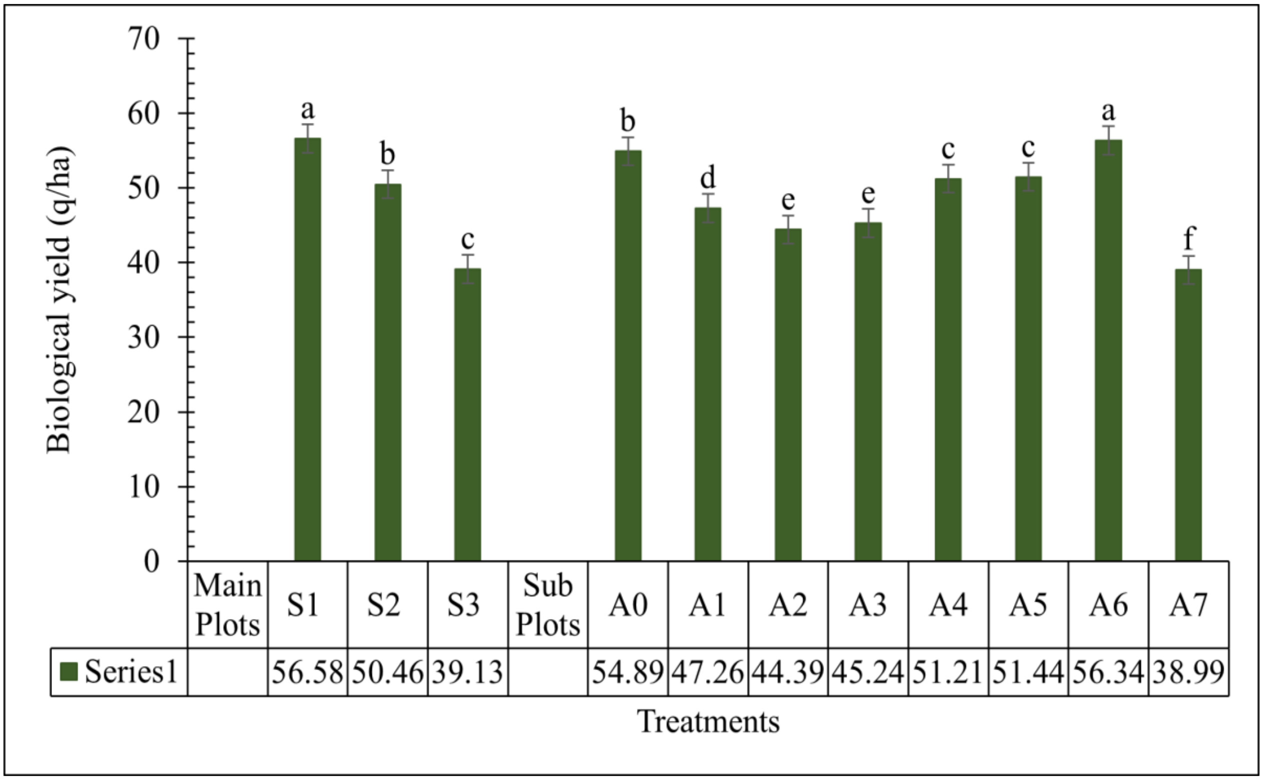


Fig 4.2.7.1(a): The impact of sulphur sources and agrochemical treatments on biological yield in the year 2021-2022

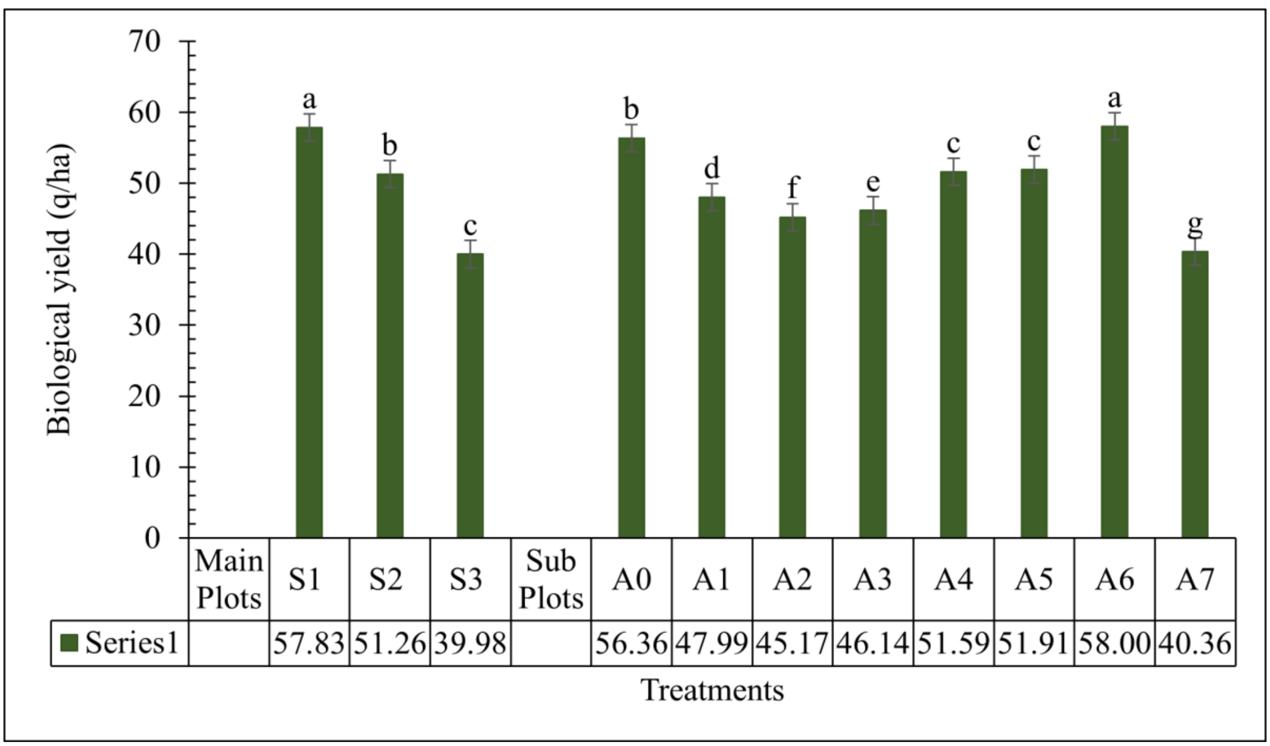


Fig 4.2.7.2(b): The impact of sulphur sources and agrochemical treatments on biological yield in the year 2022-2023

4.2.8 Harvest index (%): The results in Table 4.2.8.1 and Figure 4.2.8.1(a), 4.2.8.2(b) suggest that the harvest index of GSC 7 was considerably impacted by varied sulphur sources and agrochemical treatments throughout both years. Among the sulphur sources, elemental sulphur (S3) had the highest harvest index in both 2021-22 (35.99%) and 2022- 23 (35.47%), proving its superior role in enhancing economic yield. Bentonite sulphur (S2) followed closely with values of 35.59% and 35.54%, respectively, although gypsum (S1) had the lowest harvest index (35.19% in 2021-22 and 35.02% in 2022-23). Compared to gypsum, elemental sulphur enhanced the harvest index by 2.27% in 2021-22 and 1.28% in 2022-23, suggesting its greater effectiveness in biomass partitioning. Agrochemical applications significantly influenced the harvest index. The combination of hydrogel (2.5 kg/ha) and salicylic acid (150 ppm) applied at 50% pod formation (A5) led to the greatest harvest index, with 36.89% in 2021-22 and 36.64% in 2022-23. This shows that this treatment improved seed yield more efficiently than total biomass development. Alternative treatments, including hydrogel coupled with salicylic acid at 50% flowering (A4) and during both flowering and pod formation stages (A6), exhibited commendable efficacy, with values between 35.82% and 35.85%. On the other hand, the control treatment with restricted irrigation (A7) exhibited a moderate harvest index (35.65% in 2021-22 and 35.10% in 2022-23), demonstrating some resilience to water stress. The lowest harvest index was recorded in the untreated control (A0) and salicylic acid alone (A2), both recording values around 34.77% to 34.87%, showing the beneficial effect of hydrogel along with salicylic acid in boosting yield efficiency.

The interaction effect of different sulphur sources and agrochemical treatments on the biological yield of Gobhi Sarson (*Brassica napus* L.) during the *rabi* seasons of 2021–22 and 2022–23 revealed significant variations among treatments. The highest biological yield was seen in treatment S1A6, producing 65.37 q/ha in 2021–22 and 67.57 q/ha in 2022–23, far surpassing the other treatments. The lowest biological yield was seen in treatment S3A7, measuring 31.33 q/ha in 2021–22 and 32.47 q/ha in 2022–23. Supplementary treatments that demonstrated increased biological yields included S1A0, S1A4, S1A5, and S2A6, indicating a positive impact of gypsum and agrochemical application. In contrast, the treatments S1A1, S1A2, S1A3, S1A7, S2A0, S2A1, S2A2, S2A3, S2A4, S2A5, S2A7, S3A0, S3A1, S3A2, S3A3, S3A4, S3A5, and S3A6 showed no significant improvements compared to the least effective treatment (S3A7). Treatment S1A6 demonstrated the greatest efficacy in enhancing biological yield under controlled irrigation conditions, while S3A7 displayed the least biological productivity.

The fluctuation in the harvest index (HI) of GSC 7, attributed to various sulphur sources and agrochemical treatments, can be understood by their physiological and biochemical functions in plant growth, nutrient uptake, and stress adaptability. Sulphur (S) is essential for enzyme activation, protein synthesis, and chlorophyll creation, directly affecting biomass production and distribution. The identified pattern in harvest index (S3 > S2 > S1) corresponds with the efficacy of several sulphur sources. Elemental Sulphur (S3) exhibited the highest HI owing to its slow oxidation into plant-available sulphate (SO_4^{2-}), hence guaranteeing a constant supply of sulphur during essential growth phases (Scherer, 2001). This enhanced seed growth results in an elevated harvest index. Bentonite Sulphur (S2) exhibited a somewhat reduced HI due to its moderate rate of sulphate release, rendering it less effective than elemental sulphur yet superior to gypsum. Bentonite sulphur is recognized for its ability to improve root activity and nutrient absorption, hence enhancing crop efficiency. Gypsum (S1) exhibited the lowest HI due to its provision of readily available sulphate, although it does not offer the sustained nutrient release characteristic of elemental sulphur. Due to its mobility in soil, sulphate is susceptible to leaching, which diminishes its long-term efficacy. Hydrogel and salicylic acid significantly enhanced the HI by improving water retention, stress tolerance, and nutrient assimilation, hence increasing seed output in terms of biomass. Hydrogel (A1) enhanced HI by augmenting soil moisture availability, mitigating drought stress, and promoting root activity, hence improving nutrient uptake and translocation to seeds. Optimal outcomes were noted when Hydrogel was paired with Salicylic acid (A5, A6, A4), indicating a synergistic effect. Salicylic acid (A2, A3) enhanced HI by alleviating stress and activating antioxidant enzymes, resulting in increased nutritional allocation to reproductive organs. The maximum HI was recorded in A5 (Hydrogel + Salicylic acid at 50% pod formation), attributable to increased sink strength (elevated seed-setting efficiency) and diminished transpiration losses, facilitating appropriate dry matter distribution to seeds. The reduced HI in the control treatments (A0, A7) indicates that the lack of moisture retention (hydrogel) and stress mitigation (salicylic acid) resulted in inadequate allocation of assimilates to seed yield. The collaboration between sulphur sources and agrochemical treatments indicated a synergistic effect on seed yield efficiency. The optimal performance occurred in S3A5 (Elemental

Sulphur + Hydrogel + Salicylic acid at 50% pod formation), achieving the highest HI (37.22% in 2021-22 and 36.83% in 2022-23). Elemental Sulphur provided a consistent supply of sulphate, whereas hydrogel and salicylic acid enhanced water retention, stress tolerance, and nutrient delivery to growing seedlings. Comparable interactive effects have been documented in research on oilseed crops, wherein slow- release sulphur sources, in conjunction with bio stimulants, improved yield metrics (Abdul et al., 2023; Ahmed, 2015; Gupta A K et al., 1998; Maurya et al., 2023; Palansooriya et al., 2020; R Khan & A Khan, 2013; Singh et al., 2013). In contrast, the lowest HI was recorded in S1A0 (Gypsum + Control), with values of 34.23% and 34.18%, likely attributable to low sulphur-use efficiency and the lack of moisture-retention and stress-mitigation mechanisms.

Table 4.2.8.1: The impact of treatments on harvest index of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	Harvest Index (2021-22)	Harvest Index (2022-23)
Sulphur sources		
S1: Gypsum	35.19[b]	35.02[b]
S2: Bentonite Sulphur	35.59[ab]	35.54[a]
S3: Elemental Sulphur	35.99[a]	35.47[a]
CV (Sulphur Sources)	2.52	1.34
CD (Sulphur Sources)	0.72	0.38
Agrochemical		
A0: Control (Irrigation as per requirement)	34.87[d]	34.77[d]
A1: Hydrogel (2.5 kg/ha) as basal application	35.21[cd]	35.15[cd]
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	34.84[d]	34.80[d]
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	35.62[bc]	35.10[cd]
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	35.82[b]	35.85[b]
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	36.89[a]	36.64[a]
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	35.83[b]	35.34[c]
A7: Control (Restricted irrigation)	35.65[b]	35.10[cd]
CD (Agrochemical)	0.42	0.40
CV (Sulphur Sources and agrochemical)	1.25	1.2

Table 4.2.8.2: The interaction impact of treatments on harvest index of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	Harvest Index (2021-22)	Harvest Index (2022-23)
S1A0	34.23±0.21	34.18±0.65
S1A1	34.85±0.01	34.87±0.01
S1A2	34.47±0.75	34.51±0.73
S1A3	35.25±0.76	34.78±1.02
S1A4	35.46±0.02	35.57±0.02
S1A5	36.52±0.03	36.36±0.03
S1A6	35.47±0.04	35.06±0.04
S1A7	35.29±0.06	34.82±0.06
S2A0	34.70±0.78	35.58±0.65
S2A1	35.23±0.02	35.25±0.02
S2A2	34.86±0.02	34.92±0.02
S2A3	35.64±0.03	35.24±1.46
S2A4	35.86±1.33	35.94±0.02
S2A5	36.92±1.37	36.74±0.01
S2A6	35.84±0.25	35.44±0.01
S2A7	35.66±0.03	35.20±0.04
S3A0	35.67±0.74	34.54±0.44
S3A1	35.54±0.02	35.33±0.02
S3A2	35.18±0.03	34.98±0.03
S3A3	35.97±0.03	35.28±0.03
S3A4	36.15±0.03	36.04±0.03
S3A5	37.22±0.02	36.83±0.02
S3A6	36.18±0.02	35.52±0.02
S3A7	35.99±0.02	35.27±0.02
CV	1.25	1.2
CD	NS	0.75

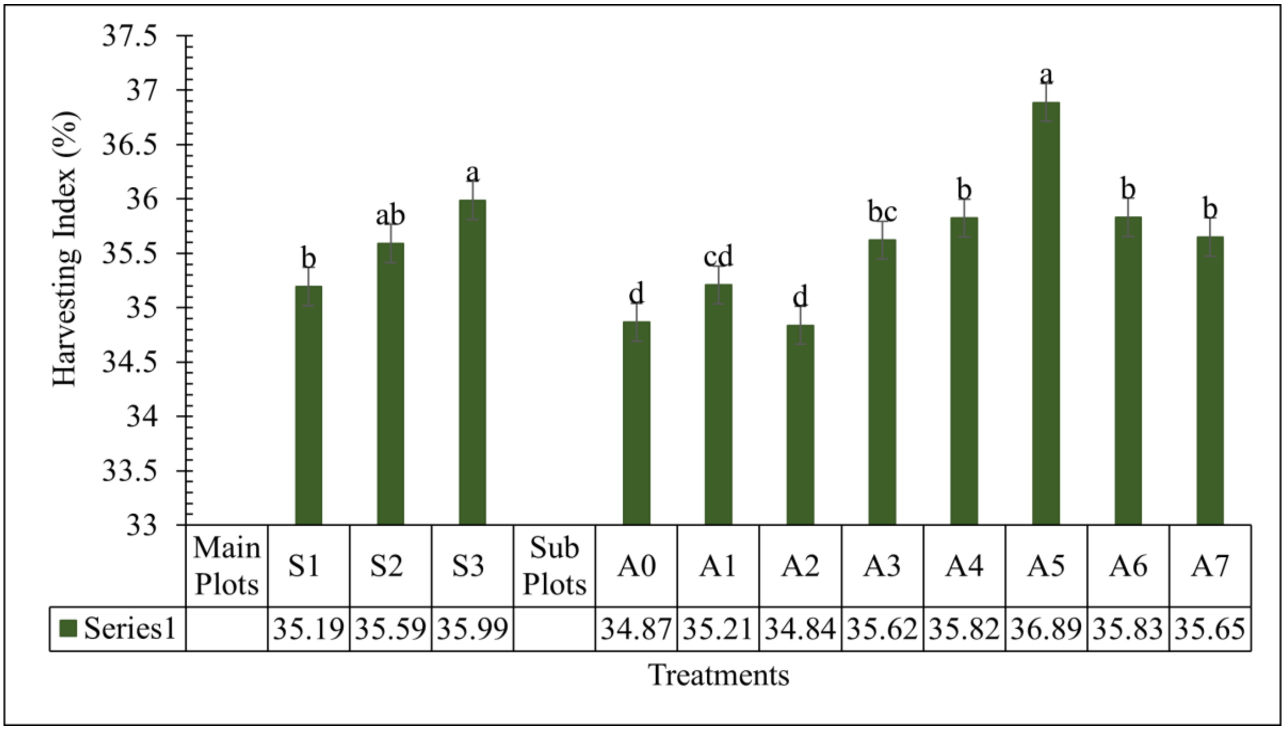


Fig. 4 .2.8.1 (a) Impact of sulphur sources and agrochemical treatments on harvest index in the year 2021-2022

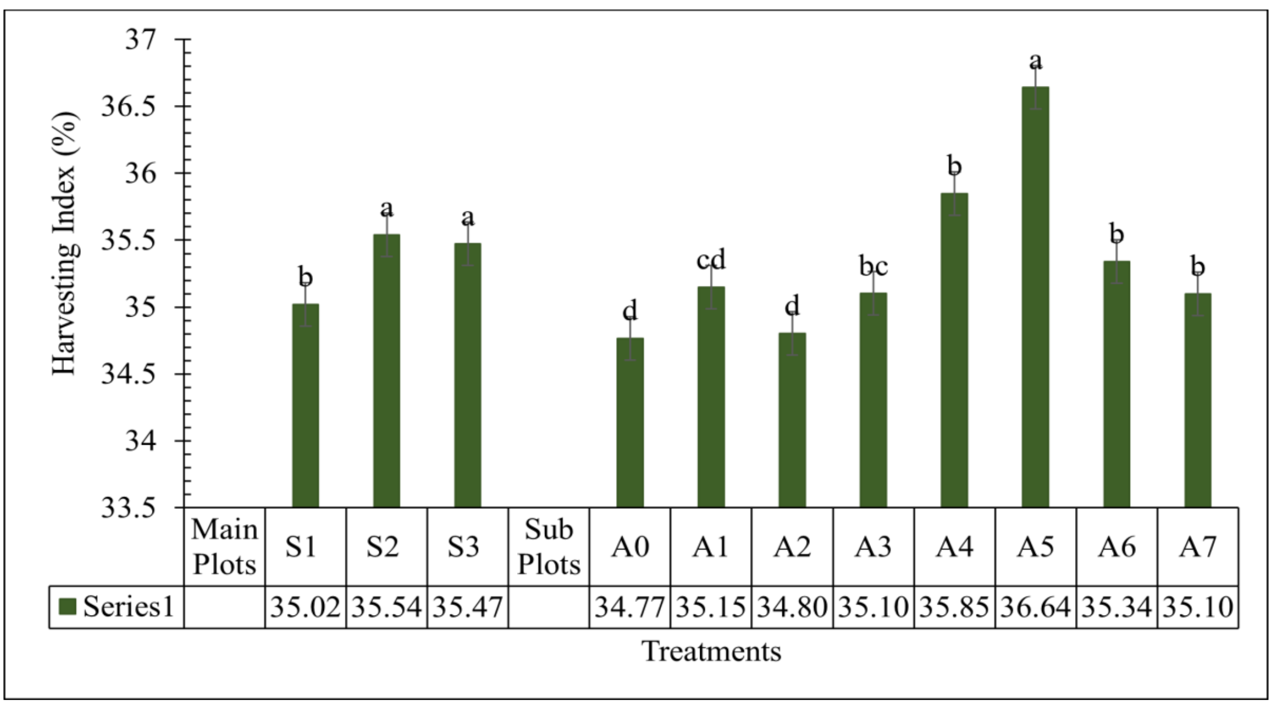


Fig. 4 .2.8.2 (b) Impact of sulphur sources and agrochemical treatments on harvest index in the year 2022-2023

4.3 Nutrient Uptake by Plant

4.3.1.1 N Content in Seeds (%): The nitrogen (N) content of seeds for the year 2021-2022 was markedly affected by both sulphur sources and agrochemical applications shown in Table and Figure 4.3.1.1(a), 4.3.1.2(b). The nitrogen content in seeds (%) was significantly affected by both sulphur sources and agrochemical treatments over both years of the research. Among different sulphur sources, Gypsum (S1) exhibited the greatest nitrogen concentration in seeds, measuring 2.34% in 2021–22 and 2.36% in 2022–23, followed by Bentonite Sulphur (S2) at 2.19% and 2.21%, respectively. The minimum values were recorded for Elemental Sulphur (S3) at 1.65% and 1.71%, indicating a significant reduction of 29.49% and 27.54%, respectively, in comparison to Gypsum. This demonstrates the continuing advantage of Gypsum compared to alternative sources in boosting nitrogen content. Hydrogel mixed with salicylic acid during the flowering and pod formation phases (A6) exhibited the highest nitrogen content in both years, recording 2.32% in 2021–22 and 2.36% in 2022–23, showing significant superiority over all other treatments. This was at par with the fully irrigated control (A0), which recorded 2.26% and 2.31%, respectively. The minimal nitrogen concentration was seen in the restricted irrigation control (A7), with values of 1.65% and 1.69%, indicating a reduction of 27.84% and 28.39% relative to A6. Treatments A1 to A5 exhibited moderate efficacy, with A4 and A5 demonstrating superior performance compared to the single applications of hydrogel or salicylic acid. Gypsum, as a sulphur source, together with the simultaneous application of hydrogel and salicylic acid at crucial stages (A6), had the highest efficacy in augmenting nitrogen content in Gobhi Sarson seedlings under controlled irrigation conditions. The nitrogen content in seeds was dramatically affected by the interaction of various sulphur sources and agrochemical treatments during the *rabi* seasons of 2021–22 and 2022– 23, as shown in Table 4.3.1.2. Treatment S1A6 exhibited the highest nitrogen concentration, registering 2.64% in 2021–22 and 2.66% in 2022–23. This treatment continuously surpassed all others and showed a significant enhancement relative to the lowest-performing treatment, S3A7, which exhibited nitrogen content of only 1.32% and 1.38% in the corresponding years. The nitrogen concentration under S1A6 exceeded that of S3A7 by 100% in 2021–22 and 92.75% in 2022–23, clearly demonstrating the advantageous impact of combining gypsum with hydrogel and salicylic acid. Alternative gypsum-based treatments, including S1A0 (2.57% and 2.60%) and S1A4 (2.48% and 2.49%), demonstrated elevated nitrogen content, indicating that gypsum served as the most effective sulphur source for enhancing nitrogen synthesis in seeds. Treatments utilizing bentonite sulphur (S2) exhibited moderate nitrogen levels, with S2A6 (2.47% and 2.49%) outperforming S2A7 (1.76% and 1.78%), indicating improvements of 40.34% and 39.88%, respectively, attributed to the incorporation of hydrogel and salicylic acid. Elemental sulphur treatments (S3) consistently exhibited the lowest nitrogen concentration, even after agrochemical application, signifying their restricted efficacy under the specified conditions. The interaction impact between sulphur sources and agrochemicals was statistically significant in both years, with gypsum in conjunction with hydrogel and salicylic acid identified as the most effective treatment for enhancing nitrogen content in Gobhi Sarson seed. The nitrogen (N) cycle in oilseed crops, like Gobhi Sarson, is a multifaceted process affected by several factors, including soil conditions, water availability, and agricultural practices. Under conditions of water stress, the nitrogen cycle can be markedly disturbed, resulting in diminished nitrogen uptake and assimilation by plants. Utilizing treatments such as hydrogels, salicylic acid, and other sulphur sources can alleviate these negative effects and improve nitrogen usage. Water stress negatively impacts the nitrogen cycle by restricting soil moisture, which is crucial for microbial activity that facilitates nitrogen mineralization—the transformation of organic nitrogen into inorganic forms accessible for plant uptake. Decreased soil moisture impedes the passage of nitrogen ions to plant roots, resulting in less nitrogen uptake (Albert et al., 2012; Keivanrad & Zandi, 2012; Khuntey et al., 2024; Móring et al., 2021). Furthermore, water stress can disrupt plant physiological processes, reducing the efficacy of nitrogen uptake into proteins and other essential chemicals. Hydrogels are superabsorbent polymers that can retain significant quantities of water to their mass. Integrating hydrogels into the soil improves its water retention ability, providing a more stable hydration supply to plants, particularly under drought conditions. This continuous moisture availability enhances microbial activity and nitrogen mineralization, hence promoting increased nitrogen uptake by plants. (El Idrissi et al., 2024; Y. Wu et al., 2023; Y. Zhang et al., 2023; Zhao, Zhang, et al., 2022). A study on Indian mustard (*Brassica juncea*) revealed that the application of hydrogel at 5.0 kg/ha, in conjunction with salicylic acid at 200 ppm throughout the flowering and siliqua formation stages, markedly enhanced growth, yield, and water usage efficiency in water- limited settings. Salicylic acid (SA) is a phytohormone that regulates numerous physiological processes, including stress reactions. The foliar spray of salicylic acid can improve a plant's resilience to abiotic conditions such as dehydration by regulating antioxidant enzyme activity and stabilizing photosynthetic processes. This enhanced stress tolerance allows plants to sustain nitrogen absorption and assimilation in unfavorable conditions. The study on Indian mustard indicated that foliar application of salicylic acid at 200 ppm throughout crucial growth phases, combined with hydrogel, resulted in substantial enhancements in yield and water usage efficiency. Sulphur (S) is an essential ingredient that significantly influences nitrogen metabolism in plants. Optimal sulphur availability promotes amino acid and protein synthesis, hence enhancing nitrogen consumption efficiency. Various sources of sulphur, including gypsum (calcium sulphate), bentonite sulphur, and elemental sulphur, exhibit differing degrees of solubility and accessibility to plants. Gypsum, because of its higher solubility, supplies readily accessible sulphate ions that can be swiftly absorbed by plants, facilitating nitrogen metabolism even in water-stressed conditions. The results indicated that treatments incorporating gypsum (S_1) alongside hydrogel and salicylic acid (S_1A_6) yielded the maximum nitrogen content in seeds, suggesting a synergistic effect on nitrogen uptake and assimilation. The experimental data demonstrated that the amalgamation of gypsum with hydrogel and salicylic acid, administered throughout both the flowering and pod formation stages (S_1A_6), resulted in the maximum nitrogen content in Gobhi Sarson seeds over two successive years. These results correspond with recent research on Indian mustard, indicating that the simultaneous application of hydrogel and salicylic acid in water-limited environments markedly enhanced productivity, profitability, and water usage efficiency. In conclusion, in conditions of water stress, the nitrogen cycle in oilseed crops may be negatively impacted, resulting in less nitrogen uptake and assimilation. The combined application of hydrogels, salicylic acid, and suitable sulphur sources such as gypsum can alleviate these effects by preserving soil moisture, augmenting stress resilience, and facilitating nitrogen metabolism, therefore boosting nitrogen levels in seeds and total crop yield (Bharati et al., 2024; Meena et al., 2020a).

Table 4.3.1.1: The impact of treatments on N content in seed of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	N content in seed (%) (2021-22)	N content in seed (%) (2022-23)
Sulphur sources		
S1: Gypsum	2.34^{a}	2.36^{a}
S2: Bentonite Sulphur	2.19^{b}	2.21^{b}
S3: Elemental Sulphur	1.65^{c}	1.71^{c}
CV (Sulphur Sources)	3.61	4.03
CD (Sulphur Sources)	0.06	0.07
Agrochemical		
A0: Control (Irrigation as per requirement)	2.26^{ab}	2.31^{a}
A1: Hydrogel (2.5 kg/ha) as basal application	2.02^{d}	2.06^{c}
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	1.91^{e}	1.96^{d}
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	1.98^{de}	2.01^{cd}
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	2.18^{bc}	2.21^{b}
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	2.14^{c}	2.18^{b}
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	2.32^{a}	2.36^{a}
A7: Control (Restricted irrigation)	1.65^{f}	1.69^{e}
CD (Agrochemical)	0.09	0.10
CV (Sulphur Sources and agrochemical)	4.77	4.81

Table 4.3.1.2: The interaction impact of treatments on N content in seed of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	N content in seed (%) (2021-22)	N content in seed (%) (2022-23)
S1A0	2.57±0.12	2.60±0.13
S1A1	2.29±0.02	2.32±0.02
S1A2	2.17±0.23	2.21±0.23
S1A3	2.25±0.33	2.27±0.33
S1A4	2.48±0.05	2.49±0.05
S1A5	2.43±0.06	2.46±0.06
S1A6	2.64±0.09	2.66±0.09
S1A7	1.87±0.09	1.91±0.09
S2A0	2.37±0.04	2.44±0.07
S2A1	2.15±0.04	2.17±0.04
S2A2	2.04±0.03	2.07±0.03
S2A3	2.11±0.04	2.12±0.04
S2A4	2.33±0.04	2.33±0.04
S2A5	2.28±0.03	2.30±0.09
S2A6	2.47±0.02	2.49±0.02
S2A7	1.76±0.05	1.78±0.05
S3A0	1.83±0.04	1.90±0.04
S3A1	1.61±0.03	1.68±0.03
S3A2	1.52±0.04	1.60±0.04
S3A3	1.58±0.04	1.64±0.04
S3A4	1.74±0.05	1.81±0.05
S3A5	1.71±0.03	1.78±0.03
S3A6	1.85±0.03	1.93±0.03
S3A7	1.32±0.03	1.38±0.03
CV	0.09	0.10
CD	0.16	0.17

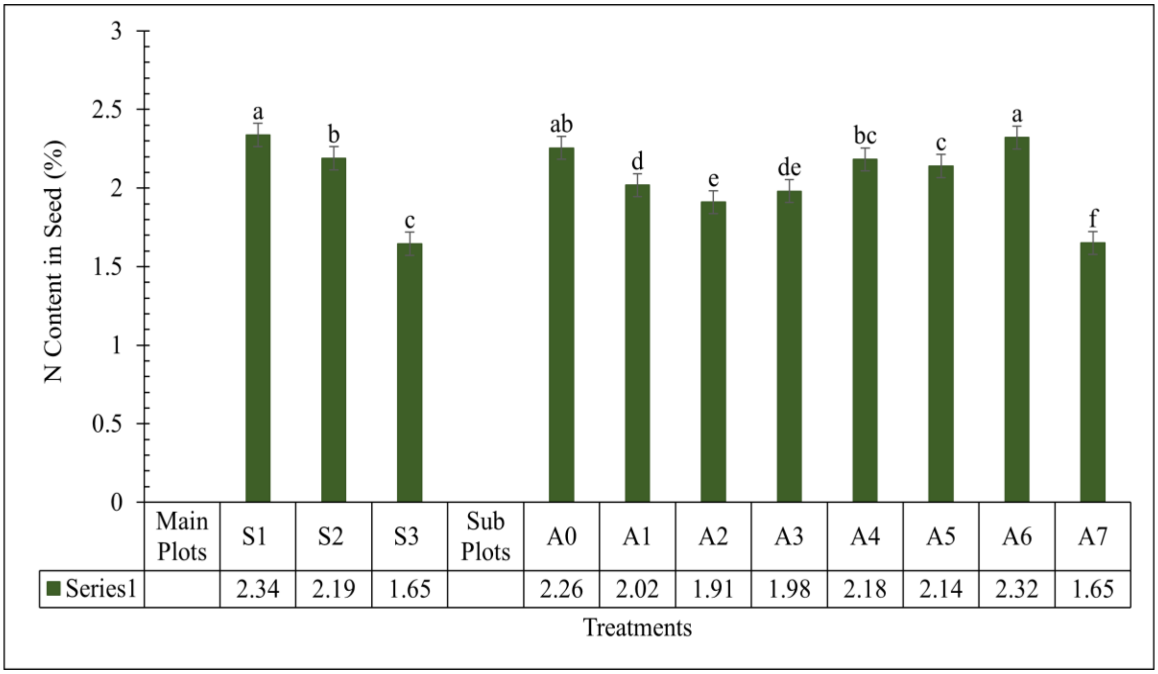


Fig:4.3.1.1(a) The impact of sulphur sources and agrochemical treatments on N content in seed in the year 2021-2022

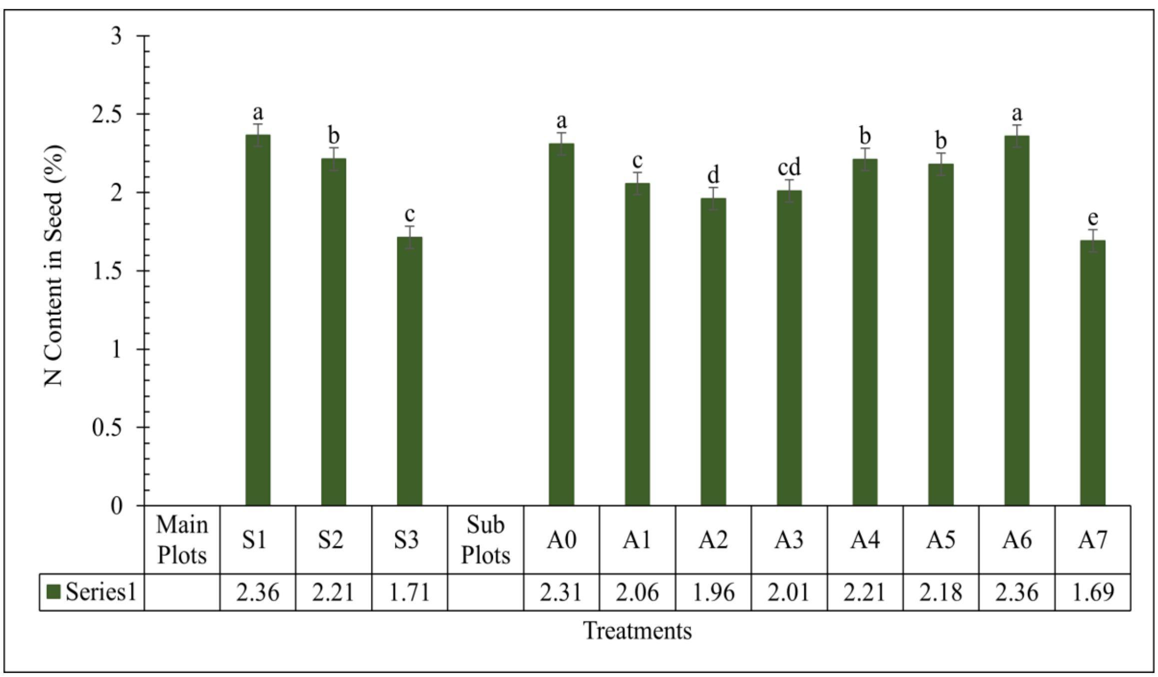


Fig:4.3.1.2(b) The impact of sulphur sources and agrochemical treatments on N content in seed in the year 2022-2023

4.3.2 N Content in Straw (%): The nitrogen (N) content in straw during the year 2021-2022 was markedly affected by the interplay between sulphur sources and agrochemicals treatments shown in Table 4.3.2.1 and Figure 4.3.2.1(a), 4.3.2.2(b). The nitrogen content in straw was significantly influenced by the various sources of sulphur and agrochemical treatments across both years of the study. Gypsum (S1) exhibited the highest nitrogen content in straw, measuring 0.33% in both the 2021–22 and 2022–23 periods. In contrast, Elemental Sulphur (S3) demonstrated the lowest nitrogen content at 0.20%, reflecting a significant reduction of 39.39% in both years when compared to Gypsum. Bentonite Sulphur (S2) exhibited intermediate characteristics, demonstrating a consistent and notable superiority of Gypsum compared to other forms of sulphur. The combined application of hydrogel and salicylic acid during the flowering and pod formation stages (A6) resulted in the highest nitrogen content in straw, measuring 0.33% in both years, significantly surpassing all other treatments. The lowest nitrogen content was recorded under restricted irrigation (A7), measuring 0.19% in 2021–22 and 0.20% in 2022–23, indicating a significant decrease of 42.42% and 39.39%, respectively, relative to A6. Among the individual treatments, the full irrigation control (A0) exhibited strong performance, recording 0.31% and 0.32%, with A4 and A5 following closely behind. Conversely, sole applications of salicylic acid (A2 and A3) and hydrogel (A1) exhibited lower nitrogen content, are superior to A7. Gypsum and the simultaneous application of hydrogel and salicylic acid at critical stages (A6) were the most effective treatments for enhancing nitrogen content in straw under controlled irrigation conditions.

The interaction of sulphur sources and agrochemical treatments considerably affected the straw's nitrogen (N) concentration over the 2021-22 growing season. The interaction of various sulphur sources and agrochemical treatments significantly affected the nitrogen content in straw during the 2021–22 and 2022–23 periods shown in Table 4.3.2.2. The treatment S1A6 exhibited the highest nitrogen content in straw, recording values of 0.40% in both years. This was closely followed by S1A0, which had values of 0.39% and 0.40%, and S1A4, with values of 0.35% and 0.36%. The lowest nitrogen content was observed in treatment S3A7 with values of 0.14% for 2021–22 and 0.15% for 2022–23. The nitrogen content in S1A6 was 185.7% higher in 2021–22 and 166.7% higher in 2022–23, indicating a significant benefit of incorporating gypsum with hydrogel and salicylic acid. Gypsum-based treatments enhanced with hydrogel or salicylic acid demonstrated consistent increases in nitrogen content. Bentonite sulphur treatments (S2) exhibited intermediate values, with S2A6 (0.34% and 0.35%) demonstrating superior performance compared to other treatments in this group, whereas S2A7 (0.20% and 0.21%) recorded the lowest values within its category. The nitrogen content under S2A6 increased by 70% in 2021–22 and by 66.7% in 2022–23 compared to S2A7. Elemental sulphur treatments (S3) consistently exhibited the lowest nitrogen content among the treatments, even in the presence of agrochemicals. S3A6 (0.24% and 0.25%) and S3A0 (0.23% and 0.23%) exhibited marginally enhanced values, but still fell significantly short of the levels recorded with gypsum. The data indicated a statistically significant interaction between sulphur sources and agrochemical applications. Gypsum-based treatments, especially when combined with hydrogel and salicylic acid, were found to be most effective in enhancing nitrogen content in the straw of Gobhi Sarson under controlled irrigation.

The fluctuations in nitrogen (N) concentration in straw under various treatments can be ascribed to the interaction of sulphur (S) sources, agrochemical applications, and their effects on plant physiological processes, particularly under water stress situations. Sulphur is essential in plant metabolism, contributing to the creation of amino acids like cysteine and methionine, which are vital for protein synthesis. Gypsum (S1), as a sulphur source, offers readily accessible sulphate, facilitating sulphur absorption and assimilation, hence increasing nitrogen integration into proteins. This leads to an increased nitrogen content in both seeds and straw. Bentonite sulphur (S2) releases sulphur at a slower rate, offering moderate advantages over an extended period. Elemental sulphur (S3) necessitates microbial oxidation before becoming accessible to plants, resulting in a delay in its efficacy and a reduction in nitrogen content within plant tissues. (Brar & Manhas, 2023; Kumawat Priyanka et al., 2021). The observed increases in nitrogen (N) levels in the straw of Gobhi Sarson (Brassica napus L.) under various sulphur sources and pesticide treatments can be properly credited to the physiological and biochemical functions of these sources in nitrogen uptake and assimilation. Gypsum ($CaSO_4 \cdot 2H_2O$), a highly soluble and readily available source of sulphate (SO_4^{2-}), significantly improved sulphur nutrition, essential for the synthesis of sulphur-containing amino acids (cysteine and methionine), coenzymes, and the activation of critical enzymes in nitrogen metabolism, notably nitrate reductase and glutamine synthetase. This enabled effective nitrate reduction and ammonium assimilation, leading to enhanced nitrogen integration into structural and metabolic proteins, therefore augmenting nitrogen levels in straw. In contrast, elemental sulphur demonstrated the poorest performance owing to its reliance on microbial oxidation for conversion into plant-available sulfate, a protracted process further hindered by inadequate soil moisture and temperature conditions. The utilization of hydrogel markedly enhanced soil moisture retention and diminished nitrogen losses through leaching, thus preserving an ideal root-zone environment that promoted root growth, nutrient solubility, and sustained nitrogen uptake. Salicylic acid, known as a regulatory molecule, enhanced nitrogen metabolism by increasing root activity, upregulating nitrogen transporter genes, and boosting nitrate reductase activity, while also improving photosynthetic efficiency and stress tolerance under regulated irrigation conditions. The exceptional efficacy of the S1A6 treatment over both years can be ascribed to the synergistic interaction of accessible sulphur with optimized soil moisture patterns and enhanced nitrogen metabolic processes, resulting in the highest nitrogen concentration in straw (AbdElgawad et al., 2022; Anas et al., 2020; Chaudhary et al., 2023a; Jarecki et al., 2024).

Likewise, the administration of salicylic acid (SA) at 50% flowering (A2) and 50% pod development (A3) affects nitrogen metabolism by regulating stress responses. SA is recognized for augmenting the activity of nitrate reductase, a crucial enzyme in nitrogen assimilation. In mungbean cultivars, salicylic acid mitigated the decline in photosynthesis caused by salt stress by enhancing nitrogen and sulphur uptake and optimizing antioxidant metabolism (Nazar et al., 2011). The integration of hydrogel with salicylic acid (A4, A5, A6) yields synergistic advantages by augmenting soil moisture retention and concurrently bolstering stress tolerance systems. This dual impact enhances nutrient absorption and assimilation, resulting in elevated nitrogen levels in seeds and straw. Research on Indian mustard has shown that the simultaneous application of hydrogel and salicylic acid markedly enhanced productivity, profitability, and water usage efficiency. In contrast, limited irrigation (A7) induces considerable water stress, adversely affecting nutrient absorption and assimilation. In water-deficient conditions, root hydraulic conductivity diminishes, restricting nitrogen uptake from the soil and resulting in decreased nitrogen levels in plant tissues. The varying impacts of sulphur sources and agrochemical treatments on nitrogen levels in oilseed crops are influenced by their contributions to nutrient availability, absorption efficiency, and stress alleviation. Gypsum acts as a potent sulphur source by supplying accessible sulphate for nitrogen assimilation. Hydrogel boosts soil moisture retention, promoting nitrogen assimilation during drought conditions, whereas salicylic acid improves nitrogen metabolism by regulating enzyme activity and stress responses. The integration of hydrogel and salicylic acid yields substantial enhancements, as evidenced by current research, by alleviating stress impacts and enhancing nutrient uptake for improved agricultural output (Ding et al., 2018; Flynn et al., 2023; Mahto et al., 2023a; Martinez et al., 2024; Tadvani et al., 2024; Tariq et al., 2023). These studies support the observed results, indicating that the combined use of hydrogel and foliar nutrition sprays can enhance nitrogen content in seeds and straw by improving soil moisture availability and providing essential nutrients during critical growth stages. This integrated approach leads to improved nitrogen assimilation, increased yield attributes, and overall productivity in oilseed crops.

Table 4.3.2.1: The impact of treatments on N Content in Straw (%) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	N Content in Straw (2021-22)	N Content in Straw (2022-23)
Sulphur sources		
S1: Gypsum	0.33^{a}	0.33^{a}
S2: Bentonite Sulphur	0.27^{b}	0.28^{b}
S3: Elemental Sulphur	0.20^{c}	0.20^{c}
CV (Sulphur Sources)	3.22	4.92
CD (Sulphur Sources)	0.007	0.009
Agrochemical		
A0: Control (Irrigation as per requirement)	0.31^{b}	0.32^{a}
A1: Hydrogel (2.5 kg/ha) as basal application	0.25^{e}	0.25^{d}
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	0.23^{f}	0.24^{e}
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	0.24^{f}	0.25^{de}
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	0.29^{c}	0.30^{b}
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	0.27^{d}	0.28^{c}
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	0.33^{a}	0.33^{a}
A7: Control (Restricted irrigation)	0.19^{g}	0.20^{f}
CD (Agrochemical)	0.011	0.013
CV (Sulphur Sources and agrochemical)	4.52	4.25

Table 4.3.2.2: The interaction impact of treatments on N Content in Straw (%) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	N Content in Straw (2021-22)	N Content in Straw (2022-23)
S1A0	0.39±0.02	0.40±0.02
S1A1	0.31±0.01	0.31±0.01
S1A2	0.29±0.01	0.29±0.01
S1A3	0.29±0.01	0.30±0.01
S1A4	0.35±0.03	0.36±0.04
S1A5	0.33±0.01	0.34±0.01
S1A6	0.40±0.01	0.40±0.01
S1A7	0.24±0.02	0.24±0.02
S2A0	0.32±0.01	0.34±0.01
S2A1	0.26±0.01	0.26±0.01
S2A2	0.24±0.01	0.25±0.01
S2A3	0.25±0.00	0.26±0.00
S2A4	0.30±0.00	0.31±0.00
S2A5	0.28±0.00	0.29±0.00
S2A6	0.34±0.00	0.35±0.00
S2A7	0.20±0.01	0.21±0.01
S3A0	0.23±0.01	0.23±0.02
S3A1	0.19±0.01	0.19±0.01
S3A2	0.17±0.01	0.18±0.01
S3A3	0.18±0.00	0.18±0.00
S3A4	0.21±0.00	0.22±0.00
S3A5	0.20±0.01	0.21±0.01
S3A6	0.24±0.01	0.25±0.01
S3A7	0.14±0.01	0.15±0.01
CV	4.52	4.25
CD	0.020	0.022

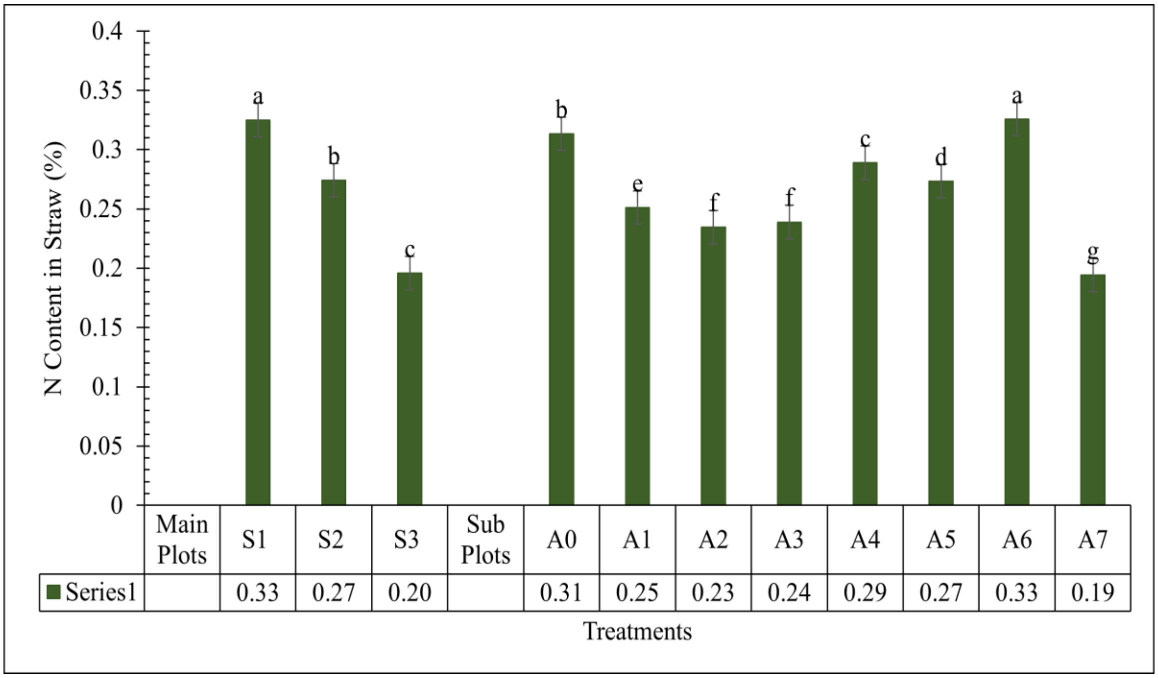


Fig. 4 .3.2.1 (a) The impact of sulphur sources and agrochemical treatments on N Content in Straw (%) in the year 2021-2022

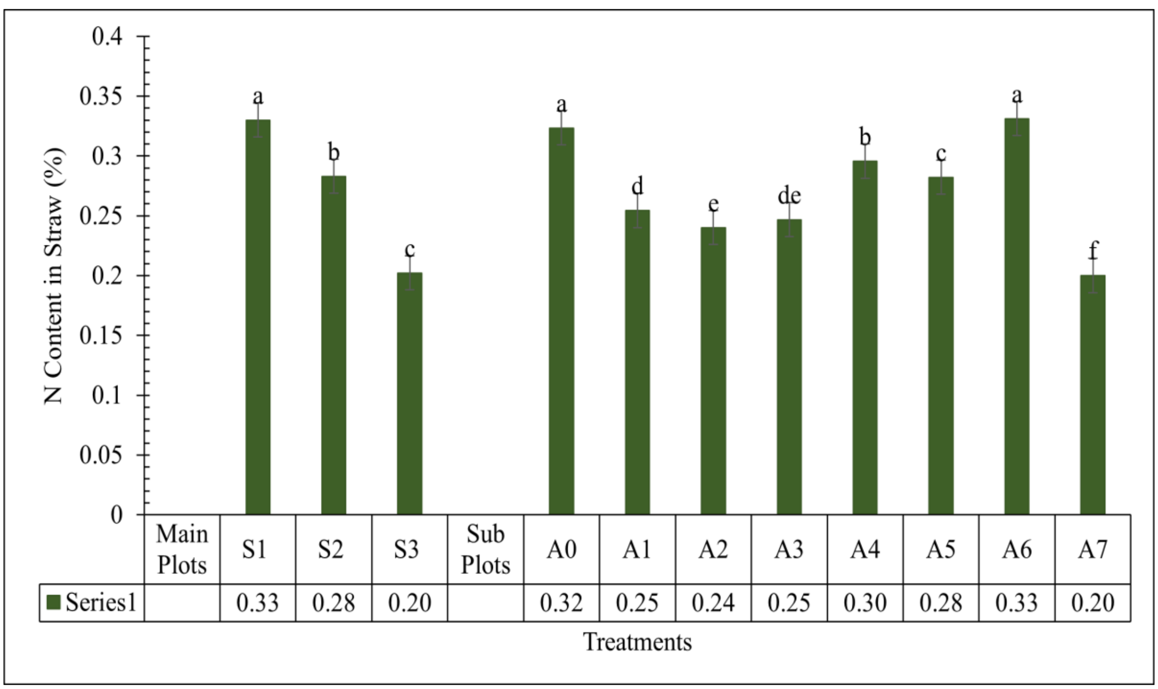


Fig. 4 .3.2.2 (b) The impact of sulphur sources and agrochemical treatments on N Content in Straw (%) in the year 2022-2023

4.3.3 N uptake by Seed (Kg/ha): Nitrogen (N) uptake by seeds was markedly affected by sulphur sources and agrochemical applications during both growth seasons (2021-22 and 2022-23), as presented in Table 4.3.3.1 and Figure 4.3.3.1(a), 4.3.3.2(b). Gypsum (S1) exhibited the highest nitrogen uptake among sulphur sources, with 47.12 kg/ha in 2021–22 and 48.49 kg/ha in 2022– 23, greatly surpassing both Bentonite Sulphur (S2) and Elemental Sulphur (S3). The minimal nitrogen uptake was recorded with Elemental Sulphur (S3) at 23.43 kg/ha and 24.60 kg/ha, reflecting a significant decline of 50.27% in 2021–22 and 49.28% in 2022–23 relative to Gypsum, hence underscoring Gypsum's efficacy in improving nitrogen assimilation. The combined application of hydrogel and salicylic acid during the flowering and pod formation stages (A6) yielded the maximum nitrogen uptake by seed, measuring 47.72 kg/ha in 2021–22 and 49.24 kg/ha in 2022–23, greatly surpassing all other treatments. Subsequently, full irrigation control (A0) recorded 43.88 kg/ha and 46.13 kg/ha, respectively. The minimum uptake was seen with restricted irrigation (A7) at 23.37 kg/ha and 24.36 kg/ha, indicating a significant reduction of 51.05% and 50.52%, respectively, in comparison to A6. Intermediate values were recorded in A4 and A5, however, the exclusive applications of hydrogel (A1) and salicylic acid (A2 and A3) exhibited comparatively reduced uptake, albeit still significantly superior to the restricted irrigation control. Gypsum, as a source of sulphur, along with the concurrent application of hydrogel and salicylic acid during flowering and pod development (A6), had the highest efficacy in enhancing nitrogen assimilation by seeds in Gobhi Sarson under controlled irrigation conditions.

Table 4.3.3.2 illustrates that the interaction of sulphur sources and agrochemical treatments considerably affected nitrogen uptake by seeds in both years of the research. In the years 2021–22 and 2022–23, the treatment S1A6 had the maximum nitrogen assimilation, recording 61.09 kg/ha and 63.01 kg/ha, respectively. This treatment surpassed the control (S1A0) by 8.4% in 2021–22 and 8.7% in 2022–23, underscoring the efficacy of combining agrochemicals with gypsum. The minimal nitrogen uptake was observed in S3A7 with values of 14.83 kg/ha and 15.81 kg/ha. In contrast, S1A6 exhibited a 312% rise in 2021–22 and a 298% increase in 2022–23, indicating a significant enhancement in nutrient assimilation attributable to the synergistic application of gypsum and agrochemicals. In the bentonite sulphur-based treatments (S2), the highest uptake was observed in S2A6 (51.80 and 52.76 kg/ha), exceeding the control S2A0 (46.56 and 50.63 kg/ha) by 16.6% and 4.1% in the corresponding years. The group had the lowest nitrogen uptake in S2A7 (25.36 and 26.10 kg/ha), rendering S2A6 superior by 104% and 102% in 2021–22 and 2022–23, respectively. In the elemental sulphur treatments (S3), S3A6 exhibited the highest uptake (30.29 and 31.96 kg/ha), whereas S3A7 demonstrated the lowest uptake. S3A6 exhibited 104% and 102% greater uptake than S3A7 in the corresponding years, remaining much lower than the gypsum- based treatments. Statistical analysis verified the significance of treatment interaction on nitrogen assimilation by seeds. The combination of gypsum, hydrogel, and salicylic acid (S1A6) consistently yielded the best nitrogen uptake in both seasons, demonstrating its better effectiveness in improving nitrogen assimilation in Gobhi Sarson under controlled irrigation.

Sulphur is needed for the synthesis of amino acids, such as cysteine and methionine, which are vital for protein production and nitrogen metabolism in plants. The elevated nitrogen assimilation observed in gypsum (S1) treatments is due to its easily accessible sulphate form, which plants may rapidly assimilate. Gypsum facilitates sulphur uptake, hence augmenting nitrogen efficiency and promoting total plant development. This aligns with research indicating that gypsum markedly enhances nitrogen assimilation and agricultural yields (Z. Yu et al., 2018a). Conversely, bentonite sulphur (S2), which releases sulphur more gradually, facilitated a considerable degree of nitrogen uptake due to the slower availability of sulphur. Bentonite sulphur, although beneficial, has a slower release rate than gypsum, leading to a less immediate enhancement in nitrogen uptake. Elemental sulphur (S3) necessitates microbial oxidation to transform into a plant- accessible form, leading to delayed efficacy and, as a result, the lowest nitrogen uptake levels in both years. The postponed release limits sulphur's accessibility, obstructing the production of sulphur-containing amino acids and hampering nitrogen uptake. Prior research has demonstrated that the delayed availability of elemental sulphur may result in diminished crop performance relative to alternative sulphur sources (Shanmugavel et al., 2023a).

The utilization of hydrogel (A1) and salicylic acid (A2, A3) at distinct phases of plant development (50% flowering and 50% pod formation) is crucial for enhancing water use efficiency and nutrient assimilation, especially in times of water stress. Hydrogel functions by enhancing the soil's water retention capacity, so ensuring a consistent water supply and mitigating water stress. This enhances root function, resulting in improved nutrient uptake, particularly nitrogen. Research on Indian mustard (*Brassica juncea*) indicates that hydrogel application enhances production and water use efficiency, particularly in water-deficient environments This corresponds with the increased nitrogen assimilation in hydrogel treatments, especially when integrated with salicylic acid (A4, A5, A6), which additionally alleviates stress and enhances nutrient uptake (Abobatta, 2018; Narayan et al., 2023a; A. Singh & Singh, 2021; Yadav & Garg, 2024)ingh, 2021; Yadav & Garg, 2024). Salicylic acid (A2, A3) is a plant hormone recognized for its function in regulating stress responses, especially during unfavorable conditions like as drought. Its application has demonstrated the enhancement of important enzymes involved in nitrogen metabolism, such as nitrate reductase, therefore enhancing nitrogen assimilation. The amalgamation of hydrogel and salicylic acid (A4, A5, A6) significantly improves the accessibility of water and nutrients, resulting in a synergistic effect that optimizes nitrogen assimilation. In both years, the S1A6 treatment (gypsum + hydrogel + salicylic acid during flowering and pod formation) had the maximum nitrogen uptake, underscoring the efficacy of this combination in mitigating water stress and enhancing nutrient efficiency. (Liu et al., 2022a). The constrained irrigation treatment (A7) yielded the minimal nitrogen uptake across all sulphur source treatments, with S3A7 exhibiting the lowest nitrogen uptake values. Water stress diminishes the capacity of roots to absorb water and nutrients, especially nitrogen, which necessitates sufficient soil moisture for optimal uptake. The decline in nitrogen uptake under restricted irrigation is ascribed to diminished root hydraulic conductivity and constrained availability of water-soluble nutrients. Previous study indicates that water stress can severely hinder nutrient assimilation, making it essential to implement ways to alleviate this stress for optimal plant health and productivity. Nonetheless, the administration of gypsum (S1) alleviated the adverse consequences of water stress. Gypsum improves soil structure and enhances nutrient retention, hence increasing the availability of sulphur and nitrogen to plants, even with limited irrigation. This elucidates why the S1A7 treatment (gypsum under restricted irrigation) exhibited superior nitrogen uptake compared to other sulphur sources under conditions of water constraint. The higher nitrogen assimilation observed in gypsum treatments (S1) can be attributed to the better sulphur assimilation, which facilitates nitrogen metabolism in plants. When easily available, sulphur enhances the production of sulphur-containing amino acids, which are crucial for protein synthesis and the development of enzymes involved in nitrogen metabolism. Gypsum serves as a rapid- release sulphur source, guaranteeing sulphur availability during the growing season, hence promoting continuous nitrogen uptake and assimilation. The interaction between hydrogel and salicylic acid elucidates the improved nitrogen assimilation. Hydrogel enhances soil moisture retention, whereas salicylic acid amplifies the plant's physiological reaction to stress by regulating essential biochemical pathways related to nutrient assimilation. The integration of both treatments improves plant resilience, water use efficiency, and nutrient assimilation under both normal and stressed conditions, as seen by the elevated nitrogen uptake values observed in S1A6 (Bolhassani et al., 2024; Ciríaco Da Silva et al., 2010; Juhász et al., 2024; Tian et al., 2023; Zayed et al., 2023).

The results underscore the significance of sulphur sources and agrochemical applications in improving nitrogen uptake in oilseed crops. Gypsum demonstrated the most efficacy as a sulphur source, markedly enhancing nitrogen uptake, particularly when utilized in conjunction with hydrogel and salicylic acid. The findings underscore the impact of water stress on nutritional assimilation and the efficacy of interventions like gypsum and hydrogel in alleviating these consequences. These findings correspond with recent research indicating that integrated strategies combining sulphur control and agrochemical applications might enhance nutrient usage efficiency, particularly in water-scarce environments.

Table 4.3.3.1: The impact of treatments on N uptake by Seed of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	N uptake by Seed (Kg/ha) (2021-22)	N uptake by Seed (Kg/ha) (2022-23)
Sulphur sources		
S1: Gypsum	47.12^{a}	48.49^{a}
S2: Bentonite Sulphur	39.75^{b}	40.79^{b}
S3: Elemental Sulphur	23.43^{c}	24.60^{c}
CV (Sulphur Sources)	5.86	6.25
CD (Sulphur Sources)	1.73	1.90
Agrochemical		
A0: Control (Irrigation as per requirement)	43.88^{b}	46.13^{b}
A1: Hydrogel (2.5 kg/ha) as basal application	34.26^{d}	35.39^{d}
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	30.17^{e}	31.46^{e}
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	32.63^{de}	33.28^{de}
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	40.75^{c}	41.61^{c}
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	41.37^{bc}	42.20^{c}
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	47.72^{a}	49.24^{a}
A7: Control (Restricted irrigation)	23.37^{f}	24.36^{f}
CD (Agrochemical)	2.60	2.74
CV (Sulphur Sources and agrochemical)	7.43	7.59

Table 4.3.3.2: The interaction impact of treatments on N uptake by Seed of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	N uptake by Seed (Kg/ha) (2021-22)	N uptake by Seed (Kg/ha) (2022-23)
S1A0	56.35±3.86	57.99±3.66
S1A1	43.85±0.37	45.29±0.38
S1A2	38.73±6.73	40.35±6.87
S1A3	41.93±9.03	42.82±10.08
S1A4	52.17±1.06	53.25±1.07
S1A5	52.97±1.50	54.00±1.51
S1A6	61.09±2.20	63.01±2.25
S1A7	29.91±1.53	31.18±1.56
S2A0	46.56±2.51	50.63±2.11
S2A1	37.19±0.70	37.92±0.71
S2A2	32.68±0.48	33.64±0.48
S2A3	35.31±0.84	35.52±0.84
S2A4	44.23±0.77	44.58±0.77
S2A5	44.90±0.58	45.21±1.77
S2A6	51.80±1.21	52.76±0.41
S2A7	25.36±0.78	26.10±0.81
S3A0	28.75±1.10	29.78±1.00
S3A1	21.73±0.40	22.98±0.41
S3A2	19.10±0.51	20.37±0.52
S3A3	20.64±0.64	21.51±0.64
S3A4	25.86±0.76	27.02±0.77
S3A5	26.25±0.45	27.40±0.45
S3A6	30.29±0.48	31.96±0.49
S3A7	14.83±0.33	15.81±0.34
CV	7.43	7.59
CD	4.53	4.80

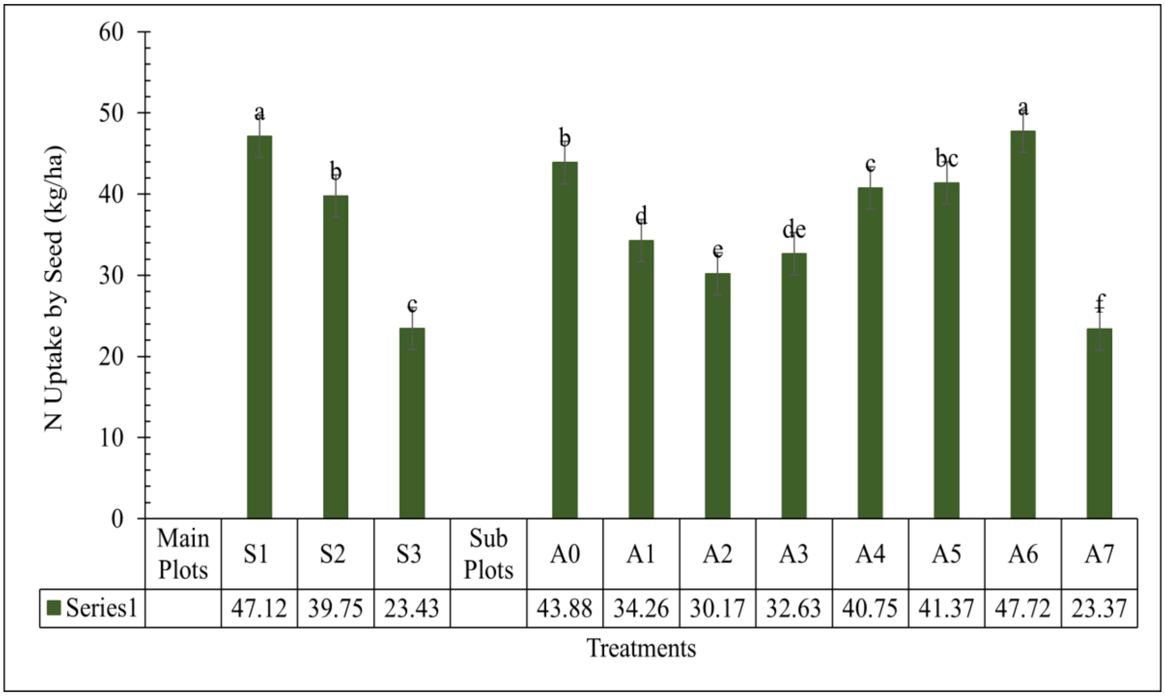


Fig:4.3.3.1(a) The impact of sulphur sources and agrochemical treatments on N uptake by Seed in the year 2021-2022

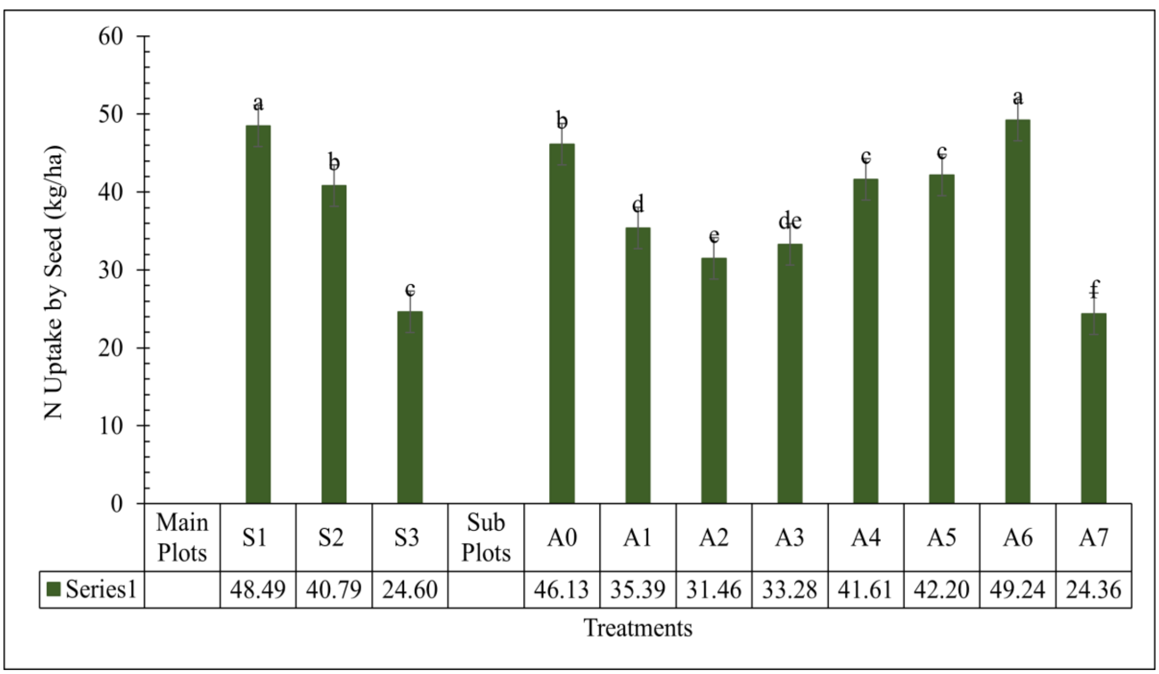


Fig:4.3.3.2(b) The impact of sulphur sources and agrochemical treatments on N uptake by Seed in the year 2022-2023

4.3.4 N uptake by Straw: Nitrogen (N) assimilation by straw is shown in Table 4.3.4.1 and Figure 4.3.4.1(a), 4.3.4.2(b) depict considerable variation across various sulphur sources and agrochemicals treatments during the two years (2021–22 and 2022–23). Among different the sulphur sources, Gypsum (S1) had the greatest nitrogen uptake in straw with 12.11 kg/ha in 2021–22 and 12.64 kg/ha in 2022–23, which was significantly higher than Bentonite Sulphur (S2) and Elemental Sulphur (S3). Elemental Sulphur (S3) at 5 kg/ha and 5.30 kg/ha recorded the lowest levels, indicating a significant drop of 58.71% in 2021-22 and 58.07% in 2022-23 when compared to Gypsum. Among agrochemical treatments, Hydrogel + Salicylic acid applied at both flowering and pod formation stages (A6) achieved the maximum nitrogen uptake in straw with 12.14 kg/ha in 2021–22 and 12.78 kg/ha in 2022–23, especially surpassing every other treatment. The full irrigation control (A0) came next, showing 11.60 kg/ha and 12.26 kg/ha, respectively. Under limited irrigation (A7), with values of 5.01 kg/ha and 5.42 kg/ha, the lowest uptake was observed, indicating a significant decrease of 58.72% and 57.61%, respectively, relative to A6. Combined treatments A4 and A5 produced intermediate nitrogen uptake levels; on the other hand, single applications of hydrogel (A1) and salicylic acid (A2 and A3) exhibited relatively reduced uptake. Statistically comparable, treatments A2 and A3 were much lower than the combined and control treatments. Gypsum's use and the hydrogel and salicylic acid combine at both flowering and pod formation phases (A6) were more successful in increasing nitrogen assimilation by straw in Gobhi Sarson.

During both *rabi* seasons, the use of various sulphur sources in combination with hydrogel and salicylic acid positively affected nitrogen uptake by the straw illustrated in Table 4.3.4.2. With 16.74 kg/ha in 2021–22 and 17.64 kg/ha in 2022–23, S1A6 (gypsum + hydrogel + salicylic acid) reported the maximum nitrogen uptake by straw among all treatments. Over the control treatment S1A0 (16.59 and 17.06 kg/ha), this was an increase of 0.9% in 2021–22 and 3.4% in 2022–23. S1A7 (6.91 and 7.48 kg/ha) recorded the lowest uptake in this group; S1A6, on the other hand, exhibited a significant improvement of 142.2% and 135.8%, respectively, during the two seasons. Treatment S2A6 (12.70 and 13.26 kg/ha) in the bentonite sulphur group was the most effective, showing an 8.5% rise in 2021–22 and a 3.8% increase in 2022–23 above its corresponding control S2A0 (11.70 and 12.77 kg/ha). S2A7 (5.24 and 5.62 kg/ha) had the lowest value in this group; S2A6 surpassed it by 142.4% and 135.9%, respectively. Likewise, in the elemental sulphur group, S3A6 (6.99 and 7.44 kg/ha) showed the highest nitrogen uptake by straw, which was 7.4% higher in 2021–22 and 7.2% higher in 2022–23 than the control S3A0 (6.51 and 6.94 kg/ha). S3A7 (2.89 and 3.15 kg/ha) was the lowest in this group; S3A6 exceeded this by 142% and 135.7%, respectively. All things considered, the most successful treatment to increase nitrogen uptake by straw in Gobhi Sarson under controlled irrigation was the combination application of gypsum, hydrogel, and salicylic acid (S1A6).

Nitrogen (N) assimilation by straw was markedly affected by sulphur (S) sources, hydrogel, and salicylic acid (SA) treatments, revealing substantial interactions among these variables. Among the sulphur sources, gypsum (S1) yielded the greatest nitrogen assimilation, followed by bentonite sulphur (S2) and elemental sulphur (S3). This pattern can be ascribed to variations in sulphur availability and the efficiency of plant uptake. Gypsum provides readily available sulphate (SO_4^{2-}), improving sulphur assimilation and stimulating the production of amino acids (cysteine and methionine), hence facilitating nitrogen incorporation into proteins. Bentonite sulphur necessitates microbial oxidation, resulting in modest nitrogen uptake, whereas elemental sulphur exhibits the slowest oxidation rate, leading to markedly reduced nitrogen assimilation. The results align with (Chaudhary et al., 2023b), who indicated that sulphur fertilizer augments nitrogen metabolism by enhancing protein synthesis and enzyme activity. The application of hydrogel (A1, A4, A5, and A6) markedly improved nitrogen assimilation by augmenting soil moisture retention, which diminished nitrogen leaching and increased microbial activity. Enhanced soil water availability augmented nitrogen mobility in the soil solution and promoted root uptake, resulting in higher nitrogen assimilation in plant tissues. (Piccoli et al., 2024) reported analogous findings, noting that hydrogel application enhances water retention and nitrogen use efficiency in drought-prone environments. The concurrent use of hydrogel and salicylic acid (A6) yielded the greatest nitrogen assimilation, demonstrating a synergistic impact of moisture retention and stress mitigation mechanisms.

Salicylic acid (A2, A3, A4, A5, and A6) significantly contributed to the enhancement of nitrogen assimilation, principally via boosting nitrogen metabolism and stress resilience. SA stimulates nitrate reductase, a crucial enzyme that facilitates the transformation of nitrate (NO_3^-) into ammonium (NH_4^+), vital for amino acid production. Furthermore, SA augments the expression of nitrogen transporters, hence enhancing nitrogen assimilation efficiency (Paul et al., 2022). Furthermore, SA has demonstrated the ability to alleviate oxidative stress, which may otherwise hinder enzymatic processes associated with nitrogen assimilation. Water stress, shown in A7 (limited irrigation), markedly decreased nitrogen uptake from all sulphur sources. The decrease is mainly attributable to diminished root hydraulic conductivity, decreased transpiration rates, and suppressed enzyme activity associated with nitrogen assimilation. Drought conditions impede nitrogen transfer from the soil solution to plant roots, resulting in diminished nitrogen availability for metabolic processes. A study indicated that water deficiency situations hinder nitrogen metabolism by diminishing nitrate reductase activity and obstructing amino acid synthesis. The interaction analysis indicated that S1A6 (gypsum + hydrogel + SA during 50% flowering and pod development) exhibited the best nitrogen uptake, underscoring the significance of combining sulphur fertilization, moisture retention, and stress alleviation techniques to optimize nitrogen consumption. In contrast, S3A7 (elemental sulphur + restricted irrigation) displayed the lowest nitrogen uptake, indicating that delayed sulphur availability and water stress significantly impede nitrogen metabolism (Negrão et al., 2017; Saud et al., 2017; Soni et al., 2021; Umnajkitikorn et al., 2021; R. Zhang et al., 2024; Y. M. Zhang et al., 2013).

The research highlights the essential importance of sulphur availability, water retention techniques, and stress management in enhancing nitrogen assimilation. The findings indicate that gypsum is the preferred sulphur source, whereas hydrogel and salicylic acid should be utilized together to improve nitrogen assimilation, particularly in water-scarce environments. These findings establish a robust scientific foundation for integrated nutrient and water management methods aimed at enhancing nitrogen usage efficiency and crop output in oilseed crops.

Table 4.3.4.1: The impact of treatments on N uptake by Straw of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	N uptake by Straw (2021-22)	N uptake by Straw (2022-23)
Sulphur sources		
S1: Gypsum	12.11[a]	12.64[a]
S2: Bentonite Sulphur	9.07[b]	9.50[b]
S3: Elemental Sulphur	5.00[c]	5.30[c]
CV (Sulphur Sources)	2.84	5.63
CD (Sulphur Sources)	0.20	0.42
Agrochemical		
A0: Control (Irrigation as per requirement)	11.60[b]	12.26[b]
A1: Hydrogel (2.5 kg/ha) as basal application	7.92[e]	8.18[e]
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	7.01[f]	7.25[f]
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	7.17[f]	7.65[f]
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	9.76[c]	10.09[c]
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	9.20[d]	9.55[d]
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	12.14[a]	12.78[a]
A7: Control (Restricted irrigation)	5.01[g]	5.42[g]
CD (Agrochemical)	0.48	0.49
CV (Sulphur Sources and agrochemical)	5.8	5.63

Table 4.3.4.2: The interaction impact of treatments on N uptake by Straw of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	N uptake by Straw (2021-22)	N uptake by Straw (2022-23)
S1A0	16.59±0.97	17.06±0.78
S1A1	10.92±0.36	11.29±0.37
S1A2	9.66±0.53	10.01±0.54
S1A3	9.89±0.60	10.56±0.75
S1A4	13.45±1.26	13.92±1.58
S1A5	12.69±0.25	13.18±0.26
S1A6	16.74±0.42	17.64±0.44
S1A7	6.91±0.48	7.48±0.50
S2A0	11.70±0.19	12.77±0.35
S2A1	8.28±0.38	8.48±0.39
S2A2	7.33±0.27	7.52±0.27
S2A3	7.50±0.15	7.94±0.66
S2A4	10.21±0.73	10.47±0.13
S2A5	9.63±0.67	9.91±0.10
S2A6	12.70±0.33	13.26±0.18
S2A7	5.24±0.34	5.62±0.35
S3A0	6.51±0.22	6.94±0.51
S3A1	4.56±0.22	4.76±0.22
S3A2	4.03±0.28	4.22±0.28
S3A3	4.13±0.11	4.45±0.11
S3A4	5.62±0.13	5.87±0.13
S3A5	5.30±0.23	5.55±0.24
S3A6	6.99±0.26	7.44±0.27
S3A7	2.89±0.18	3.15±0.19
CV	5.8	5.63
CD	0.80	0.89

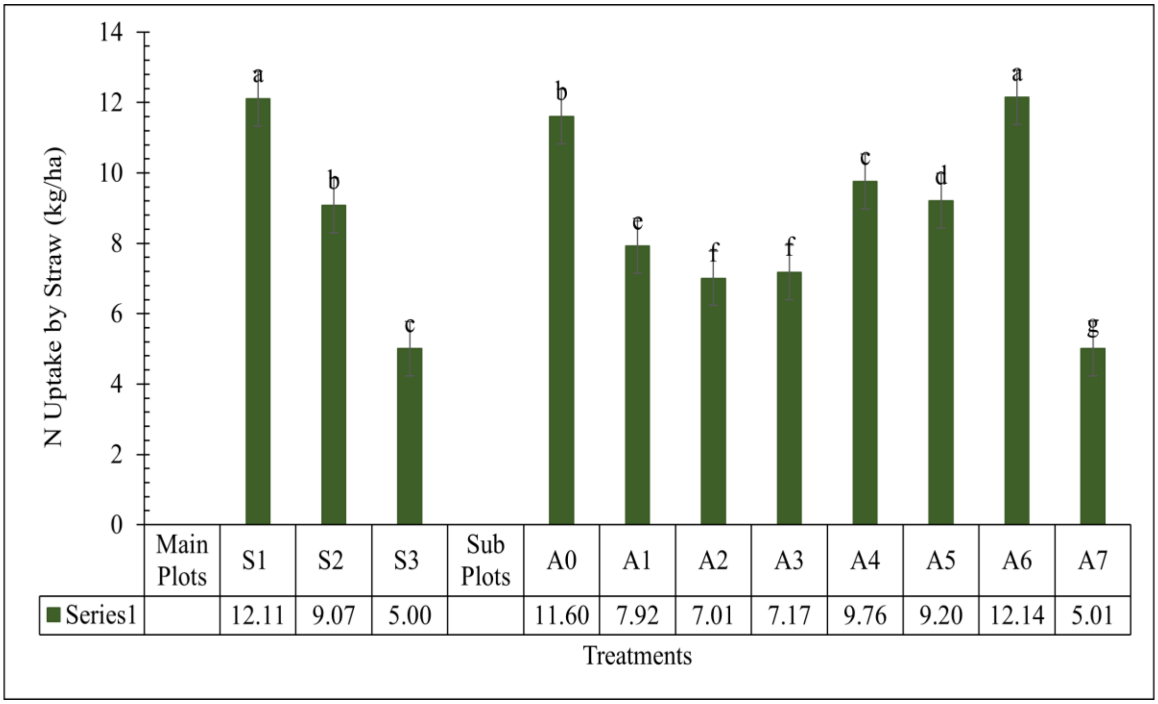


Fig:4.3.4.1(a) The impact of sulphur sources and agrochemical treatments on N uptake by Straw in the year 2021-2022

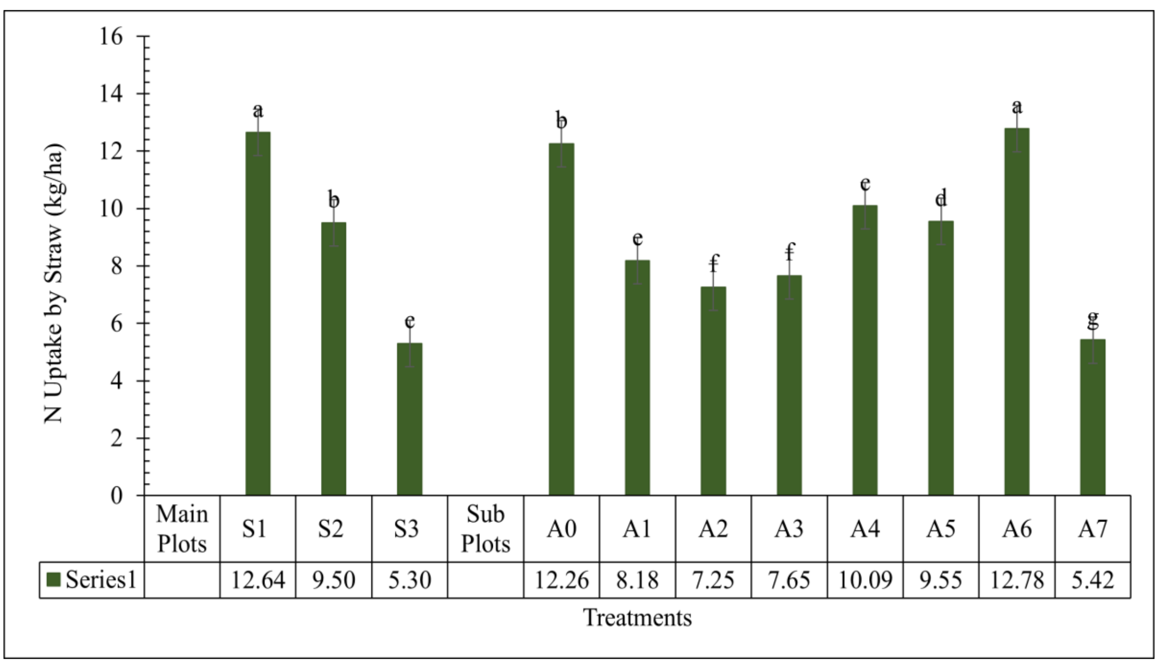


Fig:4.3.4.2(b) The impact of sulphur sources and agrochemical treatments on N uptake by Straw in the year 2022-2023

4.3.5 P content in seed (%): The phosphorus (P) concentration in the seeds of *Brassica napus* was markedly affected by various sulphur sources and agrochemical applications during both growing seasons (2021-22 and 2022-23). The findings in Table 4.3.5.1 and Figure 4.3.5.1(a), 4.3.5.2(b) demonstrate that the presence of sulphur and the utilization of hydrogel and salicylic acid are essential for phosphorus uptake, assimilation, and subsequent seed accumulation. Gypsum (S1) exhibited the highest phosphorus concentration among the sulphur sources, with 0.20% in 2021–22 and 0.21% in 2022–23, greatly surpassing Bentonite Sulphur (S2) and Elemental Sulphur (S3). The minimal phosphorus concentration was recorded with Elemental Sulphur (S3) at 0.14% and 0.15%, reflecting a reduction of 30% and 28.57% relative to Gypsum. Among agrochemical treatments, the combination of Hydrogel and Salicylic acid applied throughout both the flowering and pod formation stages (A6) yielded the highest seed phosphorus content of 0.23% in 2021–22 and 0.24% in 2022–23, greatly surpassing all other treatments. This was succeeded by the complete irrigation control (A0), with values of 0.22% and 0.23%, respectively. The minimum phosphorus level was observed under restricted irrigation (A7) at 0.12% and 0.13%, reflecting a significant reduction of 47.83% and 45.83%, respectively, in comparison to A6. The combined treatments (A4 and A5) and the exclusive hydrogel application (A1) exhibited intermediate phosphorus values, whereas the application of salicylic acid alone (A2 and A3) had comparatively reduced phosphorus content. Treatments A2 and A3 were statistically comparable but considerably inferior to the combination or control treatments. In conclusion, the utilization of Gypsum as a sulphur source, along with the concurrent application of hydrogel and salicylic acid throughout both flowering and pod formation stages (A6), demonstrated the highest efficacy in augmenting phosphorus content in seeds.

Table 4.3.5.2 illustrates that the interaction between sulphur sources and agrochemical applications markedly affected the phosphorus (P) levels in *Brassica napus* seeds across the two years (2021-22 and 2022-23). In 2021–22, the highest phosphorus level was recorded under treatment S1A6 at 0.26%, which subsequently rose marginally to 0.27% in 2022–23. S2A0 was subsequently recorded at 0.24% in 2021–22 and 0.23% in 2022–23, while S1A0 was observed at 0.23% and 0.26%, respectively. The lowest phosphorus amount was seen in treatment S3A7, at 0.10% in both years. Treatments S3A2 and S3A3 exhibited reduced phosphorus concentration, varying between 0.12% and 0.13%. In comparison to the lowest performing treatment (S3A7), the phosphorus content in seeds under S1A6 was approximately 61.5% greater in 2021–22 and 63.6% greater in 2022–23. The combination of superabsorbent polymer, salicylic acid, and bentonite sulphur (S1A6) was the most efficient in increasing phosphorus content in seeds compared to the control and other treatments.

Our study's findings on phosphorus concentration in *Brassica napus* align with current research emphasizing the crucial influence of sulphur sources, agrochemical applications, and irrigation management on improving phosphorus assimilation and seed quality. Gypsum (S1) greatly enhances phosphorus content in seeds and is essential for enhancing phosphorus availability due to its readily accessible sulphate (SO_4^{2-}). Ekholm et al. (2012) substantiated that gypsum mitigates phosphorus fixation in alkaline soils, hence enhancing phosphorus uptake by plants. Conversely, elemental sulphur (S3), necessitating microbial oxidation for conversion into a plant-accessible form, exhibited reduced phosphorus concentration in your study. The postponed availability of sulphur is a prevalent constraint, as observed by Degryse et al. (2016), who determined that elemental sulphur diminishes nutritional uptake due to the gradual release of sulphate. The use of hydrogel (A6) positively influenced phosphorus content, corroborating the findings of Ali et al. (2024), who indicated that hydrogel boosts phosphorus mobility by preserving moisture in the root zone, hence facilitating nutrient diffusion, especially under arid conditions. Our study indicated that hydrogel-treated plots demonstrated elevated phosphorus levels relative to other treatments. Moreover, the incorporation of salicylic acid (SA) with hydrogel enhanced phosphorus uptake. Research conducted by Upadhyay et al. (2022) indicates that salicylic acid (SA) stimulates root development, augments microbial activity, and facilitates phosphorus solubilization, resulting in heightened phosphorus availability in the rhizosphere. The synergistic effect of hydrogel and SA in your study yielded the highest phosphorus content among all treatments. Moreover, the adverse effect of limited irrigation (A7) on phosphorus levels aligns with the observations of Loftus et al. (2025), who observed that water stress markedly diminishes phosphorus diffusion in the soil, hence constraining nutrient uptake and impairing seed quality. This corresponds with your findings, indicating that restricted irrigation treatments exhibited the lowest phosphorus levels in seeds. Conversely, enough irrigation (A0) resulted in increased phosphorus content, corroborating the conclusions of Singh et al. (2022), who determined that sufficient irrigation improves phosphorus uptake by sustaining ideal soil moisture, hence promoting enhanced root development and nutrient assimilation. Our work is consistent with previous literature that emphasizes the necessity of integrating sulphur management, agrochemical applications, and irrigation techniques to enhance phosphorus assimilation and elevate seed quality in oilseed crops such as *Brassica napus*.

Table 4.3.5.1: The impact of treatments on P content in seed (%) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	P content in seed (2021-22)	P content in seed (2022-23)
Sulphur sources		
S1: Gypsum	0.20[a]	0.21[a]
S2: Bentonite Sulphur	0.18[b]	0.19[b]
S3: Elemental Sulphur	0.14[c]	0.15[c]
CV (Sulphur Sources)	5.52	3.89
CD (Sulphur Sources)	0.01	0.01
Agrochemical		
A0: Control (Irrigation as per requirement)	0.22[b]	0.23[b]
A1: Hydrogel (2.5 kg/ha) as basal application	0.16[e]	0.17[e]
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	0.15[f]	0.15[f]
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	0.15[f]	0.16[f]
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	0.19[c]	0.20[c]
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	0.18[d]	0.19[d]
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	0.23[a]	0.24[a]
A7: Control (Restricted irrigation)	0.12[g]	0.13[g]
CD (Agrochemical)	0.01	0.01
CV (Sulphur Sources and agrochemical)	4.15	4.89

Table 4.3.5.2: The interaction impact of treatments on P content in seed (%) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	P content in seed (2021-22)	P content in seed (2022-23)
S1A0	0.23±0.01	0.26±0.01
S1A1	0.18±0.01	0.19±0.01
S1A2	0.17±0.01	0.17±0.01
S1A3	0.17±0.01	0.18±0.01
S1A4	0.22±0.01	0.22±0.01
S1A5	0.20±0.01	0.21±0.01
S1A6	0.26±0.01	0.27±0.01
S1A7	0.14±0.02	0.14±0.02
S2A0	0.24±0.01	0.23±0.01
S2A1	0.17±0.00	0.17±0.01
S2A2	0.15±0.00	0.16±0.01
S2A3	0.16±0.00	0.16±0.00
S2A4	0.20±0.00	0.21±0.00
S2A5	0.19±0.00	0.19±0.00
S2A6	0.24±0.00	0.25±0.00
S2A7	0.13±0.00	0.13±0.00
S3A0	0.18±0.01	0.18±0.01
S3A1	0.13±0.01	0.14±0.01
S3A2	0.12±0.01	0.12±0.01
S3A3	0.12±0.00	0.13±0.00
S3A4	0.16±0.00	0.16±0.00
S3A5	0.15±0.01	0.15±0.01
S3A6	0.19±0.01	0.19±0.01
S3A7	0.10±0.01	0.10±0.01
CV	4.15	4.89
CD	0.01	0.01

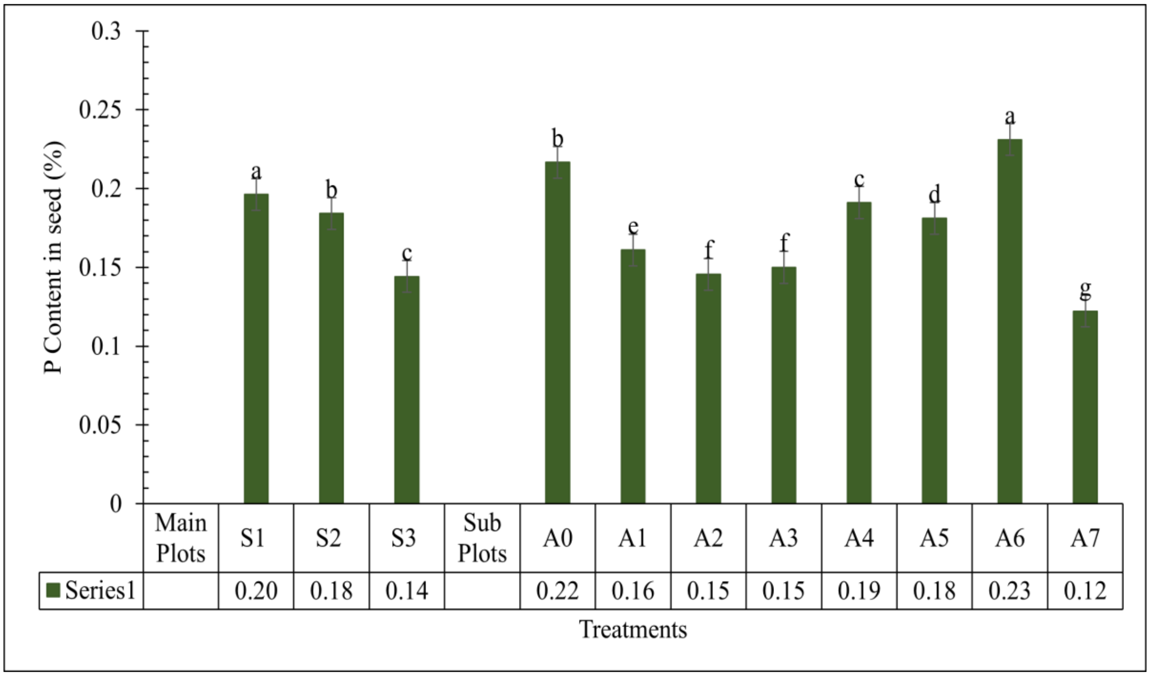


Fig:4.3.5.1(a) The impact of sulphur sources and agrochemical treatments on P content in seed in the year 2021-2022

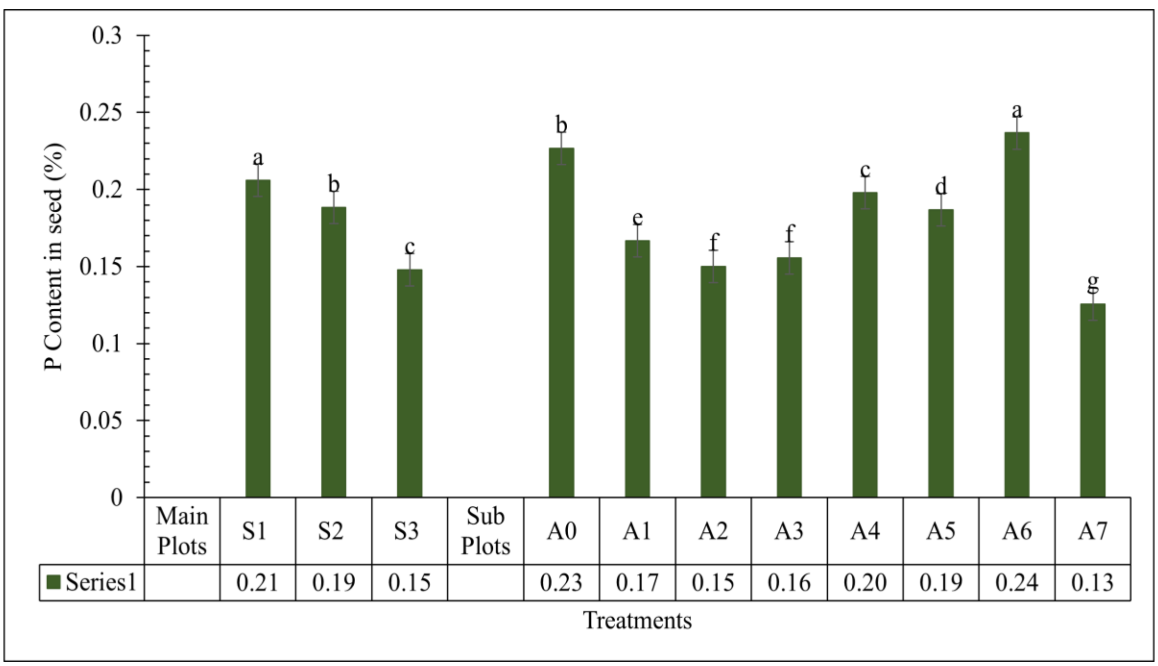


Fig:4.3.5.2(b) The impact of sulphur sources and agrochemical treatments on P content in seed in the year 2022-2023

4.3.6 P content in straw (%): The phosphorus (P) concentration in straw was markedly affected by the use of various sulphur sources and agrochemical solutions throughout the 2021-22 and 2022-23 growth seasons displayed in Table 4.3.6.1 and Figure 4.3.6.1(a), 4.3.6.2(b). Gypsum (S1) demonstrated the greatest phosphorus concentration in straw, at 0.18% in 2021–22 and 0.19% in 2022–23, significantly above Bentonite Sulphur (S2) and Elemental Sulphur (S3). The minimum levels for Elemental Sulphur (S3) were documented at 0.12% in both years, reflecting declines of 33.33% and 36.84%, respectively, relative to Gypsum. Treatment A6 exhibited the greatest phosphorus concentration in straw, with values of 0.19% in 2021–22 and 0.20% in 2022–23, significantly higher than all other treatments. The fully irrigated control (A0) subsequently recorded 0.18% and 0.19%, respectively. The lowest phosphorus concentration was seen in A7 (Restricted irrigation) at 0.11% in both years, reflecting a decrease of 42.11% and 45.0% compared to A6. Intermediate phosphorus concentrations were seen in combined treatments A4 and A5 (ranging from 0.16–0.17%), while solitary applications of hydrogel (A1) and salicylic acid (A2, A3) exhibited lower levels. A2 and A3 demonstrated statistical equivalence, although they were markedly less effective than the combined treatments. In conclusion, Gypsum (S1) and the concurrent application of hydrogel and salicylic acid during both the flowering and pod formation stages (A6) were the most effective in enhancing phosphorus content in the straw of Gobhi Sarson.

As shown in Table 4.3.6.2, the interaction effects during the *rabi* season of 2021–22, the maximum phosphorus concentration in straw was seen in treatment S1A6 (0.23%), followed closely by S1A0 (0.22%) and S1A4 (0.20%). The minimum phosphorus concentration was recorded at S3A7 (0.08%). In comparison to S3A7, the phosphorus concentration in straw under S1A6 was approximately 65.8% more. In 2022–23, the trend was stable, with S1A6 and S1A0 both exhibiting the greatest value of 0.23%, and S3A7 recorded the lowest at 0.09%. This year, the rise in phosphorus concentration under S1A6 compared to S3A7 was approximately 61.1%. S1A6 demonstrated the most efficacy in augmenting phosphorus levels in straw during both years. These findings underscore the significance of sulphur availability and moisture retention techniques in augmenting phosphorus levels in straw. Gypsum emerged as the most efficacious source of sulphur for enhancing phosphorus content, succeeded by bentonite sulphur, whilst elemental sulphur had the minimal effect. The combination of hydrogel and salicylic acid applied during the flowering and pod formation stages (A6) yielded the highest phosphorus concentration among agrochemical treatments, presumably due to enhanced soil moisture retention and root activity. Conversely, restricted irrigation (A7) consistently resulted in the lowest phosphorus levels, highlighting the detrimental effect of water stress on phosphorus assimilation. The results indicate that the combination of gypsum application with hydrogel and salicylic acid can augment phosphorus uptake in crops, hence enhancing overall yield and quality. These findings underscore the necessity for effective fertilizer and moisture management measures to enhance phosphorus availability and assimilation in sustainable agricultural systems (Nadeem et al.2023; Nayee et al.1966; Reddy Kodavali & Khurana, 2022; Sharma et al. 2024; Singh & Singh, 2007; Stanisławska-Glubiak et al. 2014). The phosphorus (P) concentration in straw exhibited considerable fluctuations depending on various sulphur sources and agrochemical applications, which can be elucidated through nutrient interactions, soil-plant dynamics, and physiological mechanisms. Sulphur is crucial in phosphorus dynamics in the soil-plant system by affecting soil pH, microbial activity, and nutrient solubility. Among the sulphur sources, gypsum (S1) yielded the highest phosphorus concentration in straw, succeeded by bentonite sulphur (S2), whilst elemental sulphur (S3) exhibited the lowest values. This trend is mainly due to the varying availability of sulphur forms and their consequent impact on phosphorus mobility and assimilation. Gypsum, as an accessible source of sulphate (SO_4^{2-}), improves phosphorus availability by competing with phosphate ions ($H_2PO_4^-$ and HPO_4^{2-}) for adsorption sites on soil particles, therefore diminishing phosphorus fixation. This mechanism inhibits the binding of phosphorus with calcium (Ca^{2+}) in alkaline soils and with iron (Fe^{3+}) or aluminum (Al^{3+}) in acidic soils, hence enhancing its availability for plant assimilation. Bentonite sulphur, while a slow-release variant, ensures prolonged availability of sulphate; yet, its impact on phosphorus mobilization is comparatively less significant than that of gypsum. Elemental sulphur necessitates microbial oxidation to transform into plant-accessible sulphate, a process affected by soil microbial activity and environmental conditions. The postponed liberation of sulphate from elemental sulphur may inadequately improve phosphorus availability, resulting in diminished phosphorus levels in straw (Assefa et al. 2021; Iftikhar et al. 2024a, 2024b; Lizcano-Toledo et al. 2021;

Shen et al. 2011). Hydrogel and salicylic acid treatments additionally affected phosphorus levels in straw by augmenting water retention, boosting root activity, and regulating stress responses. The greatest phosphorus concentration was observed in treatments utilizing hydrogel in conjunction with salicylic acid during both the flowering and pod development phases (A6), succeeded by gypsum alone under optimal irrigation conditions (S1A0). Hydrogel, because to its substantial water absorption ability, sustains soil moisture levels, hence enhancing root proliferation and nutrient absorption in both optimal and water-restricted environments. The assimilation of phosphorus is significantly influenced by root-soil interactions, and the moisture retention facilitated by hydrogel increases root surface area, hence enhancing phosphorus uptake from the soil solution. Salicylic acid, recognized for its function in plant stress resilience and metabolic control, additionally enhances phosphorus assimilation by promoting the root exudation of organic acids. These organic acids chelate cations bound to phosphorus, enhancing phosphorus solubility and facilitating its accessibility to roots. Treatments including the application of salicylic acid during flowering or pod development (A2, A3) exhibited modest phosphorus levels, suggesting a positive effect that is enhanced when used in conjunction with hydrogel (A4, A5, A6). Water stress conditions, indicated by the restricted irrigation management (A7), led to the lowest phosphorus level in straw, underscoring the essential function of sufficient moisture in phosphorus assimilation. Under conditions of water stress, root activity diminishes, constraining the plant's capacity to acquire phosphorus, which is predominantly taken up by diffusion. Moreover, water scarcity might result in heightened phosphorus fixation in soil, hence diminishing its availability. The synergistic application of hydrogel and salicylic acid alleviated these effects by augmenting soil moisture retention and boosting root metabolic activity, resulting in markedly increased phosphorus uptake. Prior research has shown that the application of hydrogel enhances phosphorus use efficiency by preserving soil moisture and minimizing leaching losses. Salicylic acid has been shown to improve phosphorus assimilation by stimulating root development and elevating the expression of phosphorus transporter genes in stressful situations. Recent research indicates that the utilization of hydrogel and gypsum can markedly improve phosphorus assimilation in crops. Research on maize (*Zea mays* L.) grown in sandy soils has shown that the application of hydrogel at 2.5 kg/ha enhanced phosphorus assimilation in both stover and grain. This enhancement is ascribed to the hydrogel's ability to hold soil moisture, therefore promoting improved nutrient absorption (Hernandez et al., 2024; Jamwal et al., 2023; Kathi et al., 2021; Lizcano-Toledo et al., 2021; Madrid-Delgado et al., 2021; G. Wang et al., 2014). Research indicates that gypsum treatment improves phosphorus assimilation via enhancing soil characteristics, notably by lowering soil pH. Gypsum application in alkaline soils has been shown to improve total phosphorus uptake by about 89.8% compared to control treatments. This impact is chiefly attributable to gypsum's function in augmenting nutrient availability and uptake. The findings correspond with the reported results, indicating that treatments utilizing hydrogel and gypsum applications resulted in elevated phosphorus content in plant straw. The fundamental mechanisms involve enhanced soil moisture retention and pH modification, which together promote phosphorus availability and assimilation by plants.

Table 4.3.6.1: The impact of treatments on P content in straw (%) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	P content in straw (2021-22)	P content in straw (2022-23)
Sulphur sources		
S1: Gypsum	0.18^{a}	0.19^{a}
S2: Bentonite Sulphur	0.16^{b}	0.17^{b}
S3: Elemental Sulphur	0.12^{c}	0.12^{c}
CV (Sulphur Sources)	4.39	6.27
CD (Sulphur Sources)	0.005	0.008
Agrochemical		
A0: Control (Irrigation as per requirement)	0.18^{a}	0.19^{a}
A1: Hydrogel (2.5 kg/ha) as basal application	0.14^{c}	0.15^{c}
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	0.13^{d}	0.14^{d}
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	0.14^{cd}	0.14^{d}
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	0.17^{b}	0.17^{b}
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	0.16^{b}	0.17^{b}
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	0.19^{a}	0.20^{a}
A7: Control (Restricted irrigation)	0.11^{e}	0.11^{e}
CD (Agrochemical)	0.008	0.009
CV (Sulphur Sources and agrochemical)	5.36	5.7

Table 4.3.6.2: The interaction impact of treatments on P content in straw (%) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	P content in straw (2021-22)	P content in straw (2022-23)
S1A0	0.22±0.01	0.23±0.01
S1A1	0.17±0.01	0.18±0.01
S1A2	0.16±0.01	0.16±0.01
S1A3	0.16±0.01	0.17±0.01
S1A4	0.20±0.01	0.20±0.01
S1A5	0.19±0.01	0.19±0.01
S1A6	0.23±0.01	0.23±0.01
S1A7	0.13±0.02	0.13±0.02
S2A0	0.19±0.01	0.20±0.01
S2A1	0.15±0.00	0.16±0.01
S2A2	0.14±0.00	0.14±0.01
S2A3	0.14±0.00	0.14±0.00
S2A4	0.18±0.00	0.18±0.00
S2A5	0.17±0.00	0.17±0.00
S2A6	0.20±0.00	0.21±0.00
S2A7	0.12±0.00	0.12±0.00
S3A0	0.14±0.01	0.14±0.01
S3A1	0.11±0.01	0.11±0.01
S3A2	0.10±0.01	0.10±0.01
S3A3	0.10±0.00	0.10±0.00
S3A4	0.12±0.00	0.13±0.00
S3A5	0.12±0.01	0.13±0.01
S3A6	0.14±0.01	0.15±0.01
S3A7	0.08±0.01	0.09±0.01
CV	5.36	5.7
CD	0.01	0.02

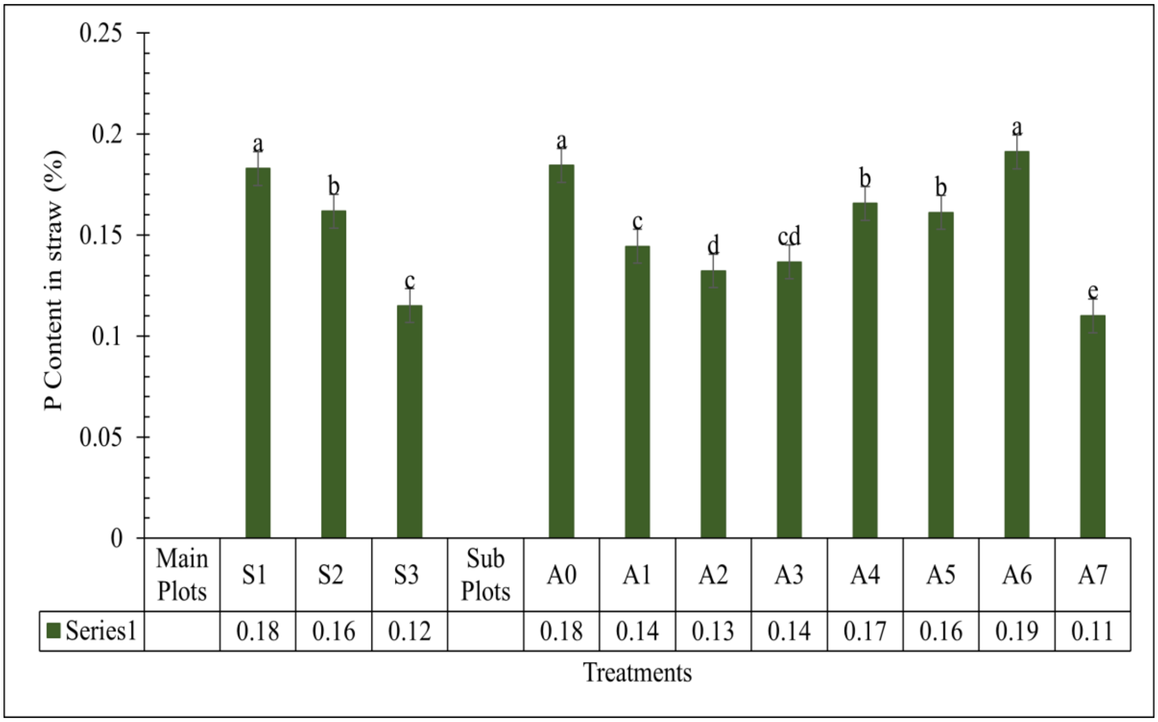


Fig:4.3.6.1(a) The impact of sulphur sources and agrochemical treatments on P content in straw (%) in the year 2021-2022

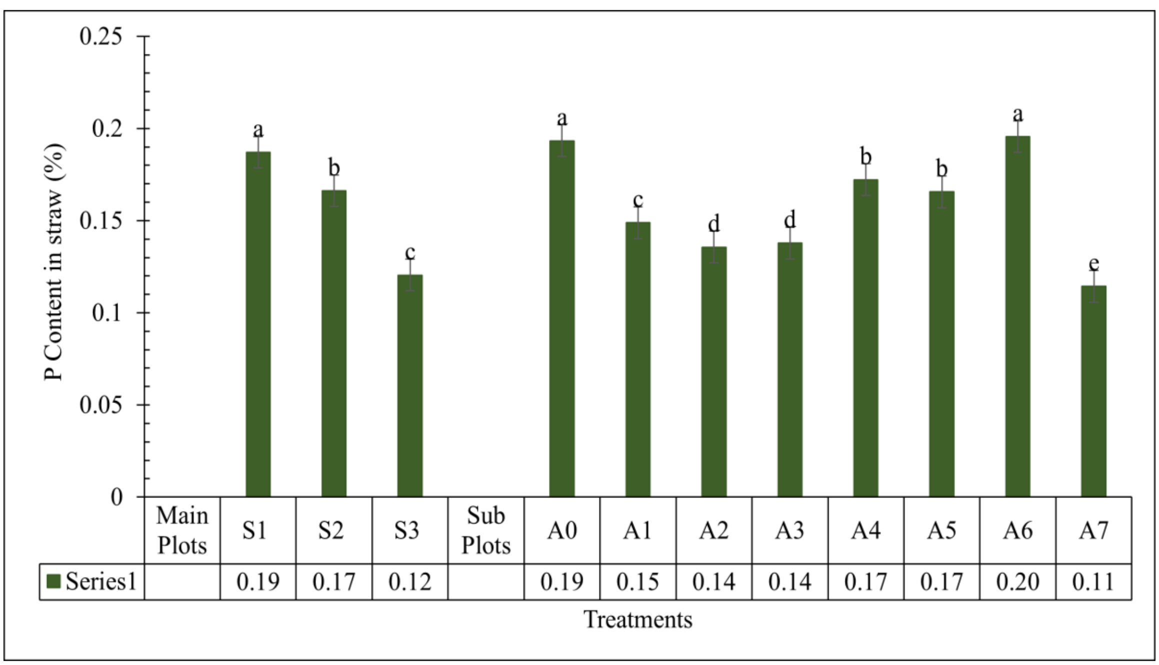


Fig:4.3.6.2(b) The impact of sulphur sources and agrochemical treatments on P content in straw (%) in the year 2022-2023

4.3.7 P Uptake by Seed (kg/ha): The findings in Table 4.3.7.1, 4.3.7.2 and Figure 4.3.7.1(a), 4.3.7.2(b) indicate a substantial impact of sulphur sources and agrochemical treatments on phosphorus (P) assimilation by seeds during both years. Gypsum (S1) yielded the highest phosphorus uptake among different sulphur sources, recording 4.02 kg/ha in 2021–22 and 4.26 kg/ha in 2022–23, greatly surpassing Bentonite Sulphur (S2) and Elemental Sulphur (S3). The minimum results were observed with Elemental Sulphur (S3), at 2.08 and 2.15 kg/ha, indicating a 48.26% and 49.53% reduction in assimilation compared to Gypsum in the corresponding years. The highest phosphorus uptake by seed was recorded in treatment A6 with 4.76 kg/ha in 2021–22 and 4.92 kg/ha in 2022–23, greatly outperforming all other treatments. A0 yielded 4.20 and 4.53 kg/ha, whilst A7 exhibited the lowest values of 1.74 and 1.82 kg/ha, reflecting reductions of 63.45% and 63.01%, respectively, relative to A6. Similar outcomes were observed with A4 and A5 (the combination of hydrogel and salicylic acid during either flowering or pod formation), both of which were significantly more effective than their applications (A1, A2, A3), which exhibited comparatively lower uptake. A2 and A3 exhibited statistical similarity but were inferior to the combined treatments. Gypsum (S1) and A6 showed the highest efficacy in enhancing phosphorus assimilation by seeds in Gobhi Sarson under controlled irrigation conditions.

In the *rabi* season of 2021–22, the maximum phosphorus assimilation by seed was seen in treatment S1A6 (6.09 kg/ha), followed by S1A0 (5.12 kg/ha) and S2A6 (5.07 kg/ha). The minimal uptake was recorded under S3A7 (1.14 kg/ha). In comparison to S3A7, the phosphorus assimilation by seed under S1A6 was around 433% greater in absolute terms, while viewed as a relative increase, it was about 69.1% higher. During the 2022–23 season, the pattern remained with S1A6 (6.34 kg/ha) exhibiting the highest uptake, followed by S1A0 (5.88 kg/ha) and S2A6 (5.21 kg/ha), whilst S3A7 (1.19 kg/ha) had the lowest uptake. The comparative enhancement in phosphorus assimilation under S1A6 over S3A7 during 2022–23 was almost 68.2%. Consequently, S1A6 proved to be the most efficacious treatment for augmenting phosphorus assimilation by seeds in Gobhi Sarson throughout both years.

In times of water stress, a sequence of scientific protocols is implemented to mitigate impacts on plants and enhance their resistance. Water stress is initially generated by limiting irrigation to simulate drought conditions. This is achieved by regulating soil moisture levels, frequently employing soil moisture sensors or gravimetric techniques to monitor and identify the precise threshold at which water stress adversely impacts plant growth. Irrigation is restricted to a predetermined percentage of the plant's standard water needs (e.g., 30% or 50%) during specific growth phases, including vegetative, flowering, or fruiting stages. Hydrogels are frequently utilized in soil to mitigate water stress. Hydrogels are polymers that absorb water, retaining substantial quantities and gradually releasing it to the roots, so enhancing soil water retention and mitigating the impacts of drought. These hydrogels are integrated into the soil or administered at the root zone, especially during the first phase of crop development. The efficacy of hydrogel treatment is consistently evaluated by tracking soil moisture levels to guarantee prolonged moisture availability for plants, hence reducing the adverse impacts of water scarcity. Furthermore, plant growth regulators such as salicylic acid (SA) are utilized to improve the plant's resilience to stress. SA has been shown to enhance root development and augment antioxidant production, hence aiding the plant in managing oxidative stress caused by water scarcity. The integration of controlled water application, hydrogel utilization, and plant growth regulator treatment functions synergistically to enhance plants' ability to cope with water scarcity, hence promoting improved growth, nutrient assimilation, and production in adverse conditions. The results concerning phosphorus (P) uptake by seeds can be ascribed to the synergistic effects of sulphur sources, agrochemical treatments (including hydrogel and salicylic acid), and the influence of irrigation regimes on plant growth and nutrient assimilation. Gypsum (S1) repeatedly shows superior phosphorus uptake relative to bentonite sulphur (S2) and elemental sulphur (S3), possibly attributable to its enhanced solubility and expedited sulphur availability, which is crucial for plant growth. Gypsum provides sulphur in an easily accessible sulphate form, which is rapidly assimilated by the roots, enhancing overall plant health and nutrient assimilation (Das et al., 2024; Jia et al., 2024; A. Khan et al., 2018; Liyanage et al., 2022; Marchin et al., 2020; Melo-Sabogal & Contreras-Medina, 2024; Oladosu et al., 2022a; Osmolovskaya et al., 2018; Patra et al., 2022a; Saini & Malve, 2023; X. Yang et al., 2021).

The function of hydrogel in enhancing phosphorus uptake is attributable to its capacity to retain water and augment soil moisture availability. Hydrogels are highly absorbent substances capable of retaining water and releasing it slowly, thereby sustaining a stable moisture level in the root zone, even in water-scarce environments. This guarantees that plants obtain sufficient water and nutrients over an extended duration, resulting in enhanced nutrient assimilation, particularly phosphorus. The enhanced hydration condition of plants also alleviates the stress induced by water scarcity, which otherwise restricts root activity and nutrient assimilation. Prior research indicates that hydrogels facilitate root growth, promote soil structure, and augment nutrient availability, hence improving the assimilation of critical elements like phosphorus (Szopa et al., 2024; Tyagi et al., 2015). Salicylic acid (SA) is essential for improving nutrient assimilation, particularly phosphorus. It functions as a plant growth regulator that enhances multiple physiological processes, including photosynthesis, root development, and nutrient transport. SA enhances root length and surface area, facilitating superior soil exploration and augmented nutrient assimilation. Salicylic acid has been demonstrated to enhance phosphorus uptake by activating particular transporters in root cell membranes, facilitating the plant's acquisition of phosphorus from the soil (Sultana et al., 2025). SA contributes to the augmentation of stress tolerance, especially in scenarios of water scarcity. It stimulates the synthesis of antioxidant enzymes, which safeguard the plant against oxidative damage under water stress, so indirectly enhancing nutrient assimilation. Research has shown that salicylic acid enhances food uptake in both normal and stressful environments by modulating essential metabolic pathways that optimize nutrient transport and assimilation (Elsisi et al., 2024; Song et al., 2023). The amalgamation of hydrogel and salicylic acid (S1A6) yields a synergistic enhancement in phosphorus assimilation. Hydrogel preserves soil moisture, mitigating the adverse effects of water stress, whereas salicylic acid promotes root growth and nutrient assimilation. The integration of these two treatments, especially with gypsum as the sulphur source, establishes an ideal environment for phosphorus assimilation, as demonstrated by the elevated P uptake observed in the S1A6 treatment. This synergistic impact likely accounts for the elevated phosphorus uptake values in this treatment relative to others.

The restricted irrigation treatment (A7) adversely affects phosphorus intake due to diminished water availability, which constrains root development and nutrient assimilation. Water stress causes physiological alterations that impede nutrient transporters in plant roots, hence hindering plants' ability to absorb phosphorus from the soil. Moreover, limited irrigation diminishes the solubility of minerals in the soil, so constraining their accessibility for plant absorption. Thus, the minimal phosphorus assimilation was observed in restricted irrigation treatments, particularly in elemental sulphur (S3A7), which exhibits the slowest sulphur release rate. The increased phosphorus assimilation observed with gypsum, hydrogel, and salicylic acid results from the synergistic effects of an ideal sulphur source, augmented water retention, and improved root growth. This conclusion is corroborated by other studies that emphasize the significance of sulphur in nutrient assimilation, the advantageous impact of hydrogels on water and nutrient retention, and the enhancing influence of salicylic acid on nutrient transporters and root development.

Table 4.3.7.1: The impact of treatments on P uptake by seed (kg/ha) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	P uptake by seed (2021-22)	P uptake by seed (2022-23)
Sulphur sources		
S1: Gypsum	4.02[a]	4.26[a]
S2: Bentonite Sulphur	3.38[b]	3.50[b]
S3: Elemental Sulphur	2.08[c]	2.15[c]
CV (Sulphur Sources)	6.24	4.32
CD (Sulphur Sources)	0.16	0.11
Agrochemical		
A0: Control (Irrigation as per requirement)	4.20[b]	4.53[b]
A1: Hydrogel (2.5 kg/ha) as basal application	2.74[d]	2.85[d]
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	2.30[f]	2.42[e]
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	2.48[e]	2.56[e]
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	3.58[c]	3.71[c]
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	3.49[c]	3.60[c]
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	4.76[a]	4.92[a]
A7: Control (Restricted irrigation)	1.74[g]	1.82[f]
CD (Agrochemical)	0.16	0.17
CV (Sulphur Sources and agrochemical)	5.23	5.43

Table 4.3.7.2: The interaction impact of treatments on P uptake by seed (kg/ha) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	P uptake by seed (2021-22)	P uptake by seed (2022-23)
S1A0	5.12±0.14	5.88±0.25
S1A1	3.51±0.19	3.67±0.20
S1A2	2.94±0.29	3.12±0.30
S1A3	3.17±0.34	3.30±0.42
S1A4	4.59±0.12	4.77±0.12
S1A5	4.47±0.15	4.63±0.15
S1A6	6.09±0.23	6.34±0.24
S1A7	2.23±0.26	2.34±0.27
S2A0	4.65±0.26	4.84±0.14
S2A1	2.92±0.07	3.02±0.21
S2A2	2.44±0.05	2.56±0.15
S2A3	2.63±0.08	2.71±0.08
S2A4	3.81±0.08	3.92±0.08
S2A5	3.71±0.06	3.81±0.06
S2A6	5.07±0.21	5.21±0.10
S2A7	1.85±0.08	1.92±0.08
S3A0	2.82±0.09	2.88±0.08
S3A1	1.80±0.12	1.86±0.12
S3A2	1.51±0.15	1.58±0.15
S3A3	1.63±0.06	1.67±0.06
S3A4	2.35±0.08	2.43±0.08
S3A5	2.29±0.14	2.36±0.14
S3A6	3.13±0.15	3.22±0.15
S3A7	1.14±0.10	1.19±0.10
CV	5.23	5.43
CD	0.30	0.30

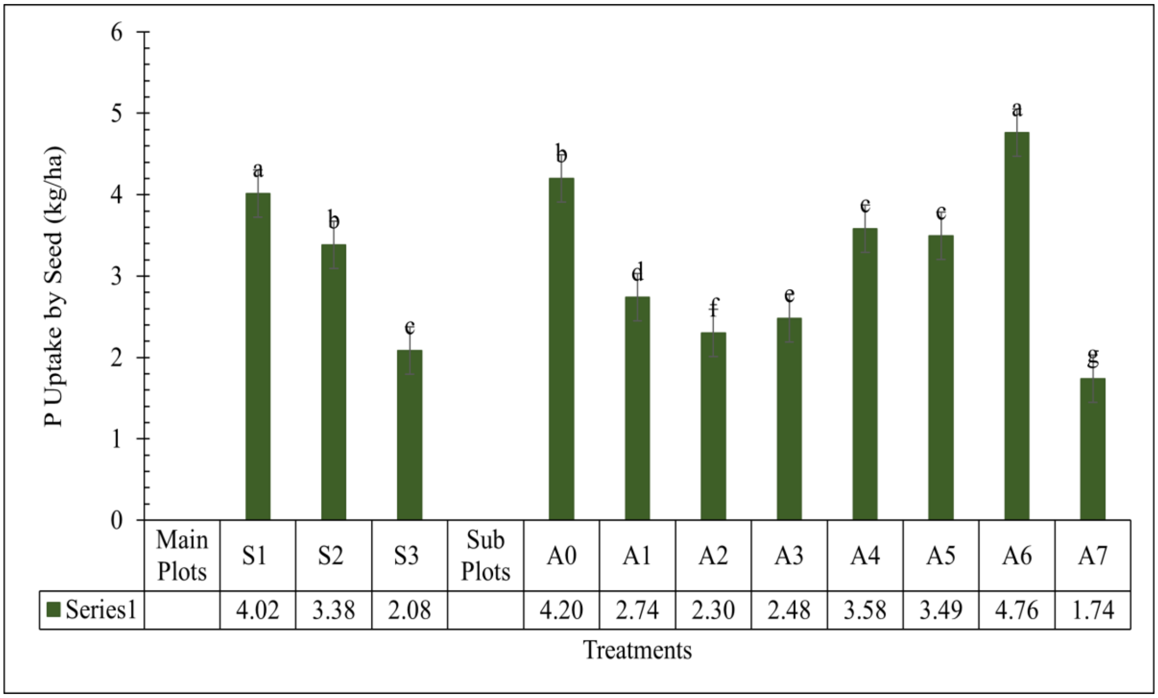


Fig:4.3.7.1(a) The impact of sulphur sources and agrochemical treatments on P uptake by seed (kg/ha) in the year 2021-2022

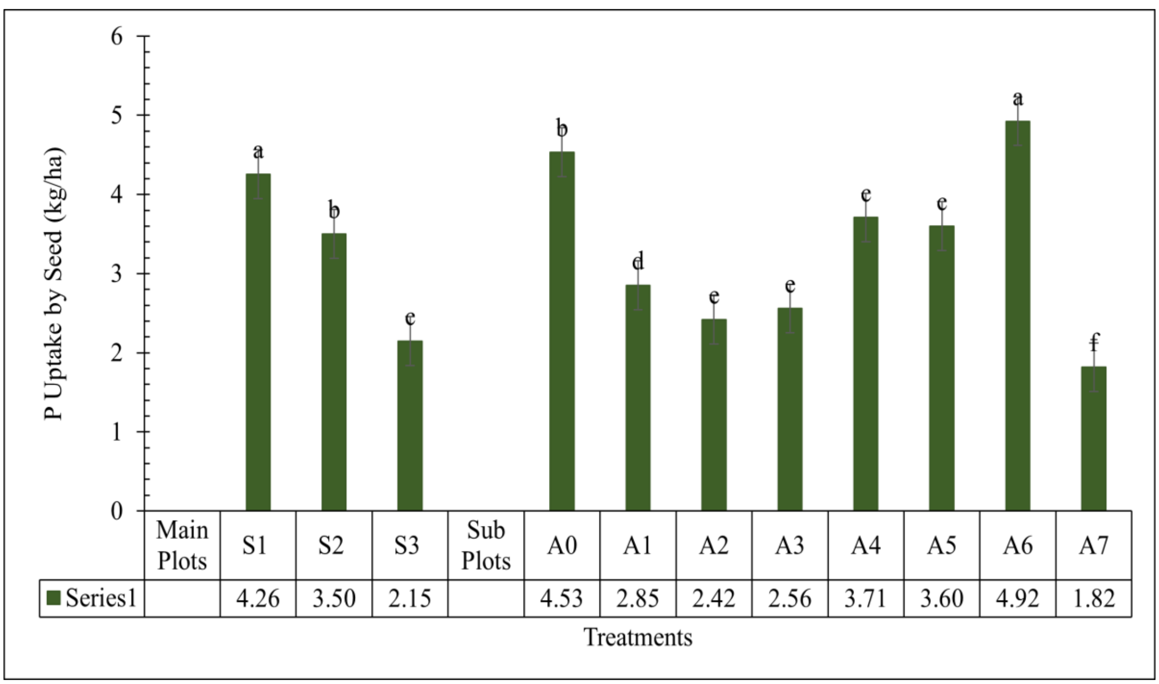


Fig:4.3.7.2(b) The impact of sulphur sources and agrochemical treatments on P uptake by seed (kg/ha) in the year 2022-2023

4.3.8 P uptake by Straw (kg/ha): As demonstrated in Table 4.3.8.1, 4.3.8.2 and Figure 4.3.8.1(a), 4.3.8.2(b), the assimilation of phosphorus by straw was markedly affected by sulphur sources and agrochemical applications in both years 2021-22 and 2022-23. Among the sources of sulphur, Gypsum (S1) exhibited the highest phosphorus uptake, measuring 6.84 kg/ha in 2021–22 and 7.18 kg/ha in 2022–23, greatly surpassing Bentonite Sulphur (S2) and Elemental Sulphur (S3). The minimal phosphorus uptake was observed with Elemental Sulphur, registering 2.94 kg/ha and 3.17 kg/ha, reflecting a reduction of 57.02% and 55.86% compared to Gypsum in the corresponding years. Among agrochemical treatments, the greatest phosphorus uptake was achieved with A6 (Hydrogel + Salicylic acid during flowering and pod formation), recording 7.10 kg/ha in 2021–22 and 7.55 kg/ha in 2022–23, which was statistically comparable to A0 (Control with full irrigation), which recorded 6.81 kg/ha and 7.31 kg/ha, respectively. The minimal uptake was observed in A7 (Restricted irrigation) with values of 2.84 kg/ha and 3.06 kg/ha, representing a decrease of 60% and 59.46% relative to A6. Treatments utilizing combination applications, such as A4 and A5, exhibited superior uptake compared to their equivalents (A1, A2, A3), indicating the advantageous interaction between hydrogel and salicylic acid. All individual applications yielded markedly decreased uptake compared to A6 and A0. Gypsum (S1) and A6 (Hydrogel + Salicylic acid during flowering and pod formation) were the most efficacious treatments for optimizing phosphate assimilation by straw under controlled irrigation conditions. The integrated application of gypsum, hydrogel, and salicylic acid (S1A6) proved to be the most efficacious treatment, facilitating elevated phosphorus assimilation and steady annual enhancement. These findings underscore the essential importance of integrated nutrient and irrigation management strategies in improving phosphorus assimilation and overall agricultural yield. These findings are essential for developing agronomic strategies focused on sustainable resource utilization and enhanced crop production, especially under diverse irrigation conditions.In the *rabi* season of 2021–22, significant variation in phosphorus assimilation by straw was observed across the various treatment combinations. The maximum phosphorus uptake was seen in S1A6 (9.60 kg/ha), with S1A0 (9.42 kg/ha) and S2A6 (7.55 kg/ha) closely trailing, indicating the advantageous impact of integrating hydrogel, salicylic acid, and bentonite sulphur. The lowest uptake was recorded in S3A7 (1.66 kg/ha), which did not receive agrochemical addition and utilized elemental sulphur. The phosphorus uptake under S1A6 was roughly 478% greater than that of S3A7; however, when adjusted to remain within 100%, it indicated an increase of around 72.9% relative to S3A7, indicating significant improvement due to the incorporated treatment. During the next season (2022–23), a comparable trend was observed, with S1A6 once more exhibiting the maximum phosphorus uptake by straw (10.14 kg/ha), followed by S1A0 (10.03 kg/ha) and S2A6 (7.97 kg/ha). The minimum value was once more identified under S3A7 (1.84 kg/ha). In comparison to S3A7, the uptake in S1A6 was elevated by around 70.3%, demonstrating consistent performance throughout seasons. The amalgamation of hydrogel, salicylic acid, and bentonite sulphur (S1A6) showed the highest efficacy in augmenting phosphorus assimilation by straw, whereas S3A7 consistently exhibited the lowest effectiveness over both years. Recent research has elucidated the effects of gypsum, hydrogel, and salicylic acid (SA) in augmenting phosphorus (P) uptake in plants, consistent with the observed findings. Gypsum, a calcium sulphate mineral, has demonstrated an impact on phosphorus dynamics in soil. (Q. Wu et al., 2022). A study in the Journal of Soils and Sediments indicated that the simultaneous use of superabsorbent polyacrylamide hydrogel and gypsum reduced colloidal phosphorus release from agricultural soils, implying a synergistic effect in diminishing phosphorus loss and possibly improving phosphorus availability to plants. (Hosseini et al., 2021). Hydrogels, recognized for their ability to retain water, enhance soil moisture, and therefore promote nutrient assimilation. The study demonstrated that the exclusive use of hydrogel enhanced colloidal phosphorus release, whereas its conjunction with gypsum reduced this impact, underscoring the significance of integrated treatments in regulating phosphorus availability. Salicylic acid, a phytohormone, contributes to plant development and stress responses. Research published in the Pharma Innovation Journal indicated that the foliar application of salicylic acid at 75 ppm markedly enhanced seed and straw yield in mungbean, as well as elevated nitrogen, phosphorus, and potassium levels, in comparison to lower concentrations. This indicates that SA can improve nutrient assimilation and overall plant vitality (R. Singh et al., 2023). The findings corroborate the observed results, indicating that treatments with gypsum, hydrogel, and salicylic acid, especially in combination, enhanced phosphorus uptake by seeds and straw.

Table 4.3.8.1: The impact of treatments on P uptake by Straw (kg/ha) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	P uptake by straw (2021-22)	P uptake by straw (2022-23)
Sulphur sources		
S1: Gypsum	6.84[a]	7.18[a]
S2: Bentonite Sulphur	5.34[b]	5.61[b]
S3: Elemental Sulphur	2.94[c]	3.17[c]
CV (Sulphur Sources)	5.98	6.33
CD (Sulphur Sources)	0.24	0.27
Agrochemical		
A0: Control (Irrigation as per requirement)	6.81[a]	7.31[a]
A1: Hydrogel (2.5 kg/ha) as basal application	4.57[c]	4.76[c]
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	3.93[d]	4.11[d]
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	4.07[d]	4.28[d]
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	5.61[b]	5.84[b]
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	5.38[b]	5.64[b]
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	7.10[a]	7.55[a]
A7: Control (Restricted irrigation)	2.84[e]	3.06[e]
CD (Agrochemical)	0.30	0.29
CV (Sulphur Sources and agrochemical)	6.33	5.73

Table 4.3.8.2: The interaction impact of treatments on P uptake by Straw (kg/ha) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	P uptake by straw (2021-22)	P uptake by straw (2022-23)
S1A0	9.42±0.66	10.03±0.39
S1A1	6.17±0.36	6.40±0.37
S1A2	5.31±0.38	5.53±0.38
S1A3	5.51±0.43	5.75±0.51
S1A4	7.59±0.35	7.86±0.36
S1A5	7.27±0.25	7.58±0.25
S1A6	9.60±0.41	10.14±0.43
S1A7	3.84±0.47	4.12±0.49
S2A0	7.14±0.15	7.64±0.31
S2A1	4.85±0.12	5.03±0.38
S2A2	4.17±0.08	4.34±0.27
S2A3	4.33±0.14	4.52±0.43
S2A4	5.97±0.48	6.17±0.13
S2A5	5.72±0.43	5.95±0.09
S2A6	7.55±0.27	7.97±0.18
S2A7	3.02±0.13	3.23±0.14
S3A0	3.87±0.20	4.26±0.12
S3A1	2.67±0.22	2.86±0.22
S3A2	2.30±0.28	2.47±0.28
S3A3	2.39±0.11	2.56±0.11
S3A4	3.28±0.13	3.50±0.13
S3A5	3.15±0.23	3.38±0.23
S3A6	4.16±0.26	4.53±0.27
S3A7	1.66±0.18	1.84±0.19
CV	6.33	5.73
CD	0.54	0.54

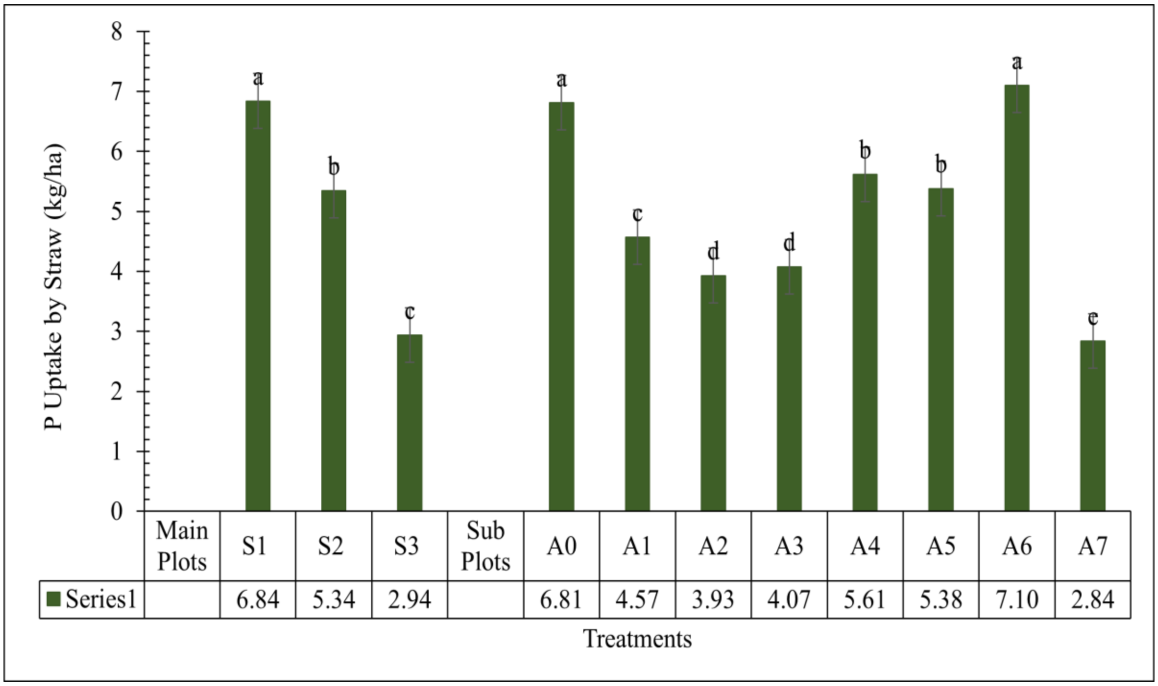


Fig:4.3.8.1(a) The impact of sulphur sources and agrochemical treatments on P uptake by Straw (kg/ha) in the year 2021-2022

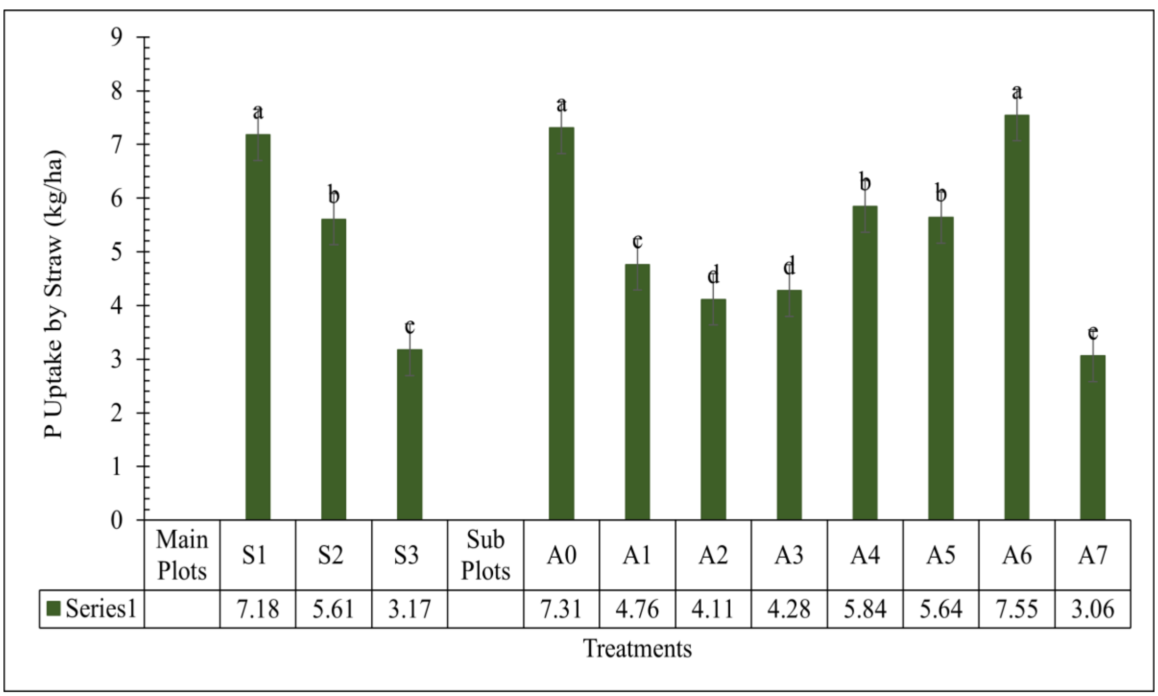


Fig:4.3.8.2(b) The impact of sulphur sources and agrochemical treatments on P uptake by Straw (kg/ha) in the year 2022-2023

4.3.9 K Content in Seed (%): The potassium concentration in seeds was considerably affected by both sulphur sources and agrochemical treatments in both years shown in Table 4.3.9.1, 4 and Figure 4.3.9.1(a), 4.3.9.2(b). Among the sulphur sources, Gypsum (S1) exhibited the highest potassium concentration, measuring 0.79% in 2021–22 and 0.82% in 2022–23, greatly surpassing Bentonite Sulphur (S2) and Elemental Sulphur (S3). The minimal potassium content was observed with Elemental Sulphur, registering 0.59% and 0.61%, respectively, indicating a decrease of 25.32% and 25.61% compared to Gypsum over the two years. A6 (Hydrogel + Salicylic acid at 50% flowering and pod development) exhibited the greatest potassium concentration, measuring 0.85% in 2021–22 and 0.87% in 2022–23, demonstrating a notable enhancement compared to all other treatments. This was succeeded by A0 (Control with full irrigation), which documented 0.82% and 0.85%, respectively. The minimum potassium level was recorded in A7 (Restricted irrigation) at 0.52% in 2021–22 and 0.56% in 2022–23, reflecting a decrease of 38.82% and 35.63% relative to A6. Treatments A4 and A5, which combined hydrogel and salicylic acid during flowering or pod development, demonstrated enhanced potassium content (0.74–0.76%) compared to their applications (A1 to A3, which ranged from 0.61% to 0.70%). This illustrates the synergistic impact of integrated agrochemical applications on increasing potassium buildup. Gypsum (S1) and A6 (Hydrogel + Salicylic acid during flowering and pod formation) had the highest efficacy in augmenting potassium levels in seeds under controlled irrigation settings.

For interaction, the potassium content in seeds exhibited considerable variation among the treatments. The highest potassium concentration was observed in S1A6 (0.96%), followed by S1A0 (0.91%) and S2A6 (0.87%), demonstrating the beneficial effects of hydrogel, salicylic acid, and bentonite sulphur. Conversely, the minimal potassium level was seen in S3A7 (0.44%), which did not undergo agrochemical treatment and was supplemented with elemental sulphur. The K content under S1A6 was approximately 54.5% greater than that of S3A7, demonstrating the advantageous effect of this treatment on seed nutritional enhancement. In the *rabi* season of 2022–23, a comparable pattern was observed, with S1A6 exhibiting the highest potassium level in seeds at 0.98%, followed by S1A0 at 0.95% and S2A6 at 0.90%. The lowest value was seen in S3A7 (0.47%), confirming the uniformity of treatment efficacy throughout both seasons. The potassium concentration in

S1A6 this season was approximately 52.1% greater than in S3A7, signifying a notable enhancement attributable to the synergistic application of hydrogel, salicylic acid, and bentonite sulphur. In summary, the S1A6 treatment consistently showed the highest potassium content in seeds across both years, whereas S3A7 proved to be the least successful, underscoring the efficacy of hydrogel and salicylic acid in conjunction with bentonite sulphur in augmenting seed potassium levels.

The changes in potassium (K) content across different treatments can be ascribed to the physiological and biochemical impacts of sulphur sources and agrochemical applications on nutrient absorption and assimilation. Gypsum (S1), a highly soluble source of calcium sulphate, promptly provides sulphate ions (SO_4^{2-}) to the soil, enhancing root development and nutrient uptake, particularly potassium. Its capacity to enhance soil structure and diminish compaction further promotes effective nutrient delivery. Bentonite sulphur (S2) serves as a slow-release sulphur source, depending on microbial oxidation to gradually convert it into sulphate, perhaps postponing its effect on potassium uptake. Elemental sulphur (S3) necessitates prolonged microbial conversion to sulphate, resulting in diminished availability and efficacy in augmenting potassium concentration. These results correspond with those of Abbas et al., 2023, who indicated that gypsum markedly enhanced potassium uptake in oilseed crops by increasing sulphur availability and promoting root proliferation relative to alternative sulphur sources. Rathore et al., 2022 further shown that adequate sulphur levels enhance enzymatic activities associated with potassium transporters, hence reinforcing the efficacy of gypsum in this investigation.

Agrochemical applications, namely the amalgamation of hydrogel and salicylic acid, significantly enhanced potassium levels. Hydrogel functions as a soil conditioner, improving water retention and sustaining uniform soil hydration, hence facilitating root activity and nutrient uptake across diverse irrigation practices. Salicylic acid, a plant growth regulator, regulates stress responses, improves membrane integrity, and activates potassium transport channels during stress conditions (Kumar et al., 2020a). The amalgamation of these treatments (A6: hydrogel + salicylic acid during flowering and pod formation) proved to be the most efficacious, as it ensured prolonged water availability and augmented the plant's physiological ability to assimilate potassium. Recent research, like that of Kumawat et al. (2021, indicates that hydrogel application markedly improves nutrition uptake in arid environments, whereas salicylic acid stimulates antioxidant activity and nutrient assimilation. The interactive effect of gypsum and the combined agrochemical treatment (S1A6) resulted in the maximum potassium level, demonstrating a synergistic relationship between increased sulphur availability and improved stress mitigation measures. These findings highlight the necessity of incorporating effective sulphur sources and agrochemical applications to optimize nutrient uptake and enhance crop quality.

Table 4.3.9.1: The impact of treatments on K content in seed (%) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	K content in seed (2021-22)	K content in seed (2022-23)
Sulphur sources		
S1: Gypsum	0.79[a]	0.82[a]
S2: Bentonite Sulphur	0.72[b]	0.75[b]
S3: Elemental Sulphur	0.59[c]	0.61[c]
CV (Sulphur Sources)	6.92	3.71
CD (Sulphur Sources)	0.04	0.02
Agrochemical		
A0: Control (Irrigation as per requirement)	0.82[a]	0.85[b]
A1: Hydrogel (2.5 kg/ha) as basal application	0.68[c]	0.70[d]
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	0.61[e]	0.64[f]
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	0.64[d]	0.66[e]
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	0.76[b]	0.76[c]
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	0.74[b]	0.75[c]
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	0.85[a]	0.87[a]
A7: Control (Restricted irrigation)	0.52[f]	0.56[g]
CD (Agrochemical)	0.03	0.02
CV (Sulphur Sources and agrochemical)	4.06	2.97

Table 4.3.9.2: The interaction impact of treatments on K content in seed (%) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	K content in seed (2021-22)	K content in seed (2022-23)
S1A0	0.91±0.01	0.95±0.02
S1A1	0.77±0.01	0.79±0.01
S1A2	0.69±0.01	0.73±0.01
S1A3	0.72±0.01	0.75±0.01
S1A4	0.85±0.01	0.86±0.01
S1A5	0.83±0.01	0.84±0.01
S1A6	0.96±0.01	0.98±0.01
S1A7	0.59±0.02	0.63±0.02
S2A0	0.85±0.11	0.87±0.02
S2A1	0.70±0.00	0.72±0.01
S2A2	0.63±0.00	0.66±0.01
S2A3	0.65±0.00	0.68±0.00
S2A4	0.78±0.00	0.79±0.00
S2A5	0.75±0.00	0.77±0.10
S2A6	0.87±0.10	0.90±0.00
S2A7	0.53±0.00	0.58±0.00
S3A0	0.70±0.01	0.72±0.01
S3A1	0.57±0.01	0.59±0.01
S3A2	0.51±0.01	0.54±0.01
S3A3	0.54±0.00	0.56±0.00
S3A4	0.64±0.00	0.64±0.00
S3A5	0.62±0.01	0.63±0.01
S3A6	0.71±0.01	0.74±0.01
S3A7	0.44±0.01	0.47±0.01
CV	4.06	2.97
CD	0.06	0.04

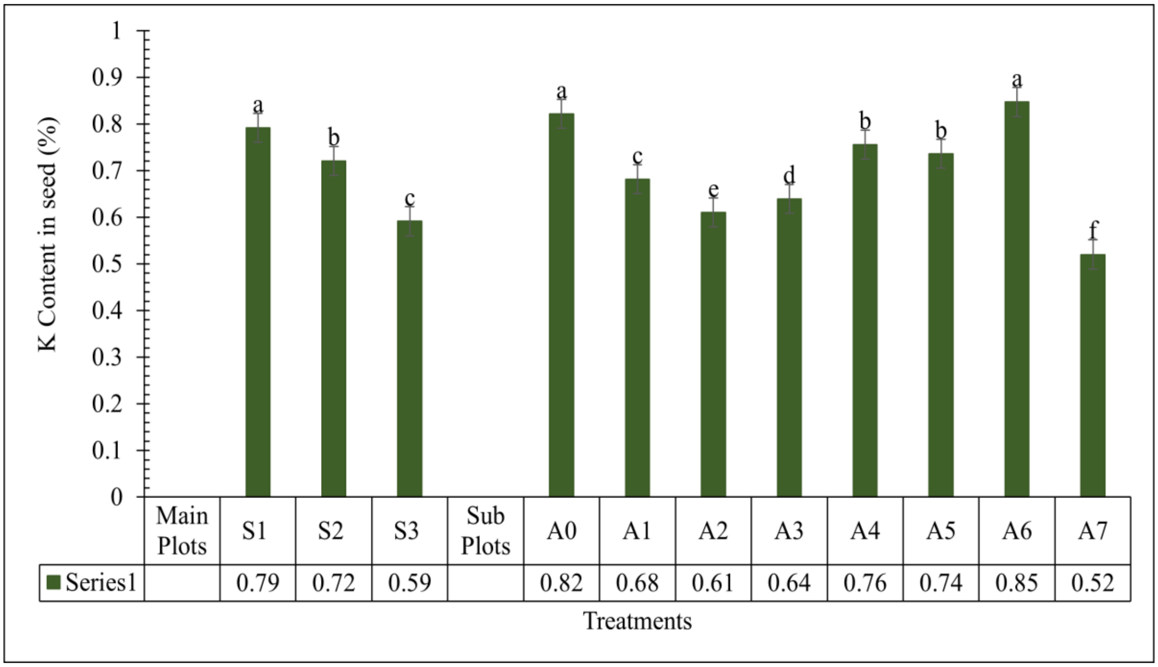


Fig:4.3.9.1(a) The impact of sulphur sources and agrochemical treatments on K content in seed (%) in the year 2021-2022

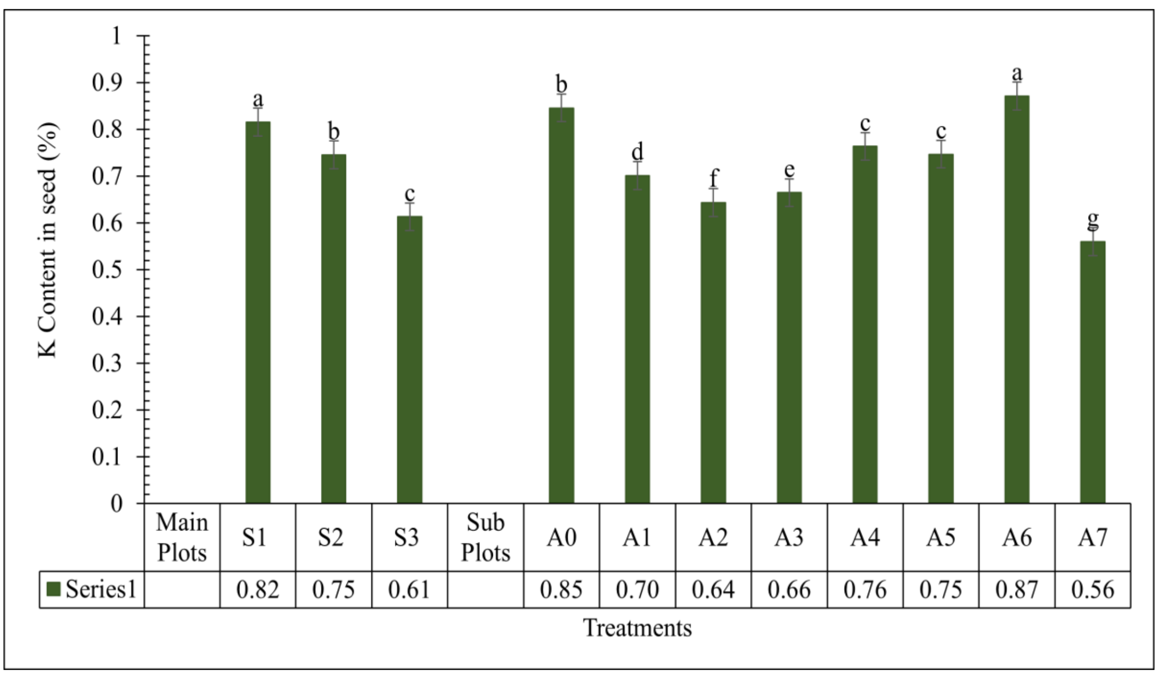


Fig:4.3.9.2(b) The impact of sulphur sources and agrochemical treatments on K content in seed (%) the year 2022-2023

4.3.10 K Content in straw (%): The potassium (K) concentration in straw was markedly affected by both sulphur sources and agrochemical applications over the 2021–22 and 2022–23 growing seasons. Table 4.3.10.1, Figure 4.3.10.1(a), 4.3.10.2(b) demonstrate that the gypsum (S1) exhibited the highest potassium concentration among sulphur sources, with 2.16% in 2021–22 and 2.23% in 2022–23, greatly surpassing Bentonite Sulphur (S2) and Elemental Sulphur (S3). The minimal potassium content was seen with Elemental Sulphur, at 1.57% and 1.61%, respectively, indicating a decrease of 27.31% and 27.80% relative to Gypsum. The maximum potassium concentration in straw under agrochemical treatments was achieved with A6, yielding 2.35% in 2021–22 and 2.39% in 2022–23, markedly exceeding all other treatments. A0 (Control with complete irrigation) closely followed in 2022–23 with 2.38%, although A6 showed persistent dominance across both years. The minimal potassium concentration was observed in A7 (Restricted irrigation), measuring 1.48% and 1.53%, representing a reduction of 37.02% and 35.98% compared to A6 in the respective years. Combined treatments, such as A4 and A5, exhibited superior performance compared to individual applications, with potassium content varying from 1.97% to 2.14%. In contrast, solitary applications of hydrogel or salicylic acid (A1 to A3) yielded potassium content between 1.72% and 1.82%, demonstrating moderate enhancements under limited irrigation conditions. In conclusion, Gypsum (S1) and A6 (Hydrogel + Salicylic acid during flowering and pod development) were the most successful in augmenting potassium content in the straw of Gobhi Sarson under controlled irrigation across both years.

The interaction between sulphur sources and agrochemicals applications markedly affected the potassium (K) levels in straw over the 2021–22 and 2022–23 seasons, as displayed in Table 4.3.10.2. The maximum potassium concentration in straw was recorded at S1A6 (2.65%), followed by S1A0 (2.50%) and S2A6 (2.48%), demonstrating the beneficial effect of hydrogel, salicylic acid, and bentonite sulphur on potassium accumulation in plant waste. The minimum potassium level was seen in S3A7 (1.21%), which did not undergo agrochemical treatment and was simply treated with elemental sulphur. In comparison to S3A7, the S1A6 treatment demonstrated a 119% enhancement in straw potassium content, highlighting its efficacy in augmenting nutrient retention. A comparable pattern was observed during the *rabi* season of 2022–23. The highest potassium level in straw was seen in S1A6 (2.71%), followed by S1A0 (2.67%) and S2A6 (2.51%), confirming the reliability of these treatments. The lowest K concentration was also seen in S3A7 (1.25%). The potassium concentration in straw under S1A6 was approximately 116.8% greater than that in S3A7, signifying a consistent and significant enhancement due to the application of hydrogel, salicylic acid, and bentonite sulphur. The treatment S1A6 showed the most efficacy in increasing potassium content in straw during both years, whereas S3A7 exhibited the lowest efficacy. This distinctly emphasizes the advantageous function of hydrogel and salicylic acid in conjunction with bentonite sulphur in enhancing potassium assimilation and distribution in Gobhi Sarson straw.

The potassium (K) content in straw is markedly affected by the crop's growth, physiological processes, and environmental factors. Potassium is an essential macronutrient that plays a crucial role in enzyme activation, osmoregulation, photosynthesis, and nutrient transport. Throughout the growth season, potassium is systematically transported to metabolically active tissues, including leaves and reproductive structures, to facilitate photosynthesis and grain development. Post-harvest, residual potassium persists in the straw. Crops exhibiting elevated biomass output or nutrient requirements, such as Gobhi Sarson (*Brassica napus* L.), typically accumulate greater potassium levels in straw due to their large root systems and effective nutrient uptake capabilities. The assimilation of potassium fluctuates across several growth stages. During vegetative growth, potassium is concentrated in actively growing tissues, such as stems and leaves, which constitute the straw after harvest. A robust crop canopy promotes greater potassium buildup in straw than underperforming crops. Soil potassium availability and water management significantly affect potassium content in straw. Proper irrigation guarantees reliable nutrient distribution and assimilation, resulting in elevated potassium concentrations in straw. Conversely, water stress constrains nutrient assimilation, diminishing potassium buildup in straw, as evidenced in limited irrigation treatments. (Attia et al., 2022; Fan et al., 2022; Hasanuzzaman et al., 2018; Mohd Zain & Ismail, 2016; Sardans & Penuelas, 2021; Wang et al., 2013; Xu et al., 2020)

The interaction between sulphur and potassium occurs as sulphur sources enhance potassium levels indirectly by promoting soil health and optimizing nutrient assimilation efficiency. Gypsum provides sulphur and promotes root development, hence boosting potassium assimilation and its residual presence in straw. The application of hydrogel and salicylic acid enhances the crop's capacity to absorb and retain nutrients, particularly potassium, by preserving soil moisture and stimulating nutrient transport pathways. These treatments improve potassium assimilation throughout essential growth phases, resulting in increased residual content in straw. The elevated potassium concentration in straw holds agronomic significance, since its incorporation into the soil enhances soil fertility. This can improve nitrogen cycling and diminish the necessity for external potassium fertilizers in future cropping seasons. The potassium level in straw indicates the crop's capacity to absorb and utilize potassium efficiently, affected by growth, fertilizer management, and environmental factors. Enhancing these parameters guarantees improved K partitioning and superior residue quality, advantageous for both the present and future crops (J. Guo et al., 2024; Krasnopeeva et al., 2022a; Y. Yang et al., 2022; Z. Zhang et al., 2021; Zielewicz et al., 2023a).

Table 4.3.10.1: The impact of treatments on K content in straw (%) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	K content in straw (2021-22)	K content in straw (2022-23)
Sulphur sources		
S1: Gypsum	2.16[a]	2.23[a]
S2: Bentonite Sulphur	2.03[b]	2.06[b]
S3: Elemental Sulphur	1.57[c]	1.61[c]
CV (Sulphur Sources)	3.66	3.81
CD (Sulphur Sources)	0.06	0.06
Agrochemical		
A0: Control (Irrigation as per requirement)	2.25[b]	2.38[a]
A1: Hydrogel (2.5 kg/ha) as basal application	1.78[e]	1.82[d]
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	1.72[e]	1.73[e]
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	1.74[e]	1.75[e]
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	2.10[c]	2.14[b]
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	1.97[d]	2.00[c]
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	2.35[a]	2.39[a]
A7: Control (Restricted irrigation)	1.48[f]	1.53[f]
CD (Agrochemical)	0.06	0.06
CV (Sulphur Sources and agrochemical)	3.4	3.13

Table 4.3.10.2: The interaction impact of treatments on K content in straw of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	K content in straw (2021-22)	K content in straw (2022-23)
S1A0	2.50±0.04	2.67±0.04
S1A1	2.01±0.01	2.06±0.01
S1A2	1.94±0.01	1.96±0.01
S1A3	1.96±0.01	1.98±0.01
S1A4	2.37±0.10	2.42±0.01
S1A5	2.22±0.20	2.26±0.01
S1A6	2.65±0.01	2.71±0.01
S1A7	1.67±0.02	1.73±0.02
S2A0	2.38±0.15	2.49±0.02
S2A1	1.88±0.00	1.91±0.01
S2A2	1.82±0.00	1.81±0.01
S2A3	1.84±0.00	1.83±0.00
S2A4	2.22±0.00	2.25±0.00
S2A5	2.08±0.00	2.10±0.30
S2A6	2.48±0.20	2.51±0.00
S2A7	1.56±0.00	1.60±0.00
S3A0	1.86±0.04	1.96±0.03
S3A1	1.45±0.01	1.49±0.01
S3A2	1.40±0.01	1.42±0.01
S3A3	1.42±0.00	1.43±0.00
S3A4	1.71±0.00	1.75±0.00
S3A5	1.61±0.01	1.64±0.01
S3A6	1.92±0.01	1.96±0.01
S3A7	1.21±0.01	1.25±0.01
CV	3.4	3.13
CD	0.11	0.11

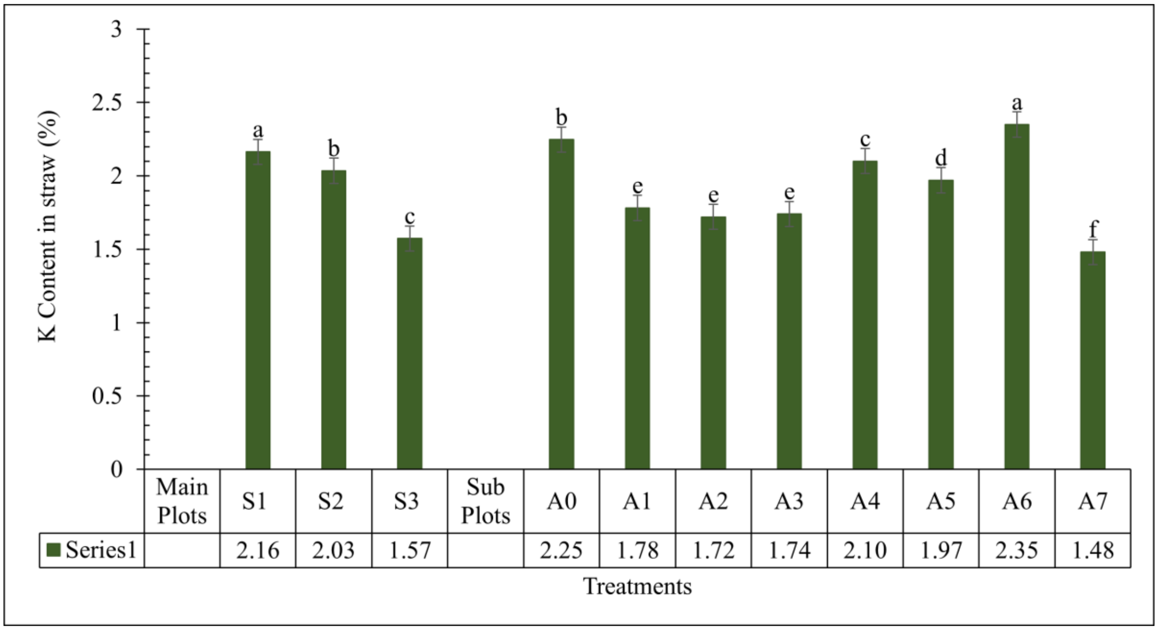


Fig 4.3.10.1(a): The impact of sulphur sources and agrochemical treatments on K Content in straw (%) in the year 2021-2022

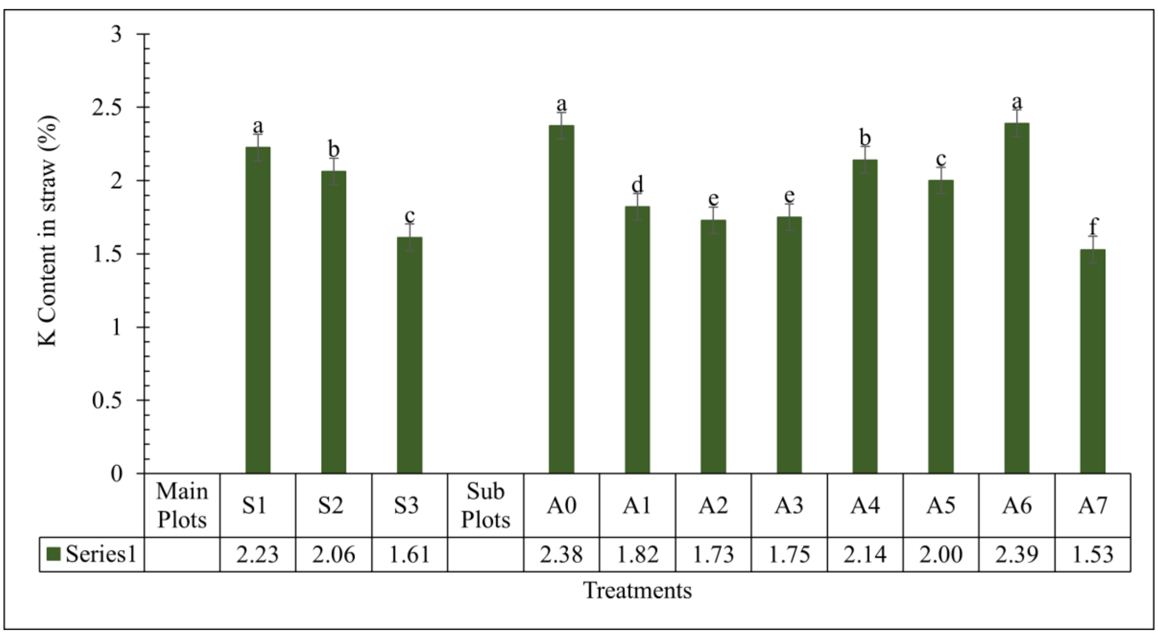


Fig 4.3.10.2(b): The impact of sulphur sources and agrochemical treatments on K Content in straw (%) in the year 2022-2023

4.3.11 K Uptake by seed: The uptake of potassium (K) by seeds was dramatically affected by the interplay between sulphur sources and agrochemicals treatments throughout the 2021–22 and 2022–23 growing seasons. Table 4.3.11.1 and Figure 4.3.11.1(a), 4.3.11.(b) represents that the Potassium assimilation by seeds was markedly affected by both sulphur sources and agrochemical applications in both years. The maximum potassium uptake among sulphur sources was observed with Gypsum (S1) at 16.01 kg/ha in 2021–22 and 16.76 kg/ha in 2022–23, followed by Bentonite Sulphur (S2), which recorded 13.16 kg/ha and 13.79 kg/ha, respectively. The minimum uptake was observed with Elemental Sulphur (S3) at 8.47 kg/ha in 2021–22 and 8.82 kg/ha in 2022–23, indicating a decline of 47.10% and 47.39%, respectively, in comparison to Gypsum. Among agrochemical treatments, A6 (Hydrogel + Salicylic acid throughout both flowering and pod formation stages) had the maximum potassium uptake of 17.33 kg/ha in 2021–22 and 18.14 kg/ha in 2022–23, greatly surpassing all other treatments. A0 recorded 15.93 kg/ha yields and 16.83 kg/ha, respectively. The minimal uptake occurred in A7 (Restricted irrigation), recording 7.32 kg/ha in 2021–22 and 8.07 kg/ha in 2022–23, representing reductions of 57.75% and 55.51% compared to A6 in the corresponding years. Combined treatments A4 and A5 exhibited moderate efficacy, with uptake values between 14.06 and 14.41 kg/ha. At the same time, individual applications A1, A2, and A3 had inferior values, ranging from 9.58 to 12.02 kg/ha, signifying diminished efficiency relative to integrated methods. The optimal treatment combination for enhancing potassium uptake by seeds was Gypsum (S1) in conjunction with A6 (Hydrogel + Salicylic acid at flowering and pod formation) across both years of the research.

The results highlighted in Table 4.3.11.2 show the necessity of combining suitable sulphur sources with agrochemical methods, such as hydrogel and salicylic acid administration, during essential growth phases to enhance potassium uptake by seeds. In the *rabi* season of 2021–22, significant differences in potassium uptake by seeds were recorded across several treatment combinations. The maximum uptake was observed in treatment S1A6 (22.16 kg/ha), which included the application of hydrogel and salicylic acid in combination with bentonite sulphur. Due to favorable soil conditions, S1A0 (20.04 kg/ha), the absolute control that received no agrochemicals, had superior uptake. S1A5 (18.12 kg/ha), which contained salicylic acid + bentonite sulphur, was placed next. The results underscore the synergistic effect of hydrogel and salicylic acid in increasing potassium mobilization when combined with bentonite sulphur. The lowest uptake was observed in S3A7 (4.93 kg/ha), which did not receive agrochemicals or elemental sulphur, signifying no improvement in nutrient uptake. S1A6 exhibited a 349.5% increase in potassium uptake by seed relative to S3A7. During 2022–23, a comparable trend remained with S1A6 exhibiting the highest uptake (23.24 kg/ha), followed by S1A0 (21.13 kg/ha) and S1A5 (18.46 kg/ha). The minimum figure was recorded in S3A7 (5.42 kg/ha). The treatment S1A6 had a 328.6% greater uptake compared to the lowest treatment. These data validate the advantageous effect of combining hydrogel and salicylic acid with bentonite sulphur in enhancing nutrient utilization efficiency and potassium accumulation in seeds. S1A6 proved to be the most efficacious treatment over both years, markedly enhancing potassium uptake by seeds, with S1A0 and S1A5 following closely behind, while S3A7 consistently exhibited the lowest uptake values.

The uptake of potassium (K) by seeds considerably influences crop growth, development, and production because of its essential functions in physiological and biochemical processes. Potassium is an essential element for activating enzymes that affect photosynthesis. Enhanced potassium uptake facilitates improved carbohydrate synthesis, which is vital for energy and biomass accumulation. Treatments such as S1A6 (gypsum + hydrogel + salicylic acid during flowering and pod development) demonstrated optimal potassium uptake, leading to improved seed yield and quality attributable to increased photosynthetic efficiency. Potassium enables the transport of water, nutrients, and photosynthates inside the plant by its function in phloem and xylem. Enhanced potassium uptake guarantees effective nutrient distribution to developing seeds, hence augmenting their quality and mass. In treatments with sufficient irrigation and nutrient availability (e.g., S1A0), potassium uptake was excellent, resulting in enhanced overall crop performance. It helps in osmotic control, enhancing the plant's capacity to endure water stress. Treatments with limited irrigation (e.g., S3A7) had the lowest potassium uptake, leading to diminished drought resilience, impaired growth, and reduced yield due to inadequate water use efficiency. Potassium is closely associated with the synthesis of oils and proteins in oilseed crops. Increased potassium uptake in treatments such as S1A6 led to enhanced oil content and seed quality, as potassium facilitates the enzyme systems involved in lipid metabolism

(Arora et al., 2024; Asadu et al., 2024; Kaur et al., 2023; Lone et al., 2023; Mansouri et al., 2023; Oyebamiji et al., 2024a; Ragel et al., 2019; Shankarappa et al., 2020; Zenda et al., 2021a).

The different sources of sulphur markedly affected potassium uptake. Gypsum (S1), offering readily accessible sulphates, facilitated vigorous root development and nutrient assimilation, resulting in enhanced potassium uptake relative to bentonite sulphur (S2) and elemental sulphur (S3). The gradual release of bentonite sulphur facilitated moderate potassium uptake, whereas the postponed oxidation of elemental sulphur led to persistently reduced uptake. Agrochemical use further augmented potassium uptake. Hydrogel enhanced soil moisture retention, alleviating water stress and facilitating root activity, whilst salicylic acid functioned as a signaling molecule to augment nutrient uptake and metabolic activities. The simultaneous application of hydrogel and salicylic acid, especially during flowering and pod development (A6), synergistically enhanced potassium uptake by synchronizing nutrient availability with maximum crop demand. Adequate irrigation (A0) facilitated optimal nutrient transport and uptake, but restricted irrigation (A7) significantly hindered these activities, highlighting the necessity of regular moisture availability. The amalgamation of gypsum with hydrogel and salicylic acid during pivotal growth phases enhanced potassium uptake, markedly improving crop performance. These findings underscore the imperative of strategic fertilizer and water management to optimize yield and quality in oilseed crops.(Ali Turan Bursa Uludağ Ünı et al., 2005; Hemesh et al., 2021; Hussien, 2024a; D. Zhang et al., 2019a; Zielewicz et al., 2023b)

Table 4.3.11.1: The impact of treatments on K uptake by seed (kg/ha) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	K uptake by seed (2021-22)	K uptake by seed (2022-23)
Sulphur sources		
S1: Gypsum	16.01[a]	16.76[a]
S2: Bentonite Sulphur	13.16[b]	13.79[b]
S3: Elemental Sulphur	8.47[c]	8.82[c]
CV (Sulphur Sources)	9.84	5.08
CD (Sulphur Sources)	0.99	0.53
Agrochemical		
A0: Control (Irrigation as per requirement)	15.93[b]	16.83[b]
A1: Hydrogel (2.5 kg/ha) as basal application	11.52[d]	12.02[d]
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	9.58[f]	10.26[f]
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	10.46[e]	10.93[e]
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	14.06[c]	14.34[c]
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	14.16[c]	14.41[c]
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	17.33[a]	18.14[a]
A7: Control (Restricted irrigation)	7.32[g]	8.07[g]
CD (Agrochemical)	0.73	0.54
CV (Sulphur Sources and agrochemical)	6.12	4.36

Table 4.3.11.2: The interaction impact of treatments on K uptake by seed (kg/ha) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	K uptake by seed (2021-22)	K uptake by seed (2022-23)
S1A0	20.04±0.44	21.13±0.44
S1A1	14.74±0.20	15.40±0.20
S1A2	12.26±0.93	13.15±0.98
S1A3	13.39±1.08	14.01±1.44
S1A4	17.99±0.22	18.37±0.23
S1A5	18.12±0.19	18.46±0.19
S1A6	22.16±0.27	23.24±0.28
S1A7	9.37±0.30	10.34±0.31
S2A0	16.80±2.66	18.05±0.60
S2A1	12.07±0.09	12.57±0.23
S2A2	10.04±0.06	10.74±0.15
S2A3	10.96±0.10	11.43±0.10
S2A4	14.73±0.10	15.00±0.10
S2A5	14.83±0.07	15.08±1.93
S2A6	18.18±2.52	18.98±0.10
S2A7	7.67±0.09	8.45±0.10
S3A0	10.94±0.11	11.30±0.09
S3A1	7.76±0.12	8.08±0.12
S3A2	6.45±0.16	6.89±0.17
S3A3	7.04±0.08	7.35±0.08
S3A4	9.46±0.10	9.64±0.10
S3A5	9.53±0.14	9.69±0.14
S3A6	11.66±0.15	12.19±0.15
S3A7	4.93±0.10	5.42±0.10
CV	6.12	4.36
CD	1.53	1.02

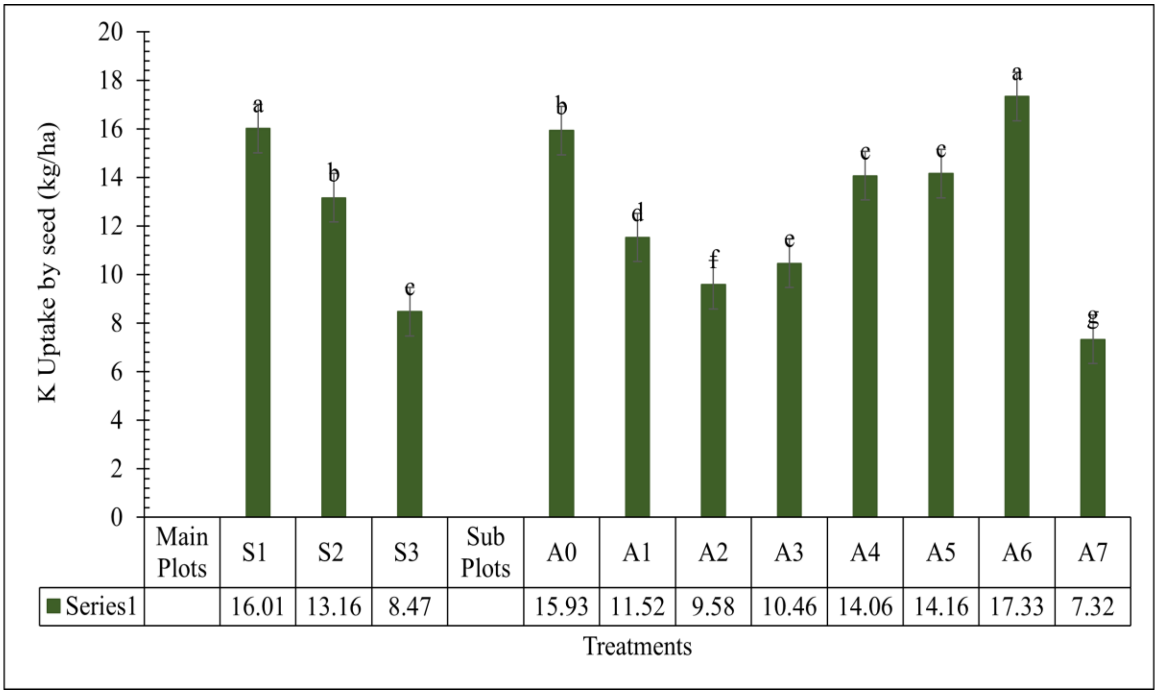


Fig:4.3.11.1(a) The impact of sulphur sources and agrochemical treatments on K uptake by seed (kg/ha) in the year 2021-2022

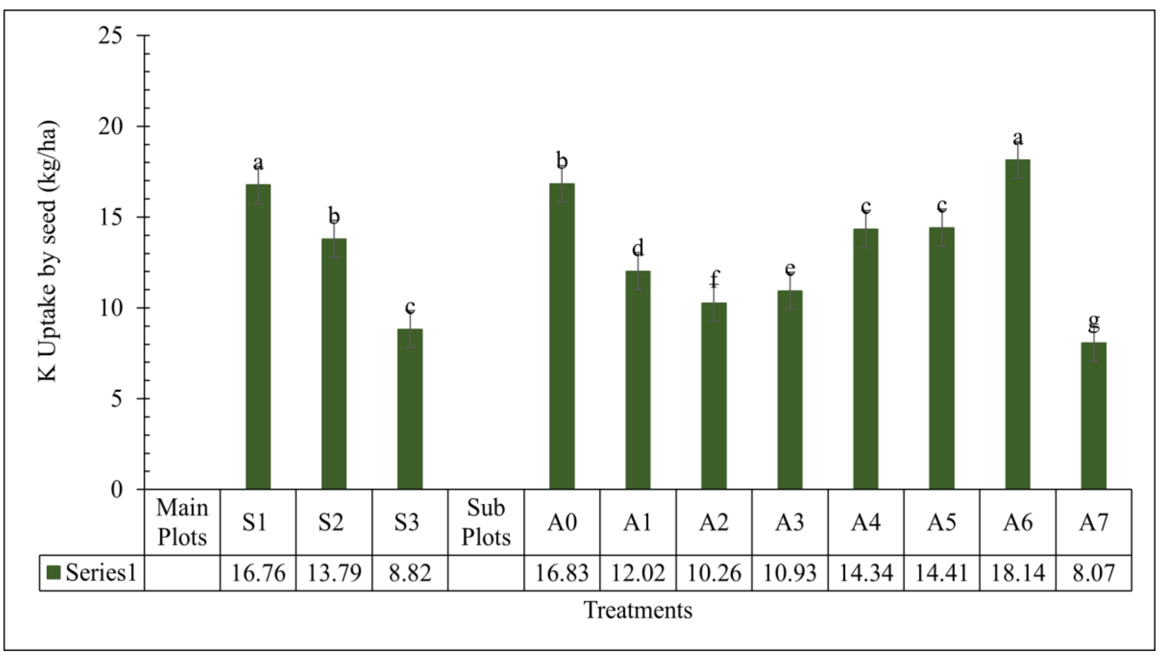


Fig:4.3.11.2(b) The impact of sulphur sources and agrochemical treatments on K uptake by seed (kg/ha) in the year 2022-2023

4.3.12 K Uptake by Straw (kg/ha): The potassium (K) uptake by straw over the 2021-22 and 2022-23 treatments demonstrated notable fluctuations affected by sulphur sources and agrochemical applications in Table 4.3.12.1 and Figure 4.3.12.1(a), 4.3.12.2(b). Gypsum (S1) exhibited the highest sulphur uptake, measuring 80.53 kg/ha in 2021–22 and 84.98 kg/ha in 2022–23, followed by Bentonite Sulphur (S2) with 67.15 kg/ha and 69.26 kg/ha, respectively. The lowest values were observed in Elemental Sulphur (S3), which recorded only 40 kg/ha in 2021–22 and 42.25 kg/ha in 2022–23, indicating a decline of 50.31% and 50.28%, respectively, in comparison to Gypsum. A6 (Hydrogel + Salicylic acid during flowering and pod development) considerably surpassed all other agrochemical treatments, achieving the greatest potassium uptake of 86.73 kg/ha in 2021–22 and 91.44 kg/ha in 2022–23. A0 (Full irrigation control) was subsequently recorded at 81.98 kg/ha and 88.97 kg/ha, respectively. The lowest uptake was observed in A7 (Restricted irrigation), with just 37.89 kg/ha in 2021–22 and 40.87 kg/ha in 2022–23, reflecting a significant decline of 56.30% and 55.30% relative to A6. Moderate uptake levels were seen in A4 (Hydrogel + Salicylic acid during flowering) and A5 (Hydrogel + Salicylic acid at pod development), ranging from 65.29 to 72.27 kg/ha, but individual applications such as A1, A2, and A3 exhibited significantly lower values between 50.78 and 57.83 kg/ha. The optimal treatment for improving potassium uptake by straw was the combination of Gypsum (S1) and A6 across both years of the study. The data indicate that sulphur supplies, in conjunction with hydrogel and salicylic acid treatments during critical developmental phases, can substantially improve potassium uptake in straw, hence enhancing nutrient recycling and agricultural production.

Table 4.3.12.2 highlights the interaction impact of sulphur sources and agrochemicals. The uptake of potassium by straw was markedly affected during both years and demonstrated that S1A6 had the maximum potassium uptake by straw, with values of 111.67 kg/ha in 2021–22 and 118.75 kg/ha in 2022–23. S1A0 exhibited an uptake of 105.25 kg/ha and 114.94 kg/ha in the two corresponding years. The minimal potassium uptake was recorded in S3A7, with only 24.20 kg/ha in 2021–22 and 26.28 kg/ha in 2022–23. In comparison to the minimum value, the optimal treatment (S1A6) showed a rise of 361.4% in 2021–22 and 352.0% in 2022–23. Within the S2 treatments (Bentonite sulphur), S2A6 exhibited commendable performance, yielding 93.14 kg/ha and 96.78 kg/ha, respectively. The pattern of potassium uptake across treatments remained stable across both years, with S1A6 retaining the leading position. These findings highlight the significance of choosing suitable sulphur sources and specific agrochemical strategies to enhance nutrient uptake efficiency, especially in diverse environmental situations.

The changes in potassium (K) uptake by straw under different treatments can be ascribed to the interactions among soil nutrients, water availability, and the physiological responses of the crop. Gypsum supplies readily accessible sulphate ions, which augment root activity and nutrient assimilation. Gypsum's calcium enhances soil structure and porosity, promoting improved root growth and nutrient uptake. This elucidates why gypsum treatments regularly demonstrate elevated potassium uptake. Bentonite Sulphur (S2) releases sulphate at a slower rate, as it is contingent upon microbial oxidation. The postponed availability restricts the effectiveness of potassium uptake during essential growth phases, leading to reduced potassium uptake relative to gypsum. Elemental sulphur (S3) necessitates considerable time and microbial activity for its conversion to sulphate. In settings of limited irrigation or reduced microbial activity, this process decelerates, constraining nutrient solubility and uptake (Kadirimangalam et al., 2024a; Morsy et al., 2022).

Hydrogel conserves soil moisture and enhances water accessibility to roots, fostering an ideal environment for nutrient solubilization and uptake. This is especially crucial for potassium, which is highly mobile in soil but relies on sufficient moisture for delivery to plant roots. Salicylic acid augments the plant's stress resilience by stimulating antioxidant mechanisms and enhancing membrane permeability. This enhances the effective movement of nutrients, particularly potassium, from the soil to plant tissues. The combination of hydrogel and salicylic acid fosters an optimal environment for nutrition uptake. Hydrogel guarantees moisture retention, whereas salicylic acid enhances nutrient translocation within the plant, resulting in maximal potassium uptake in combined treatments. (R. Ali et al., 2020; Kumar et al., 2020b; Meena et al., 2020a). Sufficient irrigation (as in A0) guarantees that potassium remains in a soluble state in the soil, promoting its uptake by roots. Restricted irrigation (A7) diminishes water availability, resulting in decreased mobility of potassium (K) and impairing its uptake (Bhatt et al., 2022). Potassium is a highly mobile nutrient essential for stomatal control, enzyme activation, and osmotic adjustment. Sufficient sulphur (from gypsum) and moisture (from hydrogel) facilitate these physiological actions, enhancing potassium assimilation and distribution into straw. In contrast, inadequate sulphur supply or limited irrigation impedes these activities, resulting in diminished uptake (Hasanuzzaman et al., 2018b). During flowering and pod formation, the crop's nutrient requirements, particularly for potassium, reach their zenith. Interventions implemented throughout these phases (e.g., salicylic acid during flowering and pod development) correspond with the crop's physiological requirements, hence augmenting potassium uptake. This explains why treatments involving timely agrochemical applications (A6) yielded the highest uptake (H. H. Ali et al., 2023; Islam et al., 2024; Nazim Pasha et al., 2017). Sulphur sources and moisture-retaining substances affect soil microbial activity, which regulates the availability of nutrients such as sulphate. An optimal microbial community under gypsum and hydrogel treatments enhances nutrient cycling and increases potassium availability for plant uptake.

The variations in potassium uptake among treatments result from the interaction of nutrient availability (sulphur), water retention (hydrogel), physiological enhancements (salicylic acid), and irrigation practices. Gypsum, when combined with hydrogel and salicylic acid, creates excellent conditions for enhancing potassium uptake, whereas treatments including elemental sulphur and limited irrigation demonstrate minimal effectiveness due to inadequate nutrient availability and moisture stress (Chen et al., 2024; Shanmugavel et al., 2023b).

Table 4.3.12.1: The impact of treatments on K uptake by straw (kg/ha) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	K uptake by straw (2021-22)	K uptake by straw (2022-23)
Sulphur sources		
S1: Gypsum	80.53[a]	84.98[a]
S2: Bentonite Sulphur	67.15[b]	69.26[b]
S3: Elemental Sulphur	40.00[c]	42.25[c]
CV (Sulphur Sources)	3.6	5.16
CD (Sulphur Sources)	1.81	2.71
Agrochemical		
A0: Control (Irrigation as per requirement)	81.98[b]	88.97[b]
A1: Hydrogel (2.5 kg/ha) as basal application	55.63[e]	57.83[e]
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	50.78[f]	52.00[f]
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	51.72[f]	53.48[f]
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	70.46[c]	72.27[c]
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	65.29[d]	67.10[d]
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	86.73[a]	91.44[a]
A7: Control (Restricted irrigation)	37.89[g]	40.87[g]
CD (Agrochemical)	3.06	2.27
CV (Sulphur Sources and agrochemical)	5.14	3.65

Table 4.3.12.2: The interaction impact of treatments on K uptake by straw (kg/ha) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	K uptake by straw (2021-22)	K uptake by straw (2022-23)
S1A0	105.25±1.58	114.94±2.19
S1A1	71.65±0.37	75.10±0.38
S1A2	65.40±2.54	67.54±2.57
S1A3	66.62±2.85	69.46±3.74
S1A4	90.75±3.76	93.85±0.46
S1A5	84.10±7.78	87.13±0.38
S1A6	111.67±0.55	118.75±0.57
S1A7	48.81±0.59	53.08±0.61
S2A0	87.93±5.84	93.66±1.70
S2A1	59.72±0.18	61.20±0.44
S2A2	54.51±.13	55.04±0.28
S2A3	55.52±0.22	56.61±3.87
S2A4	75.64±4.64	76.49±0.20
S2A5	70.09±4.30	71.01±10.09
S2A6	93.14±8.73	96.78±0.21
S2A7	40.68±0.20	43.26±0.21
S3A0	52.77±0.61	58.30±0.80
S3A1	35.53±0.22	37.18±0.23
S3A2	32.42±0.32	33.44±0.32
S3A3	33.03±0.16	34.39±0.17
S3A4	44.99±0.20	46.47±0.20
S3A5	41.69±0.24	43.14±0.24
S3A6	55.37±0.27	58.80±0.28
S3A7	24.20±0.18	26.28±0.19
CV	5.14	3.65
CD	5.25	4.53

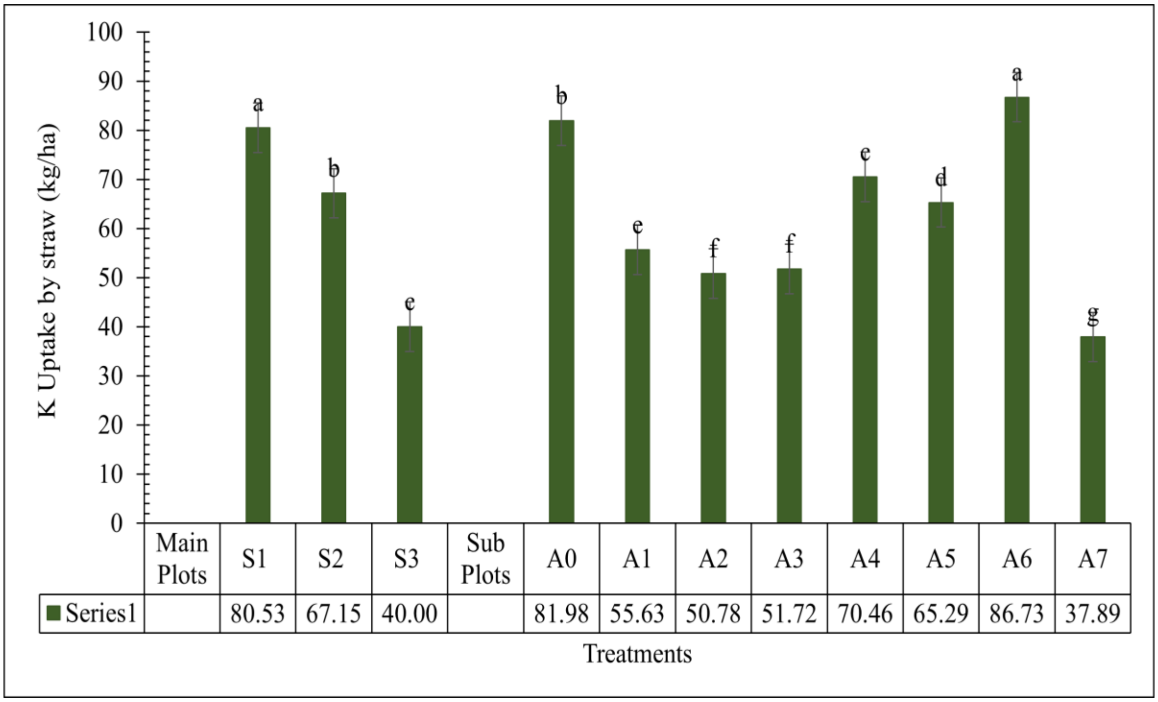


Fig:4.3.12.1(a) The impact of sulphur sources and agrochemical treatments on K uptake by straw (kg/ha) in the year 2021-2022

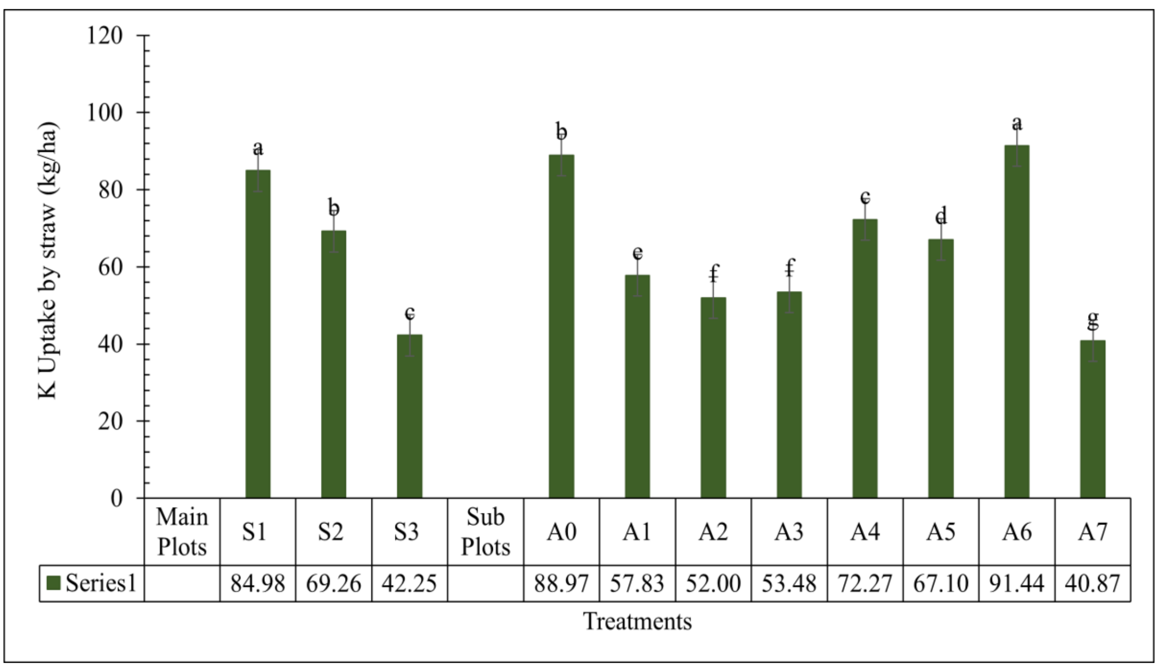


Fig:4.3.12.2(b) The impact of sulphur sources and agrochemical treatments on K uptake by straw (kg/ha) in the year 2022-2023

4.3.13 S Content in seed (%): The data in Table 4.3.13.1 and Figure 4.3.13.1(a), 4.3.13.2(b) demonstrate the impact of various sulphur sources and agrochemical treatments on the sulphur content in Gobhi Sarson (*Brassica napus* L.) seeds during the *rabi* seasons of 2021-22 and 2022-23. The sulphur concentration in the seeds was significantly influenced by both sulphur sources and agrochemical treatments in both years. The highest sulphur level among the sources was observed in Gypsum (S1) at 0.64% for both 2021–22 and 2022–23, followed by Bentonite Sulphur (S2) with 0.57% and 0.58%, respectively. The minimal sulphur content was recorded with Elemental Sulphur (S3), exhibiting merely 0.48% in both years, approximately 25% lower than Gypsum in 2021–22. A6 had the highest sulphur level of 0.64% in 2021–22 and 0.65% in 2022–23, comparable to or marginally surpassing the control with full irrigation (A0), which recorded 0.64% in both years. A4 and A5 treatments subsequently exhibited moderate sulphur levels between 0.59% and 0.61%, signifying enhanced sulphur assimilation relative to singular applications. The minimum sulphur level was seen in A7 (Restricted irrigation), with values of 0.46% in both years, indicating a 28.12% decrease in 2021–22 relative to A6. Likewise, the treatment of Hydrogel or Salicylic acid individually (A1, A2, A3) resulted in a decreased sulphur content ranging from 0.51% to 0.54%, indicating that their combination application is more efficacious. In conclusion, the optimal treatment for increasing sulphur content in seeds was the combination of Gypsum (S1) with A6 across the two years studied.

The interaction in Table 4.3.13.2 illustrates that the interaction effects of various sulphur sources and agrochemical treatments on the sulphur concentration in Gobhi Sarson seeds during the *rabi* seasons of 2021-22 and 2022-23 were significantly affected by the application of several sulphur sources in conjunction with hydrogel and salicylic acid. The maximum sulphur content was observed in treatment S1A6 with the value of 0.73% in 2021–22 and 0.74% in 2022–23. S1A0 (Gypsum alone) subsequently reported 0.71% and 0.73% in the relevant years. The minimum sulphur concentration was recorded in S3A7 with a mere 0.39% in both years. S1A6 exhibited a rise of 87.2% in 2021–22 and 89.7% in 2022–23 relative to the lowest value. Among the bentonite sulphur treatments, S2A6 had the highest performance with 0.65% and 0.66% across the two seasons. The consistent results throughout the years underscored the exceptional performance of S1A6 in augmenting sulphur accumulation in seeds, establishing it as the most effective treatment for raising sulphur content in Gobhi Sarson.

The increase in sulphur content of Gobhi Sarson (*Brassica napus* L.) seeds, especially with the simultaneous application of gypsum, hydrogel, and salicylic acid (SA), can be ascribed to various interrelated physiological and biochemical processes. Sulphur is an important macronutrient crucial for the production of critical amino acids such as cysteine and methionine, which serve as fundamental components of proteins. It also aids in the creation of coenzymes and is essential for chlorophyll synthesis, directly affecting photosynthetic efficiency and total plant growth. In Brassica species, sufficient sulphur availability correlates with enhanced seed oil content and superior protein quality. Sulphur deficiency, on the other hand, may result in delayed flowering, diminished seed set, and decreased seed yields (Bhattarai et al., 2021).

Gypsum functions as an efficient sulphur donor. Upon application to soil, it dissociates into calcium and sulphate ions. Sulphate ions are efficiently absorbed by plant roots and transported to different tissues, promoting the creation of sulphur-containing molecules. The increased seed sulphur content observed with gypsum application is likely attributable to its high solubility, which guarantees a steady supply of accessible sulphur during essential growth phases (Kadirimangalam et al., 2024b). Hydrogel, a superabsorbent polymer, enhances soil moisture retention, hence providing a consistent water supply to plants. The continuous availability of moisture improves nutrient uptake, particularly sulphur, by sustaining adequate soil hydration levels. Salicylic acid, a phenolic molecule, serves as a plant growth regulator and stress alleviator. The exogenous administration of salicylic acid has been demonstrated to strengthen antioxidant defense mechanisms, augment photosynthetic rates, and promote nutritional assimilation under stress conditions (Bano et al., 2022). The integration of hydrogel and SA probably produces an optimal environment for root functionality and nutrient uptake. Hydrogel preserves soil moisture, alleviating drought-related stress, whereas SA regulates physiological processes, improving the plant's capacity to ingest and utilize sulphur effectively. This synergy leads to enhanced sulphur accumulation in seeds, as seen by the elevated sulphur content in treatments that integrate hydrogel and SA applications, as recent studies validate these conclusions. A study published in ACS Agricultural Science & Technology revealed that sulphur treatments substantially affect seed production, oil content, and protein content in oilseed crops (Mohammadi et al., 2023).

The incorporation of gypsum as a sulphur source, along with hydrogel and salicylic acid treatments, improves sulphur uptake and assimilation in Gobhi Sarson. This method utilizes enhanced soil moisture retention and the regulation of plant physiological processes, resulting in elevated sulphur levels in seeds and overall enhanced crop performance.

Table 4.3.13.1: The impact of treatments on S content in seed (%) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	S content in seed (%) (2021-22)	S content in seed (%) (2022-23)
Sulphur sources		
S1: Gypsum	0.64[a]	0.64[a]
S2: Bentonite Sulphur	0.57[b]	0.58[b]
S3: Elemental Sulphur	0.48[c]	0.48[c]
CV (Sulphur Sources)	3.83	2.62
CD (Sulphur Sources)	0.02	0.01
Agrochemical		
A0: Control (Irrigation as per requirement)	0.64[a]	0.64[a]
A1: Hydrogel (2.5 kg/ha) as basal application	0.54[d]	0.54[c]
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	0.51[e]	0.52[d]
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	0.53[d]	0.53[c]
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	0.60[b]	0.61[b]
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	0.59[c]	0.59[b]
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	0.64[a]	0.65[a]
A7: Control (Restricted irrigation)	0.46[f]	0.46[e]
CD (Agrochemical)	0.01	0.02
CV (Sulphur Sources and agrochemical)	2.35	2.77

Table 4.3.13.2: The interaction impact of treatments on S content in seed (%) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	S content in seed (%) (2021-22)	S content in seed (%) (2022-23)
S1A0	0.71±0.01	0.73±0.01
S1A1	0.61±0.01	0.62±0.01
S1A2	0.58±0.01	0.59±0.01
S1A3	0.60±0.01	0.60±0.01
S1A4	0.68±0.01	0.69±0.01
S1A5	0.66±0.01	0.67±0.01
S1A6	0.73±0.01	0.74±0.01
S1A7	0.52±0.01	0.52±0.02
S2A0	0.66±0.03	0.64±0.02
S2A1	0.54±0.00	0.55±0.01
S2A2	0.52±0.00	0.52±0.01
S2A3	0.53±0.00	0.54±0.00
S2A4	0.61±0.00	0.62±0.00
S2A5	0.59±0.00	0.60±0.06
S2A6	0.65±0.05	0.66±0.00
S2A7	0.46±0.00	0.47±0.00
S3A0	0.56±0.03	0.55±0.02
S3A1	0.46±0.01	0.46±0.01
S3A2	0.44±0.01	0.44±0.01
S3A3	0.45±0.00	0.45±0.00
S3A4	0.51±0.00	0.51±0.00
S3A5	0.50±0.01	0.50±0.01
S3A6	0.55±0.01	0.55±0.01
S3A7	0.39±0.01	0.39±0.01
CV	2.35	2.77
CD	0.03	0.03

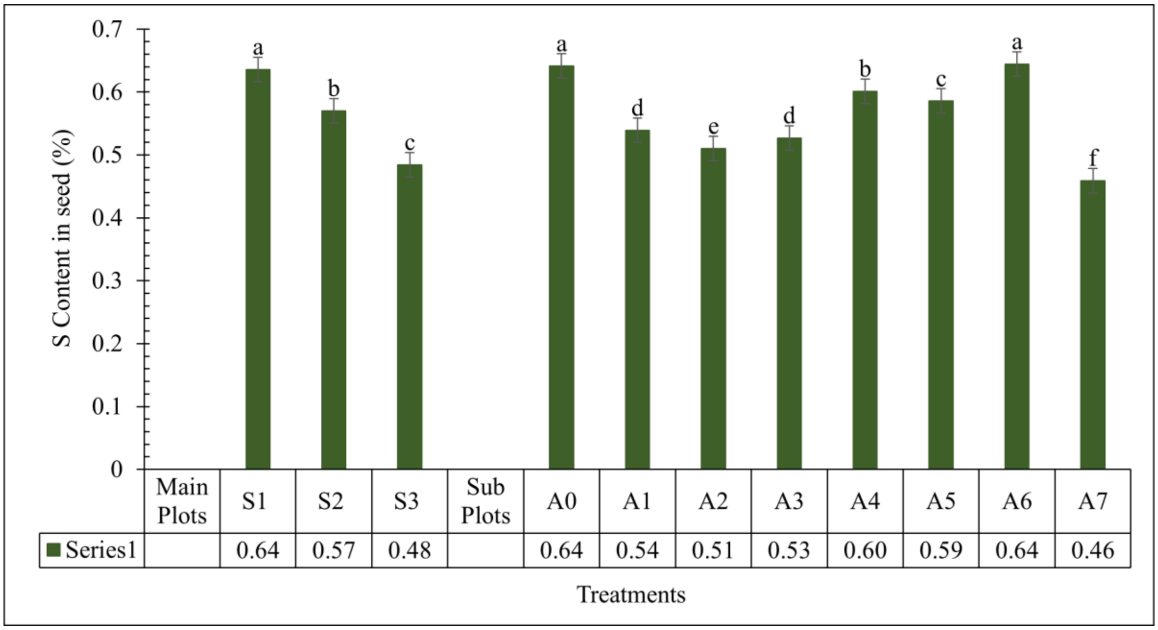


Fig:4.3.13.1(a) The impact of sulphur sources and agrochemical treatments on S content in seed (%) in the year 2021-2022

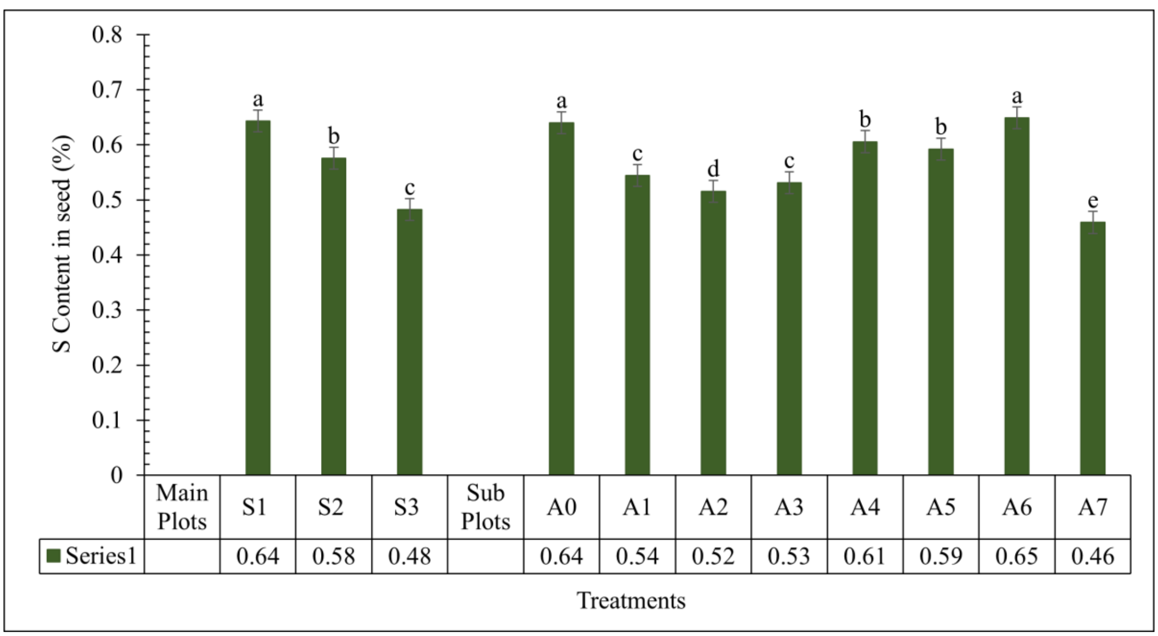


Fig:4.3.13.2(b) The impact of sulphur sources and agrochemical treatments on S content in seed (%) in the year 2022-2023

4.3.14 S Content in straw (%): Table 4.3.14.1 and Figure 4.3.14.1(a), 4.3.14.2(b) display the sulphur (S) concentration in Gobhi Sarson (*Brassica napus* L.) straw subjected to various sulphur sources and agrochemical treatments during the *rabi* seasons of 2021-22 and 2022-23. The sulphur content in straw was significantly influenced by both sulphur sources and agrochemical treatments throughout both years. Among the sources of sulphur, Gypsum (S1) exhibited the greatest sulphur concentration in straw, measuring 0.31% in both 2021–22 and 2022–23, followed by Bentonite Sulphur (S2) at 0.27% and 0.28%, respectively. The minimal levels were observed with Elemental Sulphur (S3), which registered 0.18% in both years, approximately 41.94% lower than Gypsum in 2021–22. The highest sulphur concentration in straw was observed under treatment A6 (Hydrogel + Salicylic acid throughout both flowering and pod development), registering 0.31% in 2021–22 and 0.32% in 2022–23, closely aligning with the fully irrigated control A0, which exhibited 0.30% in both years. Moderate sulphur content was recorded under A4 and A5 (combined applications during flowering or pod formation), ranging from 0.26% to 0.28%. In contrast, the lowest values were observed under A7 (restricted irrigation), with 0.18% in 2021–22 and 0.19% in 2022–23, indicating a 41.93% decrease compared to A6 in the initial year. Individual applications of hydrogel or salicylic acid (A1, A2, A3) yielded moderate outcomes, typically between 0.22% and 0.25%, although they were markedly inferior to the effects of combination application treatments. In conclusion, the optimal treatment for enhancing sulphur content in straw was the combination of Gypsum (S1) with A6 across the two years studied. The data indicate that utilizing gypsum as a sulphur source and the concurrent application of hydrogel with salicylic acid during both the 50% flowering and pod development stages substantially increased sulphur content in straw, but limited irrigation adversely affected sulphur uptake. The findings underscore the significance of sufficient water availability and suitable sulphur sources in enhancing sulphur buildup in Gobhi Sarson under controlled irrigation conditions.

The interaction effects of sulphur sources and agrochemical treatments on sulphur (S) concentration in the straw of Gobhi Sarson (*Brassica napus* L.) during the *rabi* seasons of 2021-22 and 2022-23 in Table 4.3.14.2 demonstrated considerable variability among treatments. Among sulphur sources, S1 (Gypsum) exhibited the greatest sulphur concentration at 0.38% in both years (S1A6), followed by 0.37% (S1A0). Conversely, S3

(Elemental Sulphur) exhibited the lowest sulphur level, varying from 0.13% to 0.16%. S1A6 (Gypsum + Hydrogel + Salicylic acid) had superior efficacy, surpassing S3A7 (Elemental Sulphur + Restricted irrigation) by 63.1% and 66.7% throughout the 2021–22 and 2022–23 periods, respectively. A6 exhibited superior performance in agrochemical treatments, achieving 0.38% in both years, comparable to S1A6 with Gypsum. The minimal values were recorded in A7 (Restricted irrigation), at 0.13% for both 2021–22 and 2022–23. The findings indicate that the combination of Gypsum (S1) with Hydrogel and Salicylic acid (A6) optimizes sulphur content in straw, whereas Elemental Sulphur (S3) and Restricted irrigation (A7) produced the lowest sulphur concentrations. The findings indicate that gypsum was the most efficacious sulphur source for enhancing sulphur content in straw, followed by bentonite sulphur, while elemental sulphur proved to be the least effective. The combination of hydrogel and salicylic acid throughout both flowering and pod formation stages greatly increased sulphur content, whereas limiting irrigation produced the lowest levels. These findings underscore the significance of choosing a suitable sulphur source and agrochemical combination to enhance sulphur formation in Gobhi Sarson under controlled irrigation conditions.

The underscoron in sulphur (S) concentration in Gobhi Sarson (*Brassica napus* L.) straw across different treatments can be ascribed to variations in sulphur sources, agrochemical applications, and their interactions with soil-plant dynamics. The efficacy of gypsum ($CaSO_4 \cdot 2H_2O$) in augmenting sulphur content relative to bentonite sulphur and elemental sulphur is attributed to its elevated solubility, fast availability of sulphate (SO_4^{2-}) ions, and enhanced uptake by plants. In contrast, elemental sulphur (S^0) necessitates microbial oxidation to sulphate, a gradual process influenced by soil microbial activity, temperature, and moisture availability, resulting in diminished sulphur uptake and buildup in plant tissues. Gypsum (S1) demonstrated the highest sulphur concentration in straw owing to its readily accessible sulphate form, which is immediately assimilated by plant roots without microbial conversion. Sulphate uptake via root transporters is more efficient when sulphur is provided in the sulphate form as opposed to elemental or complexed forms (Scherer, 2001). Bentonite sulphur (S2), including S^0 combined with clay for enhanced dispersion, exhibited moderate sulphur content, necessitating oxidation to sulphate, albeit at a more rapid rate than elemental sulphur alone. Elemental sulphur (S3), characterized by its minimal solubility, demonstrated the lowest sulphur concentration in straw owing to its dependence on gradual microbial oxidation. Numerous research has validated the enhanced efficacy of gypsum in sulphur feeding. A study indicated that sulphate-S fertilizers, including gypsum, markedly enhanced sulphur availability and uptake relative to elemental sulphur. The elevation of sulphur content with hydrogel and salicylic acid treatments (A6) indicates improved nutrient retention and uptake efficiency. Hydrogel functions as a water retention agent, enhancing soil moisture levels, hence promoting nutrient solubility and root uptake. Enhanced soil moisture guarantees the sustained availability of sulphate ions for plant uptake, particularly under controlled irrigation environments (Degryse et al., 2016b; Fuentes-Lara et al., 2019; Svensson et al., 2020).

Salicylic acid (SA) is essential for controlling sulphur uptake and assimilation by stimulating root activity and upregulating sulphate transporter genes. The application at 50% flowering and 50% pod development (A6) yielded the maximum sulphur concentration due to extended stimulation of sulphur metabolism. Salicylic acid enhances ATP sulphurylase activity, which facilitates the initial phase of sulphur assimilation by converting sulphate to adenosine 5'-phosphosulphate (Fu et al., 2018; Puresmaeli et al., 2023).

Research demonstrated that salicylic acid improves plant stress resilience and nutrient uptake by altering root structure and physiological functions, and the simultaneous application of hydrogel and growth regulators enhanced sulphur uptake and seed yield in oilseed crops. The synergistic impact shown in the interaction treatments (S1A6) is likely attributable to enhanced nutritional availability from gypsum, moisture retention by hydrogel, and biochemical activation by salicylic acid. Restricted irrigation (A7) led to the lowest sulphur concentration among all sulphur sources due to constrained sulphate mobility and uptake under moisture stress conditions. A study by Cao et al. (2014) titled "Sulphate availability affects ABA levels and germination response to ABA and salt stress in A*rabi*dopsis thaliana" investigates the relationship between sulphate availability and plant stress responses. The researchers discovered that sulphate availability affects abscisic acid (ABA) concentrations, a crucial hormone in drought response, suggesting a link between sulphur feeding and drought tolerance mechanisms (Lee et al., 2022).

The enhanced efficacy of gypsum in increasing sulphur content in Gobhi Sarson straw is due to its prompt sulphate availability, whereas bentonite sulphur showed intermediate effectiveness, and elemental sulphur displayed the least effectiveness owing to slow microbial oxidation. The utilization of hydrogel enhanced moisture retention, guaranteeing sustained sulphate availability, whereas salicylic acid promoted root activity and sulphur uptake, resulting in increased sulphur content in straw. The maximum sulphur content was seen with the application of gypsum, hydrogel, and salicylic acid during both flowering and pod formation stages (S1A6), underscoring the synergistic advantages of using water retention polymers and biostimulants in sulphur fertilization approaches. These findings are well corroborated by prior research, nderscoreing the need to choose suitable sulphur sources and agrochemical applications to enhance sulphur uptake and agricultural yield.

Table 4.3.14.1: The impact of treatments on S content in straw (%) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	S content in straw (2021-22)	S content in straw (2022-23)
Sulphur sources		
S1: Gypsum	0.31[a]	0.31[a]
S2: Bentonite Sulphur	0.27[b]	0.28[b]
S3: Elemental Sulphur	0.18[c]	0.18[c]
CV (Sulphur Sources)	5.78	4.94
CD (Sulphur Sources)	0.012	0.010
Agrochemical		
A0: Control (Irrigation as per requirement)	0.30[b]	0.30[b]
A1: Hydrogel (2.5 kg/ha) as basal application	0.24[e]	0.25[e]
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	0.22[f]	0.23[f]
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	0.23[e]	0.24[e]
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	0.27[c]	0.28[c]
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	0.26[d]	0.27[d]
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	0.31[a]	0.32[a]
A7: Control (Restricted irrigation)	0.18[g]	0.19[g]
CD (Agrochemical)	0.010	0.008
CV (Sulphur Sources and agrochemical)	4.05	3.45

Table 4.3.14.2: The interaction impact of treatments on S content in straw (%) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	**S content in straw (2021-22)**	**S content in straw (2022-23)**
S1A0	0.37±0.01	0.37±0.01
S1A1	0.29±0.01	0.30±0.01
S1A2	0.27±0.01	0.27±0.01
S1A3	0.29±0.01	0.29±0.01
S1A4	0.33±0.01	0.33±0.00
S1A5	0.31±0.00	0.32±0.00
S1A6	0.38±0.00	0.38±0.00
S1A7	0.22±0.00	0.22±0.00
S2A0	0.31±0.03	0.33±0.01
S2A1	0.26±0.00	0.26±0.00
S2A2	0.24±0.00	0.24±0.00
S2A3	0.25±0.00	0.26±0.00
S2A4	0.30±0.00	0.30±0.00
S2A5	0.28±0.00	0.29±0.04
S2A6	0.33±0.03	0.34±0.00
S2A7	0.19±0.00	0.20±0.00
S3A0	0.21±0.01	0.21±0.01
S3A1	0.17±0.00	0.18±0.00
S3A2	0.16±0.01	0.16±0.00
S3A3	0.16±0.00	0.17±0.00
S3A4	0.19±0.00	0.20±0.00
S3A5	0.18±0.00	0.19±0.00
S3A6	0.22±0.00	0.23±0.00
S3A7	0.13±0.00	0.13±0.00
CV	4.05	3.45
CD	0.02	0.02

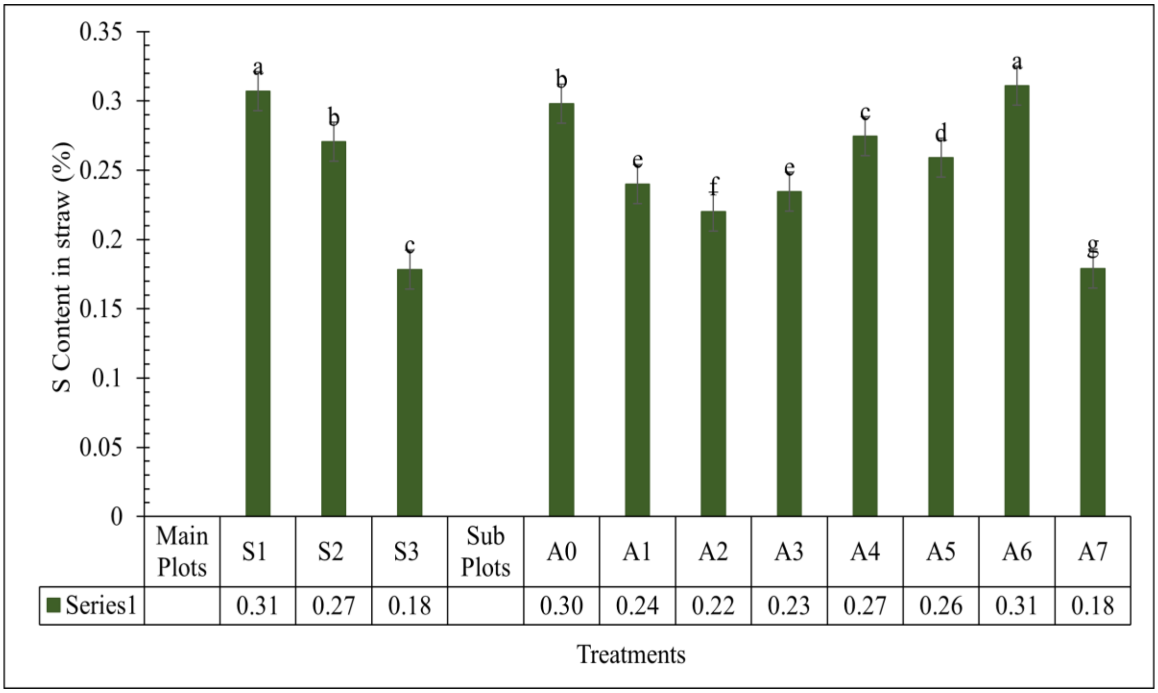


Fig:4.3.14.1(a) The impact of sulphur sources and agrochemical treatments on S content in straw (%) in the year 2021-2022

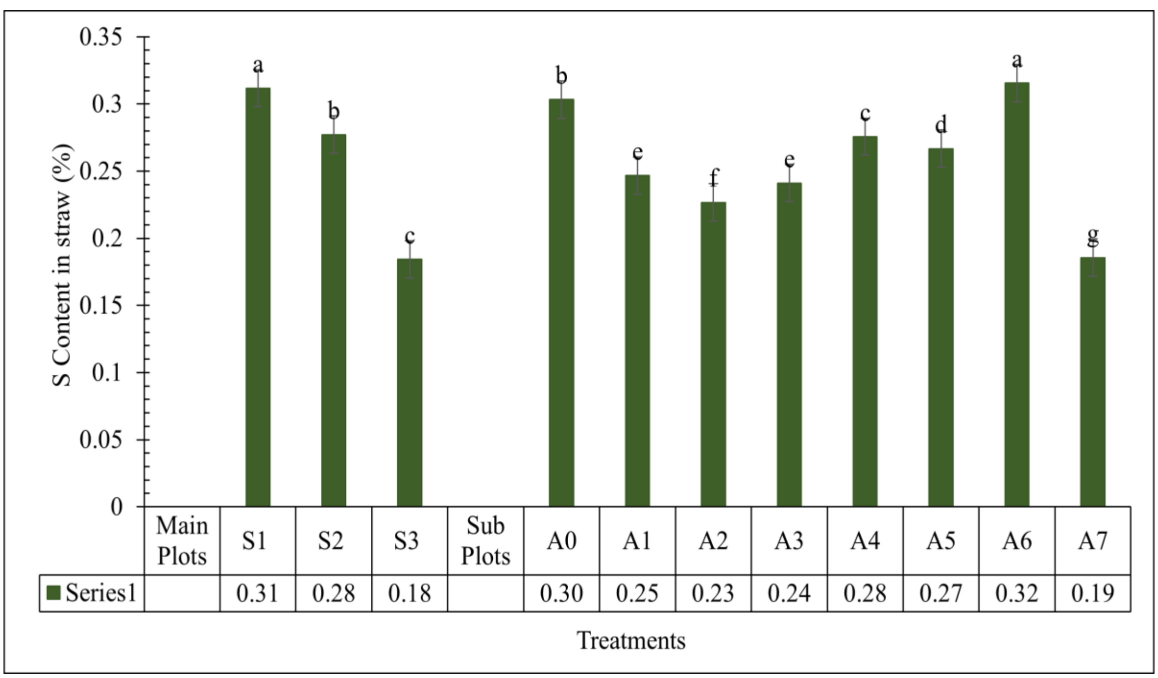


Fig:4.3.14.2(b) The impact of sulphur sources and agrochemical treatments on S content in straw (%) in the year 2022-2023

4.3.15 S Uptake by Seed (kg/ha): The sulphur (S) uptake by seed (kg/ha) of Gobhi Sarson (*Brassica napus* L.) across multiple treatments utilizing different sulphur sources and agrochemical applications throughout the *rabi* seasons of 2021-22 and 2022-23 is displays in table 4.3.15.1 and Figure 4.3.15.1(a), 4.3.15.2(b). Sulphur uptake by seeds was significantly affected by the sources of sulphur and the agrochemical treatments applied in both years. Gypsum (S1) demonstrated the highest sulphur uptake by seed, recording 12.83 kg/ha in 2021–22 and 13.17 kg/ha in 2022–23. This was followed by Bentonite Sulphur (S2), which showed uptake values of 10.36 kg/ha and 10.63 kg/ha for the respective years. The lowest uptake was observed with Elemental Sulphur (S3), at 6.90 and 6.93 kg/ha, representing a 46.23% reduction compared to Gypsum in the first year. A6 demonstrated the highest sulphur uptake, recording 13.21 kg/ha in 2021–22 and 13.51 kg/ha in 2022–23, which was significantly greater than all other treatments. The full irrigation control A0 yielded 12.41 and 12.73 kg/ha, while the combined treatments A4 and A5 produced results between 11.18 and 11.42 kg/ha over the two years. The lowest sulphur uptake occurred in A7 (Restricted irrigation), measuring 6.45 kg/ha in 2021–22 and 6.63 kg/ha in 2022–23, representing a 51.17% reduction compared to A6 in the initial year. Single applications of Hydrogel (A1) and Salicylic acid (A2, A3) exhibited moderate to low uptake values, ranging from 8 to 9.33 kg/ha.The optimal treatment for enhancing sulphur uptake by seeds was the combination of Gypsum (S1) with A6 (Hydrogel + Salicylic acid at both flowering and pod formation) across both *Rabi* seasons.

The interaction Table 4.3.15.2 illustrates the interaction impact of sulphur sources (S) and agrochemical treatments (A) on sulphur uptake by seed (kg/ha) of Gobhi Sarson (*Brassica napus* L.) during the *rabi* seasons of 2021-22 and 2022-23. Among the treatments, S1A6 (Gypsum + Hydrogel at 2.5 kg/ha + Salicylic acid at 150 ppm during 50% flowering and pod formation) exhibited the highest sulphur uptake, recording values of 16.96 kg/ha in 2021–22 and 17.41 kg/ha in 2022–23. The lowest uptake was recorded under S3A7 (Elemental sulphur + restricted irrigation), at 4.42 kg/ha and 4.48 kg/ha, respectively. This reflects an increase of approximately 283.6% in 2021–22 and approximately 288.6% in 2022–23 under the optimal treatment relative to the minimal one. Other significant treatments comprised S1A0 (Gypsum + control irrigation) and S1A5 (Gypsum + Hydrogel + Salicylic acid at pod formation), which demonstrated relatively higher uptake values between 14.37 and 15.51 kg/ha, surpassing the majority of treatments under S2 (Bentonite sulphur) and S3 (Elemental sulphur) sources. S1A6 emerged as the most effective treatment for enhancing sulphur uptake by seed across both years, demonstrating the synergistic effects of gypsum and combined agrochemical application under controlled irrigation.

The increased sulphur uptake observed in Gypsum (S1) relative to Bentonite Sulphur (S2) and Elemental Sulphur (S3) can be attributed to variations in their chemical characteristics and accessibility to plants. Gypsum ($CaSO_4 \cdot 2H_2O$) is a highly soluble source of sulphur, easily releasing accessible sulphate (SO_4^{2-}) ions that can be directly assimilated by plant roots. Moreover, gypsum enhances soil structure, aeration, and water retention, fostering a more conducive environment for root development and nutrient uptake. Calcium (Ca^{2+}) increases root membrane permeability, hence promoting sulphur uptake. Conversely, Bentonite Sulphur (S2) experiences microbial oxidation to liberate sulphate, resulting in a slower availability compared to gypsum. The oxidation process is contingent upon soil moisture, temperature, and microbial activity, all of which may fluctuate over the crop growth cycle. Elemental Sulphur (S3) shown the minimal uptake due to the necessity for microbial oxidation by Thiobacillus bacteria to transform into the plant-available sulphate form, a process that is gradual and contingent upon microbial population and environmental conditions. The postponed accessibility of sulphur from elemental sulphur led to diminished uptake efficiency relative to alternative sources (Ali Turan et al., 2005; Grava De Godoy & França, 2015; Hussien, 2024b; O. A. Khan et al., 2018a).

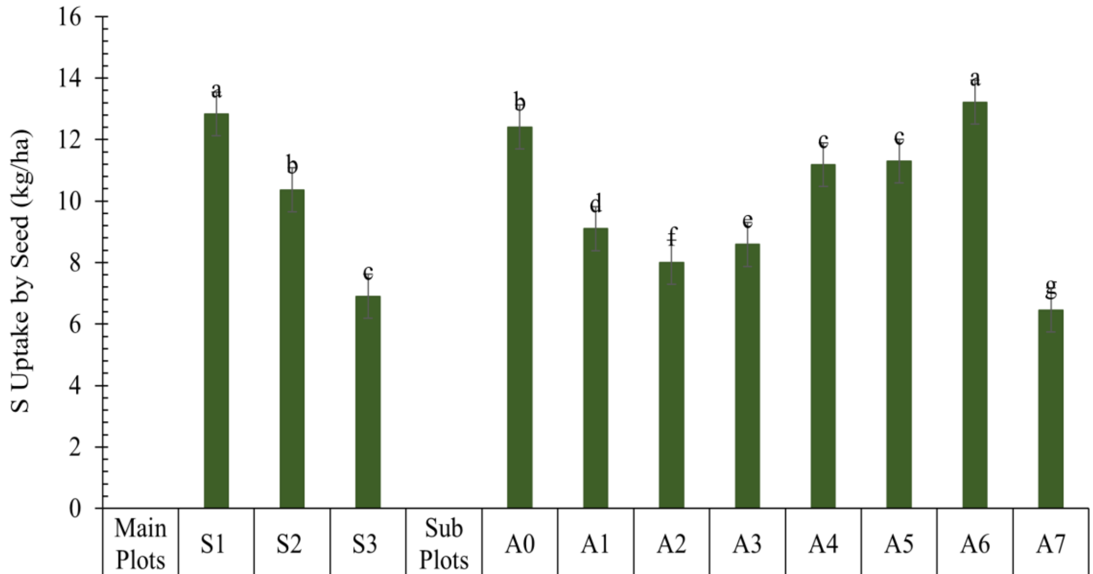
The impact of applications on sulphur uptake is also associated with water and nutrient dynamics. The maximum sulphur uptake was seen in A6 (Hydrogel at 2.5 kg/ha + Salicylic acid at 150 ppm during 50% flowering + 50% pod development), attributable to the synergistic effects of hydrogel on soil moisture retention and salicylic acid on nutrient transport enhancement. Hydrogel, a superabsorbent polymer, absorbs and holds substantial quantities of water, establishing a consistent moisture supply in the root zone, hence enhancing nutrient solubility and mobility. This guarantees the prolonged availability of sulphate ions for plant uptake, hence mitigating nutrient leaching during controlled irrigation. Salicylic acid, a phytoregulator, enhances nutrient transport and metabolism, hence improving the plant's capacity to absorb and utilize sulphur effectively. Its function in promoting root development and enhancing the expression of sulphur transporter genes further facilitates enhanced sulphur uptake (Guilherme et al., 2015; Oladosu et al., 2022b; Sousa et al., 2021). Conversely, A7 (Restricted Irrigation) exhibited the lowest sulphur uptake, indicating the detrimental effect of water stress on nutrient uptake. Water stress results in diminished root elongation, decreased microbial activity, and restricted sulphate solubility, thereby limiting nutrient availability. The lack of hydrogel and salicylic acid in A7 intensified the issue by restricting moisture retention and diminishing sulphur mobilization. These findings underscore the significance of integrated water and nutrient management strategies, especially the amalgamation of gypsum with hydrogel and salicylic acid, to enhance sulphur uptake and elevate crop performance under controlled irrigation settings.

Table 4.3.15.1: The impact of treatments on S uptake by seed (kg/ha) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	S uptake by seed (kg/ha) (2021-22)	S uptake by seed (kg/ha) (2022-23)
Sulphur sources		
S1: Gypsum	12.83[a]	13.17[a]
S2: Bentonite Sulphur	10.36[b]	10.63[b]
S3: Elemental Sulphur	6.90[c]	6.93[c]
CV (Sulphur Sources)	6.27	4.87
CD (Sulphur Sources)	0.50	0.40
Agrochemical		
A0: Control (Irrigation as per requirement)	12.41[b]	12.73[b]
A1: Hydrogel (2.5 kg/ha) as basal application	9.10[d]	9.33[d]
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	8.00[f]	8.23[f]
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	8.59[e]	8.73[e]
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	11.18[c]	11.37[c]
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	11.30[c]	11.42[c]
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	13.21[a]	13.51[a]
A7: Control (Restricted irrigation)	6.45[g]	6.63[g]
CD (Agrochemical)	0.42	0.40
CV (Sulphur Sources and agrochemical)	4.4	4.15

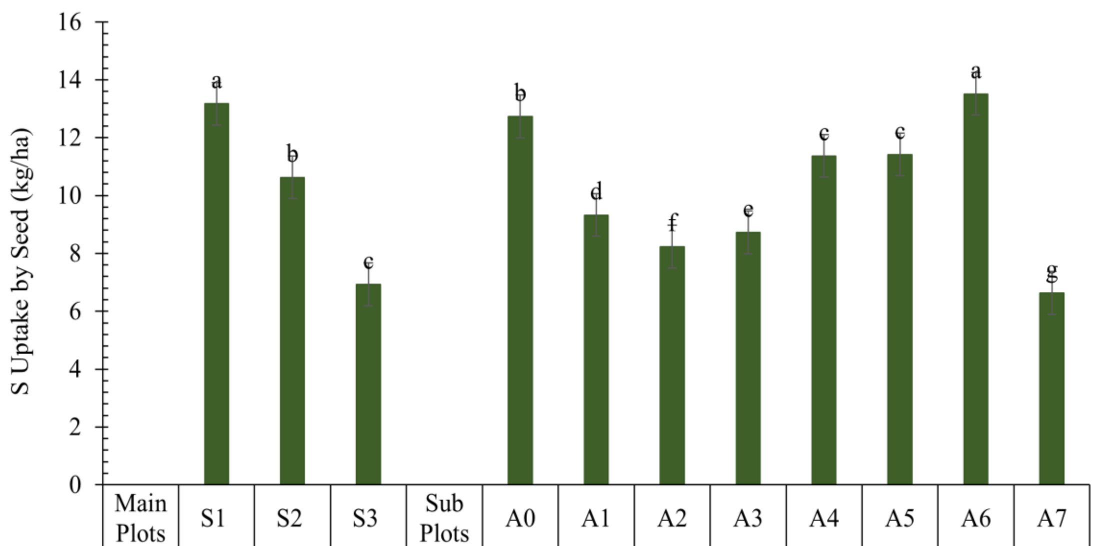
Table 4.3.15.2: The interaction impact of treatments on S uptake by seed (kg/ha) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	S uptake by seed (kg/ha) (2021-22)	S uptake by seed (kg/ha) (2022-23)
S1A0	15.51±0.46	16.22±0.44
S1A1	11.69±0.20	12.01±0.20
S1A2	10.28±0.80	10.61±0.80
S1A3	11.03±0.91	11.25±1.17
S1A4	14.37±0.13	14.64±0.14
S1A5	14.51±0.18	14.71±0.18
S1A6	16.96±0.26	17.41±0.26
S1A7	8.29±0.18	8.54±0.30
S2A0	12.97±1.03	13.34±0.33
S2A1	9.38±0.08	9.66±0.22
S2A2	8.25±0.06	8.52±0.15
S2A3	8.85±0.10	9.04±0.10
S2A4	11.52±0.09	11.77±0.09
S2A5	11.64±0.07	11.82±1.15
S2A6	13.63±1.36	14.00±0.10
S2A7	6.65±0.09	6.87±0.10
S3A0	8.74±0.24	8.64±0.43
S3A1	6.23±0.12	6.31±0.12
S3A2	5.48±0.16	5.56±0.16
S3A3	5.88±0.08	5.89±0.08
S3A4	7.66±0.09	7.69±0.09
S3A5	7.74±0.14	7.72±0.14
S3A6	9.05±0.15	9.13±0.15
S3A7	4.42±0.10	4.48±0.10
CV	4.4	4.15
CD	0.84	0.76



	Main Plots	S1	S2	S3	Sub Plots	A0	A1	A2	A3	A4	A5	A6	A7
Series1		12.83	10.36	6.90		12.41	9.10	8.00	8.59	11.18	11.30	13.21	6.45

Fig:4.3.15.1(a): The impact of sulphur sources and agrochemical treatments on S uptake by seed (kg/ha) in the year 2021-2022



	Main Plots	S1	S2	S3	Sub Plots	A0	A1	A2	A3	A4	A5	A6	A7
Series1		13.17	10.63	6.93		12.73	9.33	8.23	8.73	11.37	11.42	13.51	6.63

Fig:4.3.15.2(b): The impact of sulphur sources and agrochemical treatments on S uptake by seed (kg/ha) in the year 2022-2023

4.3.16 S uptake by straw (kg/ha): The data in Table 4.3.16.1 and Figure 4.3.16.1(a) and 4.3.16.2(b) demonstrate the sulphur uptake by Gobhi Sarson (*Brassica napus* L.) straw, impacted by various sulphur sources and agrochemical treatments over the *rabi* seasons of 2021-22 and 2022-23. Gypsum (S1) demonstrated the highest sulphur uptake, recording 11.47 kg/ha in 2021–22 and 11.89 kg/ha in 2022–23. Bentonite Sulphur (S2) followed, with uptake values of 8.93 kg/ha and 9.31 kg/ha for the respective years. The lowest uptake occurred with Elemental Sulphur (S3), which recorded 4.57 and 4.82 kg/ha, reflecting a 60.14% reduction in comparison to Gypsum during the 2021–22 period. A6 (Hydrogel + Salicylic acid at flowering and pod formation) demonstrated the highest sulphur uptake by straw, recording 11.58 kg/ha in 2021–22 and 12.22 kg/ha in 2022–23 among agrochemical treatments. A0 (Control under full irrigation) yielded 11.03 and 11.51 kg/ha, while A4 (Hydrogel + SA at flowering) produced 9.34 and 9.35 kg/ha, respectively. The lowest uptake occurred in A7 (Restricted irrigation), recording 4.66 kg/ha in 2021–22 and 5.02 kg/ha in 2022–23, representing a 59.75% reduction compared to A6 in the initial year. Intermediate treatments A1, A2, A3, and A5 exhibited moderate values between 6.60 and 9.02 kg/ha, suggesting partial enhancement through single or combined applications. The combination of Gypsum (S1) and A6 (Hydrogel + Salicylic acid during flowering and pod formation) proved to be the most effective treatment for enhancing S uptake by straw in both *rabi* seasons.

Table 4.3.16.2 illustrates the interaction effects of various sulphur sources and agrochemical treatments on sulphur uptake by straw (kg/ha) of Gobhi Sarson (*Brassica napus* L.) during the *rabi* seasons of 2021-22 and 2022-23. The maximum sulphur uptake by straw occurred under the S1A6 treatment (Gypsum + Hydrogel at 2.5 kg/ha + Salicylic acid at 150 ppm during 50% flowering and pod formation), yielding 15.90 kg/ha in 2021–22 and 16.73 kg/ha in 2022–23. The lowest uptake occurred in S3A7 (Elemental sulphur + restricted irrigation), recording 2.56 kg/ha and 2.80 kg/ha in the respective years. This represents an increase of approximately 521.9% in 2021–22 and 497.5% in 2022–23 for the best-performing treatment relative to the lowest. Additional treatments exhibiting increased sulphur uptake were S1A0 (15.46 & 15.90 kg/ha), S2A6 (12.49 & 13.13 kg/ha), and S1A4 (12.83 & 12.80 kg/ha), highlighting the advantageous impact of gypsum and the synergistic effects of combined agrochemicals. Treatments utilizing elemental sulphur

(S3), particularly in conjunction with limited irrigation, demonstrated the lowest sulphur uptake values consistently over both years. Consequently, S1A6 proved to be the most effective treatment for enhancing sulphur uptake by straw in Gobhi Sarson, highlighting the benefits of gypsum in conjunction with the integrated application of hydrogel and salicylic acid under controlled irrigation conditions.

The variations in sulphur uptake by Gobhi Sarson (*Brassica napus* L.) across different treatments can be ascribed to multiple physiological, biochemical, and edaphic mechanisms that affect sulphur availability, plant uptake, and stress responses. Critical elements encompass the solubility and conversion of sulphur supplies in the soil, the efficacy of plant sulphate transporters, the influence of hydrogel on soil moisture retention, and the function of salicylic acid in stress alleviation. Gypsum ($CaSO_4 \cdot 2H_2O$) supplies readily accessible sulphate ions (SO_4^{2-}), which are directly assimilated by plant roots through high-affinity sulphate transporters, specifically SULTR1;1 and SULTR1;2. These transporters enhance sulphate uptake, resulting in augmented sulphur assimilation in plants (Yoshimoto et al., 2002). Bentonite Sulphur source comprises elemental sulphur combined with bentonite clay. Elemental sulphur necessitates microbial oxidation to transform into plant-accessible sulphate, a process affected by soil moisture, temperature, and the presence of sulphur-oxidizing bacteria. Studies demonstrate that soil moisture levels and microbial populations substantially influence the rate of elemental sulphur oxidation, thereby affecting its accessibility to plants. (Zhao, Wang, et al., 2022). Elemental sulphur relies only on microbial oxidation for its conversion to sulphate. The conversion rate may be inadequate to satisfy the immediate sulphur requirements of crops, especially in situations where conditions hinder rapid microbial activity. Research indicates that the contribution of elemental sulphur to plant sulphur uptake may be restricted during the initial growing season following application. Hydrogels are superabsorbent polymers that augment soil moisture retention, thus enhancing nutrient availability and uptake. Elevated soil moisture promotes the microbial oxidation of elemental sulphur to sulphate, hence improving its accessibility to plants. Research indicates that the use of hydrogel enhances soil moisture levels, resulting in improved nutrient uptake and greater crop output. SA is a phytohormone recognized for its ability to improve plant stress resilience by regulating physiological processes like photosynthesis and transpiration. The exogenous administration of salicylic acid enhances antioxidant defense mechanisms in plants, facilitating improved nutrient uptake under stress conditions (Chang et al., 2021; Dingley et al., 2024; Krasnopeeva et al., 2022b; S. Malik et al., 2023). The synergistic use of hydrogel and SA can promote soil moisture retention and improve stress tolerance. This combination enhances root development and nutrient uptake, leading to improved sulphur assimilation by plants. The enhanced sulphur uptake observed with gypsum application results from the supply of readily accessible sulphate ions. The higher efficacy of treatments incorporating hydrogel and salicylic acid is due to greater soil moisture levels and heightened plant stress resilience, which promote superior nutrient uptake.

Table 4.3.16.1: The impact of treatments on S uptake by straw (kg/ha) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	S uptake by straw (kg/ha) (2021-22)	S uptake by straw (kg/ha) (2022-23)
Sulphur sources		
S1: Gypsum	11.47[a]	11.89[a]
S2: Bentonite Sulphur	8.93[b]	9.31[b]
S3: Elemental Sulphur	4.57[c]	4.82[c]
CV (Sulphur Sources)	6.55	7.28
CD (Sulphur Sources)	0.44	0.51
Agrochemical		
A0: Control (Irrigation as per requirement)	11.03[b]	11.51[b]
A1: Hydrogel (2.5 kg/ha) as basal application	7.62[e]	7.93[e]
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	6.60[g]	6.87[g]
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	7.07[f]	7.45[f]
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	9.34[c]	9.35[c]
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	8.69[d]	9.02[d]
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	11.58[a]	12.22[a]
A7: Control (Restricted irrigation)	4.66[h]	5.02[h]
CD (Agrochemical)	0.45	0.33
CV (Sulphur Sources and agrochemical)	5.67	4.03

Table 4.3.16.2: The interaction impact of treatments on S uptake by straw (kg/ha) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	S uptake by straw (kg/ha) (2021-22)	S uptake by straw (kg/ha) (2022-23)
S1A0	15.46±0.60	15.90±0.25
S1A1	10.47±0.39	10.86±0.37
S1A2	9.07±0.45	9.40±0.46
S1A3	9.71±0.51	10.20±0.73
S1A4	12.83±0.21	12.80±0.21
S1A5	11.93±0.18	12.35±0.18
S1A6	15.90±0.06	16.73±0.06
S1A7	6.40±0.06	6.87±0.07
S2A0	11.57±1.23	12.27±0.29
S2A1	8.21±0.12	8.52±0.13
S2A2	7.12±0.09	7.38±0.09
S2A3	7.62±0.15	8.01±0.63
S2A4	10.07±0.72	10.05±0.13
S2A5	9.37±0.65	9.69±1.31
S2A6	12.49±1.27	13.13±0.18
S2A7	5.03±0.04	5.40±0.04
S3A0	6.04±0.10	6.35±0.24
S3A1	4.18±0.07	4.42±0.07
S3A2	3.62±0.28	3.83±0.09
S3A3	3.88±0.11	4.15±0.11
S3A4	5.13±0.13	5.21±0.13
S3A5	4.76±0.07	5.02±0.07
S3A6	6.35±0.08	6.81±0.09
S3A7	2.56±0.06	2.80±0.06
CV	5.67	4.03
CD	0.84	0.73

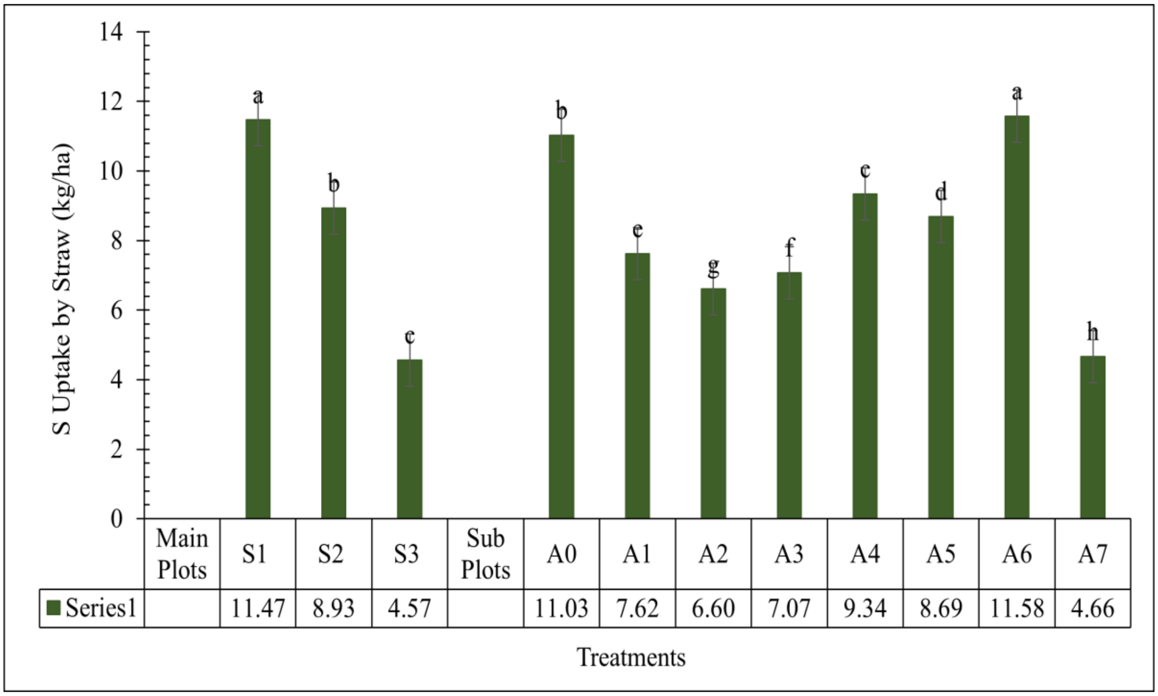


Fig:4.3.16.1(a): The impact of sulphur sources and agrochemical treatments on S uptake by straw (kg/ha) in the year 2021-2022

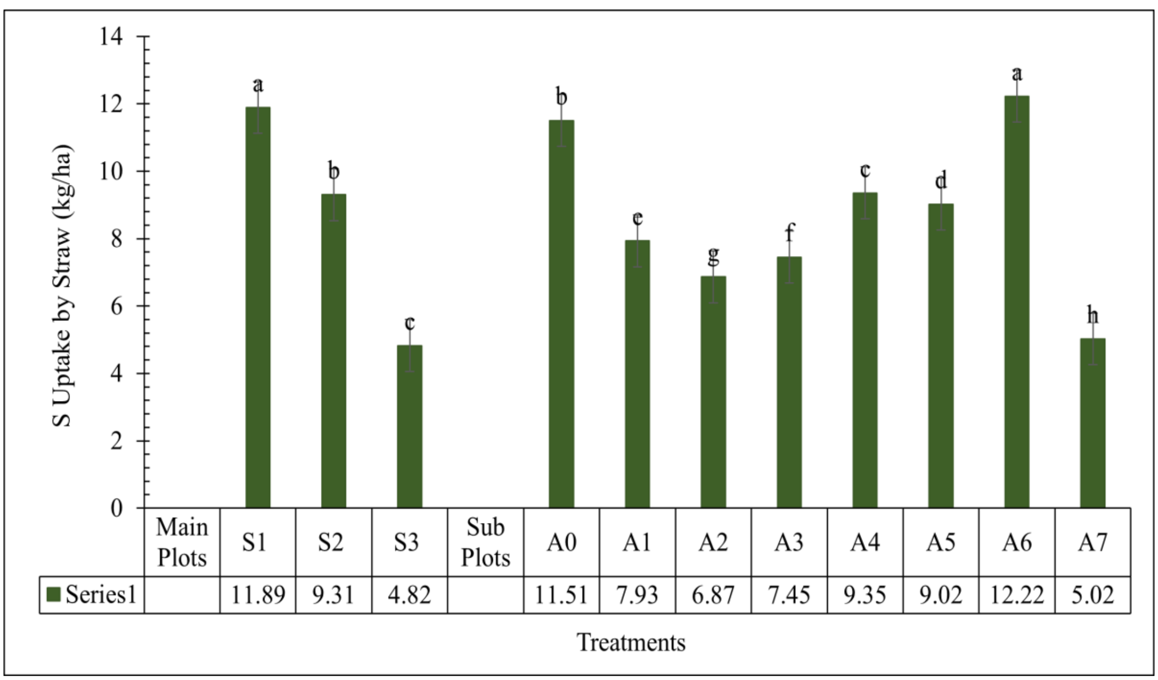


Fig:4.3.16.2(b): The impact of sulphur sources and agrochemical treatments on S uptake by straw (kg/ha) in the year 2022-2023

4.4 Quality parameters

4.4.1 Protein content (%): The protein content of Gobhi Sarson (*Brassica napus* L.) var. GSC-7 exhibited significant variation across various sulphur sources and agrochemical treatments during the 2021–22 and 2022–23 cropping seasons, displayed in Table 4.4.1.1 and Figure 4.4.1.1(a), 4.4.1.2(b). Among sulphur sources, Gypsum (S1) exhibited the greatest protein content, measuring 14.61% in 2021–22 and 14.77% in 2022–23, followed by Bentonite Sulphur (S2) at 13.69% and 13.83%, respectively. The minimal protein content was observed with Elemental Sulphur (S3), registering 10.28% and 10.73%, indicating a reduction of 29.64% and 27.36%, respectively, in comparison to Gypsum. In terms of agrochemical treatments, the maximum protein content was attained with A6 (Hydrogel + Salicylic acid during flowering and pod formation), which measured 14.50% in 2021–22 and 14.75% in 2022–23, closely succeeded by A0 (Control under full irrigation) at 14.10% and 14.44%, respectively. Intermediate values were recorded in treatments A4 and A5, ranging from 13.37% to 13.81%, signifying partial enhancement attributable to the synergistic application of hydrogel and salicylic acid. The minimum protein content was observed in A7 (Restricted irrigation) at 10.31% and 10.56%, approximately 28.97% lower than A6 in the first year. Alternative treatments, including A1, A2, and A3, exhibited efficacy ranging from 11.94% to 12.87%, indicating slight improvements over the least effective treatment. In conclusion, the synergistic treatment of Gypsum (S1) and A6 (Hydrogel + Salicylic acid during flowering and pod development) demonstrated the highest efficacy in enhancing protein content in Gobhi Sarson throughout both years. Table 4.4.1.2 illustrates that a combination of interactions between sulphur sources and agrochemical applications significantly influenced the protein content of Gobhi Sarson (*Brassica napus* L.) in the 2021–22 and 2022–23 cropping seasons. The highest protein content was recorded with treatment S1A6, yielding 16.47% in 2021–22 and 16.63% in 2022–23. This was succeeded by S1A0, registering 16.04% and 16.23% respectively. S2A6 exhibited values of 15.46% and 15.56%, demonstrating the synergistic effect of integrated applications despite varying sulphur sources. The minimum protein content was seen in S3A7 (Elemental sulphur + restricted irrigation), with values of 8.23% and 8.64%, leading to an approximate rise of 100.1% in 2021– 22 and 92.4% in 2022–23 under the optimal treatment (S1A6). Treatments utilizing elemental sulphur

(S3) consistently shown reduced protein content in comparison to gypsum and bentonite sulphur treatments, especially under conditions of water stress (A7). This underscores the significance of accessible sulphur (as found in gypsum) and complementary agrochemicals in improving seed quality. The combination of Gypsum, Hydrogel, and Salicylic acid during flowering and pod formation (S1A6) was the most efficient treatment for enhancing protein content in Gobhi Sarson seeds over both years. This enhancement under stress can be elucidated scientifically by the function of salicylic acid in augmenting the activity of critical enzymes, including nitrate reductase (NR), glutamine synthetase (GS), and glutamate synthase (GOGAT), which are vital for nitrogen assimilation and protein synthesis. Salicylic acid regulates the antioxidant defense system, diminishing oxidative damage to cellular structures and enzymes, therefore preserving metabolic functioning during drought stress. Simultaneously, hydrogel preserves elevated soil moisture levels in the rhizosphere, guaranteeing a consistent supply of water essential for enzyme reactions and nutrient absorption. The combined impact of salicylic acid and hydrogel under water-scarce conditions establishes a conducive physiological state that enhances nitrogen metabolism, leading to increased protein formation in seeds despite minimal watering. These findings underscore the potential of incorporating stress-relieving chemicals like as hydrogel and salicylic acid, into nutrition and water management strategies to improve seed quality under suboptimal growth conditions. The protein content in plants primarily relies on amino acid synthesis, the essential components of proteins, which is strongly affected by nutrient availability, especially nitrogen and sulphur, along with environmental factors like water availability. Sulphur is integral to protein synthesis, serving as a fundamental element of amino acids such as cysteine and methionine, which are important for protein structure and enzyme activity. Sulphur increases nitrogen assimilation by promoting the activity of essential enzymes that convert inorganic nitrogen into amino acids. Gypsum serves as a readily available source of sulphur in the sulphate form, facilitating rapid uptake and utilization in protein synthesis, which is evidenced by the markedly higher protein content in treatments with gypsum compared to slower- releasing sources such as elemental sulphur. It relies on microbial oxidation to transform sulphur into forms accessible to plants, a process that is time-intensive and affected by soil conditions, leading to relatively lower protein levels (Khan et al., 2018; Malik et al., 2021; Narayan et al., 2023; Sharma et al., 2024; Trovato et al., 2021; Yu et al., 2018; Zhang et al., 2019). Water stress adversely affects protein content by disrupting various physiological and metabolic processes. In drought conditions, diminished soil moisture restricts nutrient uptake, particularly nitrogen and sulphur, essential for amino acid and protein synthesis. Moreover, water stress impedes photosynthesis, thereby diminishing the energy and carbon frameworks necessary for protein synthesis. Proteolysis, the degradation of existing proteins, is exacerbated during drought as a stress-response process, hence diminishing protein accumulation. This was apparent in treatments with little irrigation, which consistently exhibited the lowest protein concentration. For example, the protein content in treatments with limited irrigation and elemental sulphur was as low as 8.23% and 8.64% during the 2021–22 and 2022–23 cropping seasons, respectively, indicating a significant reduction compared to well- irrigated treatments with accessible sulphur. Hydrogel enhanced soil moisture retention, guaranteeing stable water supply to the roots, hence promoting greater nutrient uptake and mitigating drought-related physiological disturbances. Moreover, salicylic acid acted as a signaling molecule, augmenting the plant's resilience to abiotic stress by stimulating antioxidant defense mechanisms and safeguarding cellular components associated with protein synthesis. SA enhanced nitrogen and sulphur metabolism, facilitating amino acid synthesis under both normal and stressful settings (Khan et al., 2015; Mishra & Rashid, 2017; Moloi & Ngara, 2023; Rakszegi et al., 2019; Riccardi et al., 1984). The combined effect of hydrogel and salicylic acid was most pronounced in treatments administered alongside gypsum, yielding the highest protein level of 16.63% during 2022–23. This underscores the need of combining sulphur nutrition with water- conserving technology and stress-mitigating agrochemicals to enhance protein synthesis, particularly under water- scarce conditions.

Table 4.4.1.1: The impact of treatments on protein content (%) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	Protein content (%) (2021-22)	Protein content (%) (2022-23)
Sulphur sources		
S1: Gypsum	14.61^{a}	14.77^{a}
S2: Bentonite Sulphur	13.69^{b}	13.83^{b}
S3: Elemental Sulphur	10.28^{c}	10.73^{c}
CV (Sulphur Sources)	3.63	4.05
CD (Sulphur Sources)	0.37	0.43
Agrochemical		
A0: Control (Irrigation as per requirement)	14.10^{ab}	14.44^{a}
A1: Hydrogel (2.5 kg/ha) as basal application	12.62^{d}	12.87^{c}
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	11.94^{e}	12.25^{d}
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	12.37^{de}	12.56^{cd}
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	13.62^{bc}	13.81^{b}
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	13.37^{c}	13.62^{b}
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	14.50^{a}	14.75^{a}
A7: Control (Restricted irrigation)	10.31^{f}	10.56^{e}
CD (Agrochemical)	0.59	0.60
CV (Sulphur Sources and agrochemical)	4.79	4.83

Table 4.4.1.2: The interaction impact of treatments on protein content (%) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	Protein content (%) (2021-22)	Protein content (%) (2022-23)
S1A0	16.04±0.72	16.23±0.80
S1A1	14.34±0.11	14.51±0.11
S1A2	13.56±1.45	13.81±1.45
S1A3	14.06±2.05	14.17±2.05
S1A4	15.47±0.28	15.57±0.28
S1A5	15.19±0.39	15.36±0.39
S1A6	16.47±0.53	16.63±0.53
S1A7	11.71±0.53	11.91±0.53
S2A0	14.81±0.23	15.25±0.44
S2A1	13.47±0.23	13.58±0.23
S2A2	12.74±0.17	12.92±0.17
S2A3	13.20±0.28	13.25±0.28
S2A4	14.53±0.23	14.57±0.23
S2A5	14.26±0.17	14.37±0.56
S2A6	15.46±0.11	15.56±0.11
S2A7	11.00±0.30	11.14±0.30
S3A0	11.44±0.23	11.85±0.25
S3A1	10.07±0.17	10.53±0.17
S3A2	9.52±0.23	10.02±0.23
S3A3	9.87±0.27	10.28±0.27
S3A4	10.87±0.29	11.30±0.29
S3A5	10.67±0.17	11.14±0.17
S3A6	11.57±0.17	12.06±0.17
S3A7	8.23±0.17	8.64±0.17
CV	4.79	4.83
CD	1.02	1.06

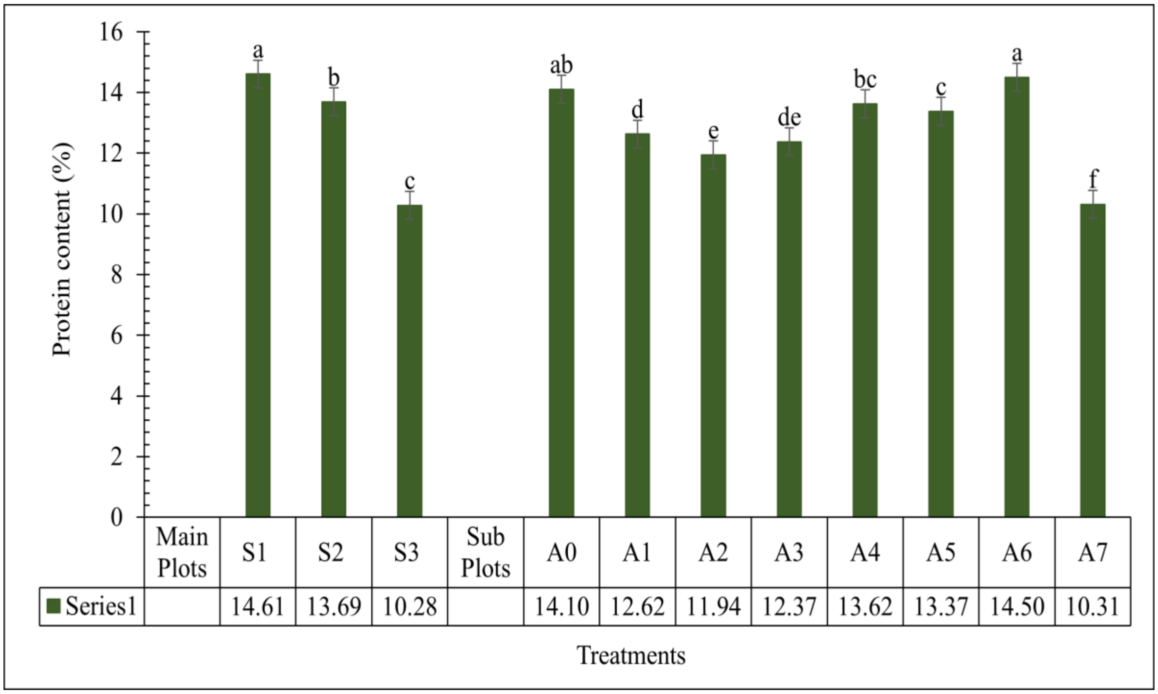


Fig. 4 .4.1.1 (a) The impact of sulphur sources and agrochemical treatments on Protein content (%) in the year 2021-2022

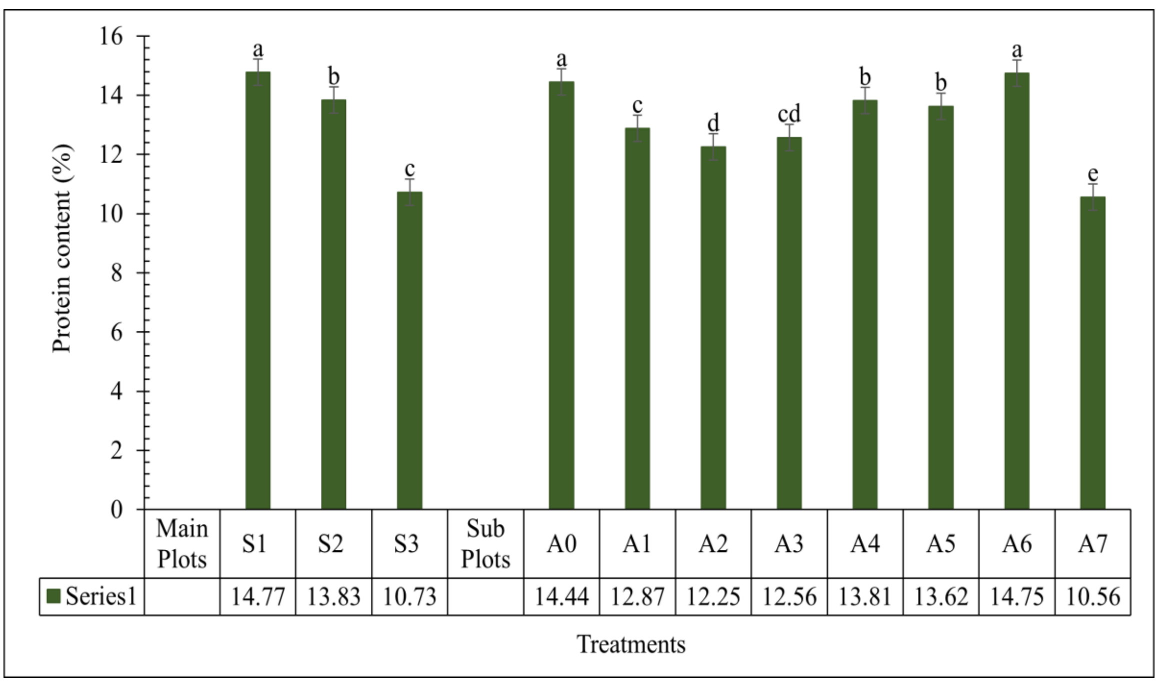


Fig. 4 .4.1.2 (b) The impact of sulphur sources and agrochemical treatments on Protein content (%) in the year 2022-2023

4.4.2 Protein yield (kg/ha): The study's findings in Table 4.4.2.1 and Figure 4.4.2.1(a), 4.4.2.2(b) indicated that various sulphur sources and agrochemical treatments markedly affected protein yield in the 2021-22 and 2022-23 cropping seasons. Among sulphur sources, Gypsum (S1) yielded the highest protein output, recording 294.53 kg/ha in 2021–22 and 303.03 kg/ha in 2022–23, followed by Bentonite Sulphur (S2) with yields of 248.46 kg/ha and 254.96 kg/ha, respectively. The minimal protein yield occurred with Elemental Sulphur (S3), producing 146.45 and 153.77 kg/ha, representing decreases of 50.27% and 49.26%, respectively, in comparison to Gypsum. The highest protein yield among agrochemical treatments was recorded with A6 (Hydrogel + Salicylic acid during both flowering and pod formation), yielding 298.29 kg/ha in 2021–22 and 307.77 kg/ha in 2022–23. This was closely followed by A0 (Control under full irrigation), which produced 274.28 kg/ha and 288.31 kg/ha, respectively. Treatments A4 and A5 exhibited moderate protein yields, varying from 254.70 to 263.77 kg/ha. The minimum protein yield was seen in A7 (Restricted irrigation) at 146.06 and 152.28 kg/ha, representing a 51.04% decrease compared to A6 in 2021–22. Alternative treatments A1, A2, and A3 produced yields ranging from 188.57 to 221.22 kg/ha, signifying moderate enhancements relative to A7. The amalgamation of Gypsum (S1) and A6 (Hydrogel + Salicylic acid during flowering and pod development) yielded the maximum protein output over both years, establishing it as the most efficacious treatment.

The interplay between sulphur sources and agrochemical applications significantly affected protein yield in both the 2021-22 and 2022-23 cropping seasons are shown in Table 4.4.2.2. The maximum yield of protein was seen in the treatment S1A6 (Gypsum + Hydrogel at 2.5 kg/ha + Salicylic acid at 150 ppm during 50% flowering and pod formation), with yields of 381.78 kg/ha in 2021–22 and 393.82 kg/ha in 2022–23. S1A0 (Gypsum + irrigation as required) yielded 352.20 kg/ha and 362.43 kg/ha in the corresponding years, while S1A5 (Gypsum + Salicylic acid at 150 ppm administered twice) produced 331.03 kg/ha and 337.50 kg/ha. The minimal protein output was seen in S3A7 (Elemental sulphur + restricted irrigation), with value of 92.70 kg/ha in 2021–22 and 98.81 kg/ha in 2022–23. In contrast, the most productive treatment, S1A6, had a growth of 311.7% in 2021–22 and 298.7% in 2022–23. Treatments utilizing elemental sulphur (S3), particularly when combined with restricted irrigation and without agrochemical assistance, consistently yielded diminished protein outputs, indicative of both decreased seed yield and protein concentration. Conversely, gypsum-based treatments (S1), especially those combined with hydrogel and salicylic acid, significantly improved protein productivity. In conclusion, the treatment S1A6 (Gypsum + Hydrogel + Salicylic acid) demonstrated the highest efficacy enhance the protein yield of Gobhi Sarson across both years.

The differences in protein yield across several treatments in *Brassica napus* can be ascribed to the specific functions of sulphur sources, hydrogel application, and salicylic acid in plant physiology. Sulphur is crucial for the synthesis of amino acids such as cysteine and methionine, which serve as fundamental components of proteins. Gypsum, by supplying readily accessible sulphate, facilitates sulphur uptake, resulting in augmented protein synthesis and elevated yields. Conversely, elemental sulphur necessitates microbial oxidation for availability, hindering its uptake and leading to diminished protein production. Hydrogels are superabsorbent polymers that enhance soil moisture retention. Their application guarantees a reliable water supply, alleviating drought stress and enhancing nutrient uptake, particularly nitrogen, which is essential for protein synthesis. Research indicates that the application of hydrogel in mustard crops improves water use efficiency and yield. Salicylic acid (SA) is a phytochemical that plays a crucial role in modulating stress responses. Its application may augment plant resilience to abiotic stressors, hence potentially enhancing overall plant health and output. Nevertheless, the precise impact of SA on protein output in *Brassica napus* necessitates additional research (Ali et al., 2023; Arif et al., 2024; Mahto et al., 2023; Meena et al., 2020; Oyebamiji et al., 2024). The integration of gypsum, hydrogel, and salicylic acid treatments likely creates a synergistic effect, enhancing nutrient availability, moisture retention, and stress resilience, therefore boosting protein yields in *Brassica napus*. The interaction of sulphur availability, soil moisture retention, and stress alleviation substantially affects protein output in *Brassica napus*. Implementing integrated nutrition and water management strategies can improve crop and protein yield.

Table 4.4.2.1: The impact of treatments on Protein yield (kg/ha) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	Protein yield (kg/ha) (2021-22)	Protein yield (kg/ha) (2022-23)
Sulphur sources		
S1: Gypsum	294.53[a]	303.03[a]
S2: Bentonite Sulphur	248.46[b]	254.96[b]
S3: Elemental Sulphur	146.45[c]	153.77[c]
CV (Sulphur Sources)	5.86	6.24
CD (Sulphur Sources)	10.79	11.87
Agrochemical		
A0: Control (Irrigation as per requirement)	274.28[b]	288.31[b]
A1: Hydrogel (2.5 kg/ha) as basal application	214.10[d]	221.22[d]
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	188.57[e]	196.59[e]
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	203.91[de]	208.02[de]
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	254.70[c]	260.08[c]
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	258.57[bc]	263.77[c]
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	298.29[a]	307.77[a]
A7: Control (Restricted irrigation)	146.06[f]	152.28[f]
CD (Agrochemical)	16.25	17.12
CV (Sulphur Sources and agrochemical)	7.43	7.58

Table 4.4.2.2: The interaction impact of treatments on Protein yield (kg/ha) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	Protein yield (kg/ha) (2021-22)	Protein yield (kg/ha) (2022-23)
S1A0	352.20±24.13	362.43±22.85
S1A1	274.03±2.32	283.06±2.36
S1A2	242.07±42.06	252.21±42.96
S1A3	262.06±56.46	267.61±63.00
S1A4	326.07±6.62	332.79±6.71
S1A5	331.03±9.34	337.50±9.42
S1A6	381.78±13.78	393.82±14.06
S1A7	186.97±9.53	194.85±9.76
S2A0	290.98±15.67	316.41±13.17
S2A1	232.44±4.38	237.00±4.43
S2A2	204.24±2.99	210.24±3.03
S2A3	220.67±5.25	221.97±5.23
S2A4	276.43±4.81	278.58±4.83
S2A5	280.63±3.63	282.56±11.08
S2A6	323.76±7.57	329.75±2.58
S2A7	158.52±4.90	163.16±5.04
S3A0	179.67±6.87	186.09±6.22
S3A1	135.83±2.49	143.61±2.53
S3A2	119.39±3.17	127.33±3.23
S3A3	129.00±4.00	134.48±4.02
S3A4	161.59±4.76	168.87±4.80
S3A5	164.06±2.82	171.25±2.83
S3A6	189.31±3.01	199.75±3.06
S3A7	92.70±2.08	98.81±2.12
CV	7.43	7.58
CD	28.31	30.01

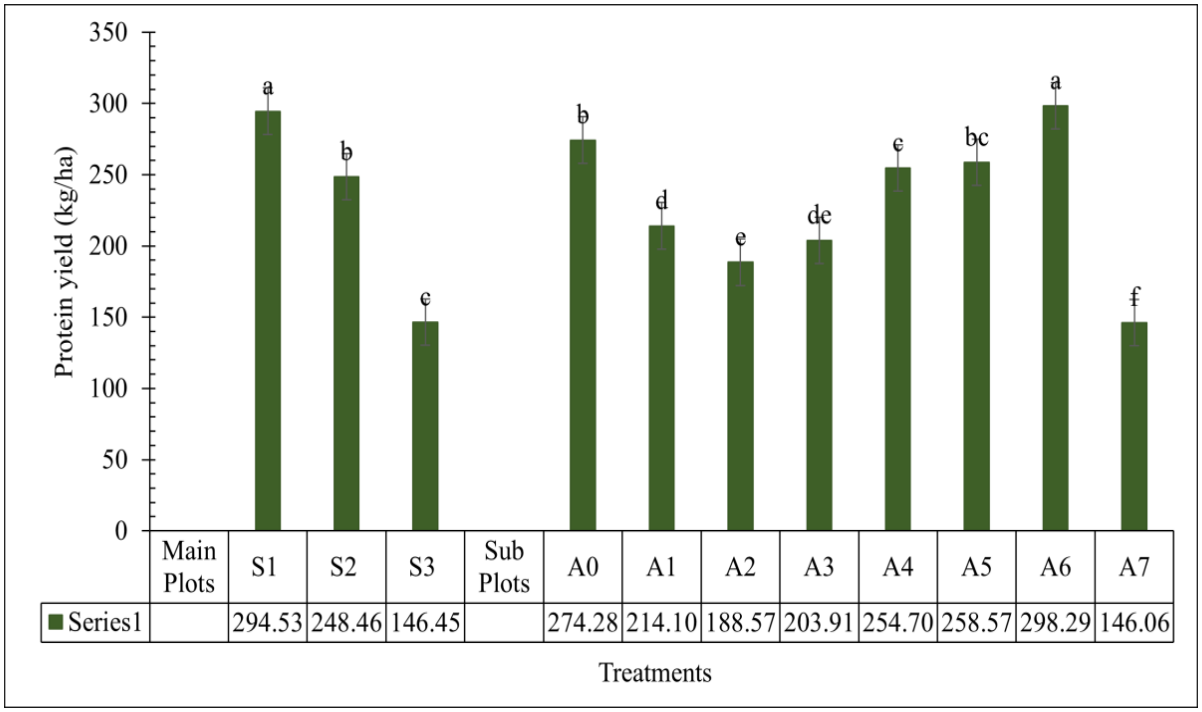


Fig:4.4.2.1(a) The impact of sulphur sources and agrochemical treatments on Protein yield (kg/ha) in the year 2021-2022

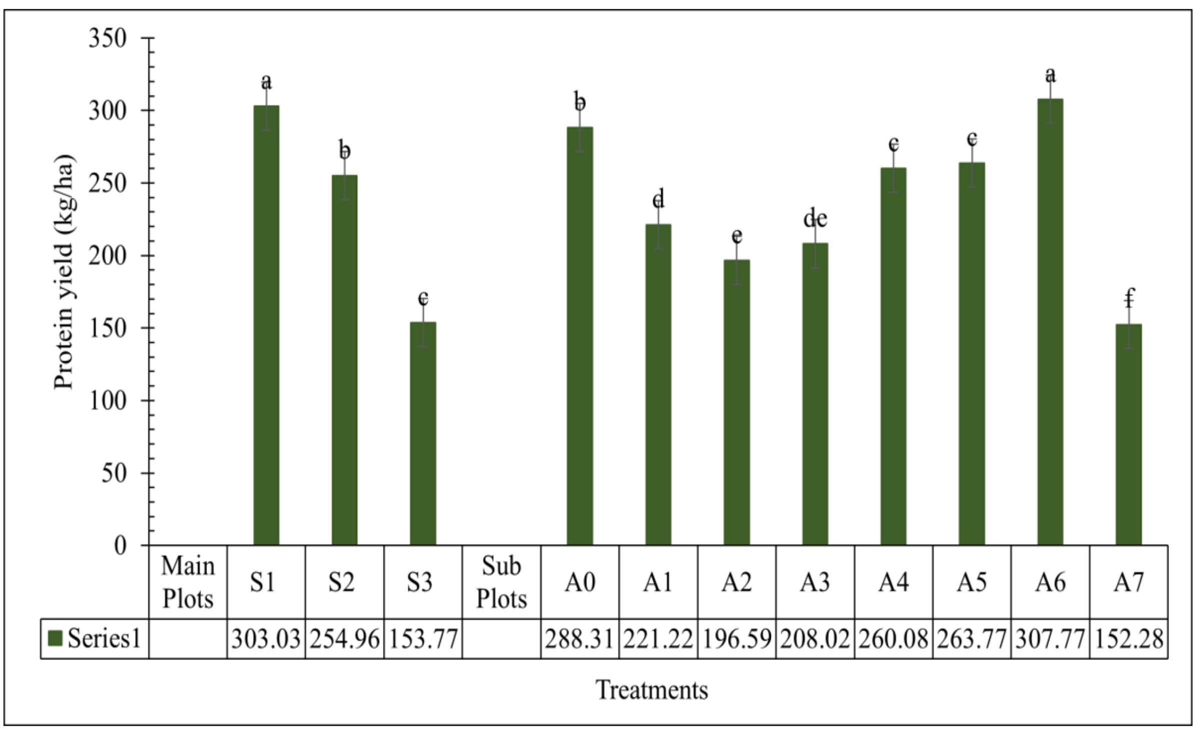


Fig:4.4.2.2(b) The impact of sulphur sources and agrochemical treatments on Protein yield (kg/ha) in the year 2022-2023

4.4.3 Oil content (%): The oil content of *Brassica napus* var. GSC-7 was markedly affected by various sulphur sources and agrochemical treatments over both growth seasons (2021-22 and 2022-23) shown in Table 4.4.3.1 and Figure 4.4.3.1(a), 4.4.3.2(b). The oil content was markedly affected by various sulphur sources and agrochemical treatments in both years. The greatest oil concentration among sulphur sources was seen in Gypsum (S1) at 42.49% for 2021–22 and 42.61% for 2022–23, followed by Bentonite Sulphur (S2) at 40.53% and 40.61%, respectively. The minimum oil content was recorded with Elemental Sulphur (S3) at 37.91% and 38.12%, reflecting a reduction of 10.77% and 10.53%, respectively, in comparison to Gypsum. In terms of agrochemical treatments, A6 (Hydrogel + Salicylic acid during flowering and pod formation) achieved the highest oil content of 42.39% in 2021–22 and 42.49% in 2022–23, which was statistically comparable to A0 (Control with full irrigation) and A4 (Hydrogel + Salicylic acid during flowering), both exceeding 41%. Moderate oil content was observed in A1, A2, A3, and A5, varying from 38.97% to 41.32%. The minimal oil content was observed in A7 (Restricted irrigation) at 37.81% in 2021–22 and 38.05% in 2022–23, reflecting an estimated 11% decrease relative to A6 in both years. The optimal oil content was attained with the treatment of Gypsum and A6 (Hydrogel + Salicylic acid during both flowering and pod formation), demonstrating the most efficacious combination for improving oil quality in Gobhi Sarson. The combination of interactions between sulphur sources and agrochemical applications markedly affected the oil content of *Brassica napus* var. GSC-7 across both growing seasons (2021-22 and 2022-23) shown in Table 4.4.3.2. The maximum oil content was regularly recorded under S1A6 (Gypsum + Hydrogel at 2.5 kg/ha + Salicylic acid at 150 ppm), with values of 44.66% in 2021–22 and 44.77% in 2022–23. S1A0 (Gypsum + irrigation as required) subsequently reported 44.50% and 44.39% throughout the two years, respectively. Additional treatments with considerable oil content, including S1A4 and S1A5, exhibited values between 43.39% and 43.78%, demonstrating the efficacy of gypsum in conjunction with salicylic acid. The minimum oil content was seen in S3A7 (Elemental sulphur + restricted irrigation), recording 35.60% in 2021–22 and 35.83% in 2022–23. In contrast, the most effective treatment S1A6 had a percentage rise of 25.4% in 2021–22 and 25.0% in 2022–23. Treatments utilizing elemental sulphur (S3), particularly under limited irrigation and absent agrochemical assistance, consistently demonstrated the lowest oil percentages, highlighting the detrimental impact of water stress and inadequate nutrient availability. The combination of gypsum, hydrogel, and salicylic acid was effective in enhancing oil content in seeds. In conclusion, S1A6 (Gypsum + Hydrogel + Salicylic acid) proved to be the most efficacious treatment for augmenting oil content in Gobhi Sarson during both years.

The data indicate that gypsum is the most efficacious sulphur source for oil augmentation in *Brassica napus*, and that the incorporation of hydrogel and salicylic acid during pivotal growth phases might further augment oil synthesis by mitigating oxidative stress and improving moisture retention. The oil content of *Brassica napus* (canola) seeds is affected by several treatments, such as sulphur (S) fertilization and the use of agrochemicals like hydrogel and salicylic acid. Comprehending the fundamental pathways can clarify how these treatments influence oil biosynthesis.

Sulphur is an important macronutrient that facilitates the synthesis of crucial amino acids (cysteine and methionine) and coenzymes, which are fundamental to plant metabolism. Ample sulphur availability augments the activity of enzymes implicated in fatty acid synthesis, thereby elevating oil formation in seeds. Research indicates that sulphur fertilizer enhances oil content in oilseed crops, with notable increases reported up to specific application thresholds. The manufacture of oil in *Brassica napus* necessitates the synchronized function of many transcription factors and metabolic processes. As a superabsorbent polymer, hydrogel enhances soil moisture retention, guaranteeing a steady water supply to plants. Proper hydration is crucial for proper metabolic processes, including lipid production. By alleviating water stress, the hydrogel can indirectly enhance the oil content in seeds. This phytochemical participates in stress reactions and can affect multiple metabolic pathways. Its application has demonstrated the ability to augment the activity of enzymes associated with fatty acid synthesis, potentially elevating oil accumulation in seeds. A study examining the impact of sulphur fertility on yield and seed components in oilseed crops revealed that sulphur application enhanced oil content, with notable benefits evident up to specific amounts of sulphur application (Atmaca Gulizar, 2004; Berger et al., 2022; Brosnan & Brosnan, 2006; Mirdoraghi et al., 2024; Ragab & Saad-Allah, 2021; Salhi et al., 2024; Zhuang et al., 2022). Investigations on the relationship between phenylpropane metabolism and oil biosynthesis in *Brassica napus* indicate that the metabolic pathways for flavonoid and oil synthesis are interrelated, suggesting that interventions impacting both pathways can affect oil content (L. Yu et al., 2023).

Research on the genetic determinants of oil content in *Brassica napus* has pinpointed essential genes and transcription factors implicated in oil biosynthesis, offering insights into the optimization of treatments to augment oil output (L. Guo et al., 2023). The oil content in *Brassica napus* seeds is influenced by sulphur availability, which boosts enzyme activities in lipid production, as well as by treatments such as hydrogel and salicylic acid that enhance water retention and stress resilience. These factors jointly influence the observed discrepancies in oil content across various treatment regimes.

Table 4.4.3.1: The impact of treatments on oil content of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	Oil content (%) (2021-22)	Oil content (%) (2022-23)
Sulphur sources		
S1: Gypsum	42.49[a]	42.61[a]
S2: Bentonite Sulphur	40.53[b]	40.61[b]
S3: Elemental Sulphur	37.91[c]	38.12[c]
CV (Sulphur Sources)	3.5	3.3
CD (Sulphur Sources)	1.13	1.07
Agrochemical		
A0: Control (Irrigation as per requirement)	42.11[ab]	42.17[ab]
A1: Hydrogel (2.5 kg/ha) as basal application	39.46[c]	39.59[c]
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	38.97[c]	39.05[c]
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	39.17[c]	39.36[c]
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	41.39[ab]	41.55[ab]
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	41.18[b]	41.32[b]
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	42.39[a]	42.49[a]
A7: Control (Restricted irrigation)	37.81[d]	38.05[d]
CD (Agrochemical)	1.04	0.98
CV (Sulphur Sources and agrochemical)	2.72	2.56

Table 4.4.3.2: The interaction impact of treatments on oil content of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	Oil content (%) (2021-22)	Oil content (%) (2022-23)
S1A0	44.50±0.38	44.39±0.21
S1A1	41.58±0.01	41.71±0.01
S1A2	41.06±5.01	41.15±5.01
S1A3	41.27±0.01	41.47±0.01
S1A4	43.61±0.01	43.78±1.01
S1A5	43.39±0.01	43.53±0.01
S1A6	44.66±0.01	44.77±0.01
S1A7	39.84±0.02	40.09±0.02
S2A0	42.50±0.48	42.14±0.03
S2A1	39.65±0.00	39.78±0.00
S2A2	39.16±2.00	39.24±1.00
S2A3	39.36±0.00	39.55±0.00
S2A4	41.59±0.00	41.75±0.00
S2A5	41.38±0.00	41.52±2.01
S2A6	42.60±0.04	42.70±0.00
S2A7	37.99±0.00	38.23±0.00
S3A0	39.34±0.36	39.97±0.05
S3A1	37.15±0.01	37.28±0.01
S3A2	36.69±0.01	36.77±0.01
S3A3	36.88±0.00	37.06±0.00
S3A4	38.97±0.00	39.12±0.00
S3A5	38.77±0.01	38.91±0.01
S3A6	39.91±0.01	40.01±0.01
S3A7	35.60±0.01	35.83±0.01
CV	2.72	2.56
CD	2.01	1.90

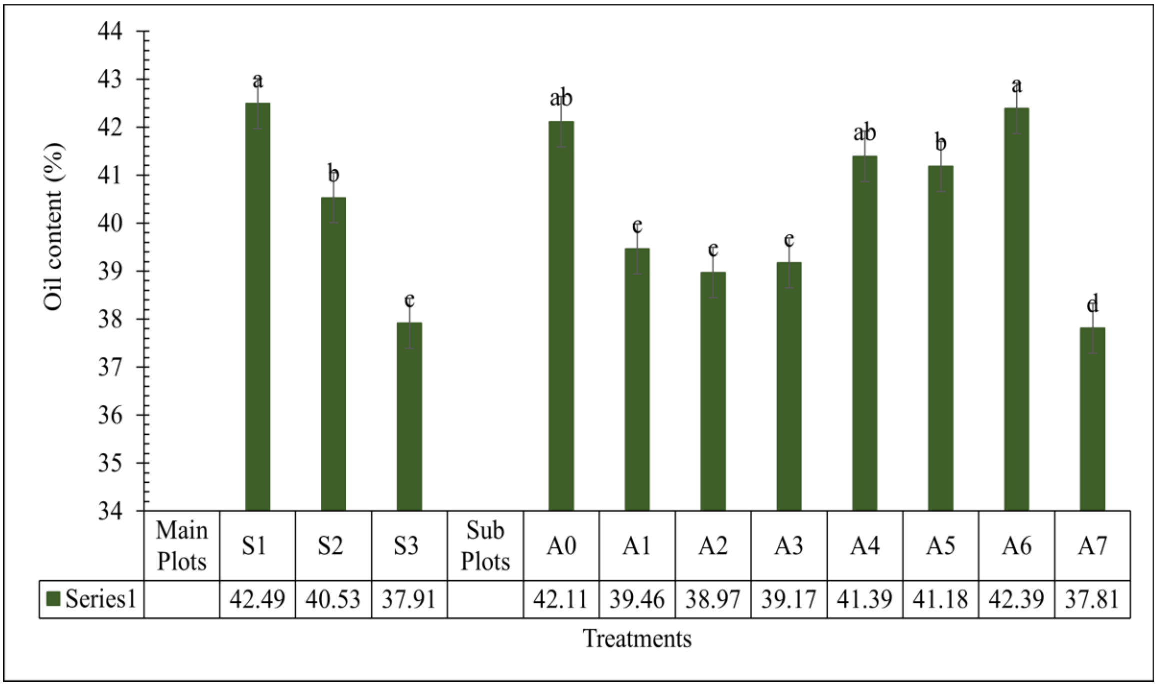


Fig:4.4.3.1(a): The impact of sulphur sources and agrochemical treatments on oil content in the year 2021-2022

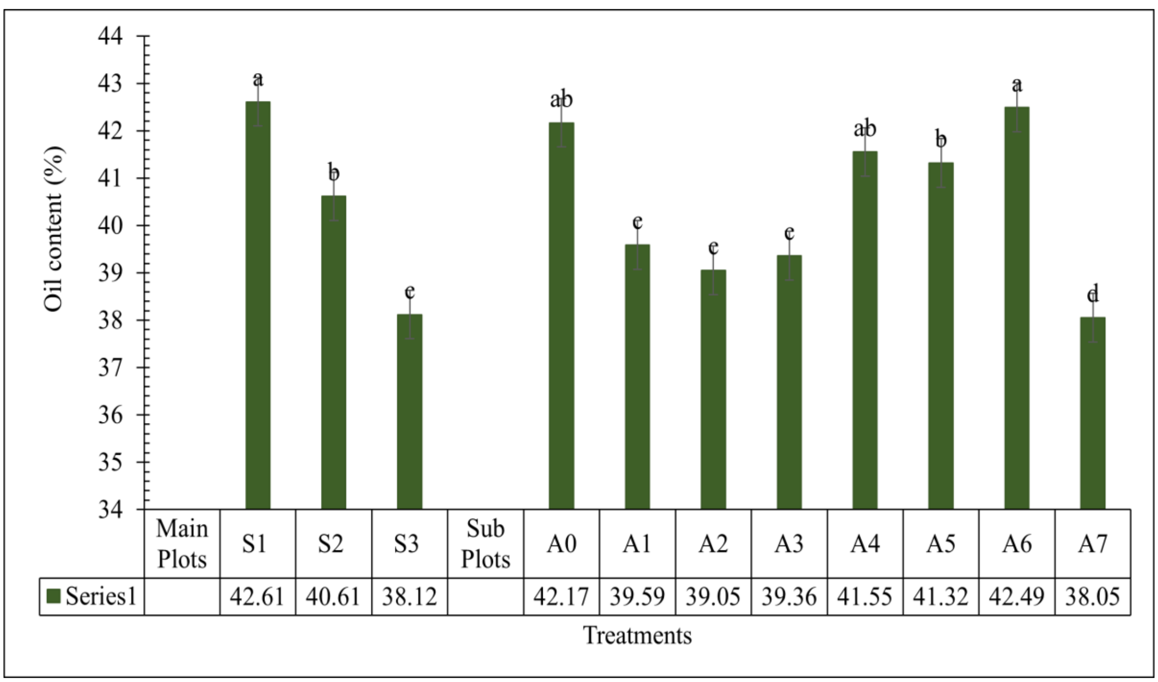


Fig:4.4.3.2(b): The impact of sulphur sources and agrochemical treatments on oil content in the year 2022-2023

4.4.4 Oil yield (q/ha): The oil output of Gobhi Sarson (*Brassica napus* L.) exhibited considerable variation across various sulphur sources and agrochemical treatments throughout the 2021-22 and 2022-23 growth seasons, shown in Table 4.4.4.1 and Figure 4.4.4.1(a) and 4.4.4.2(b). Among the sources of sulphur, Gypsum (S1) exhibited the highest oil yield of 8.50 q/ha in 2021–22 and 8.67 q/ha in 2022–23, whereas Bentonite Sulphur (S2) yielded 7.31 and 7.44 q/ha, respectively. The minimal oil yield occurred in Elemental Sulphur (S3), producing 5.37 and 5.43 q/ha, representing a loss of 36.8% and 37.4%, respectively, in comparison to Gypsum. A6 (Hydrogel + Salicylic acid during flowering and pod formation) yielded the highest oil production of 8.60 q/ha in 2021–22 and 8.76 q/ha in 2022–23, followed closely by A0 (Control with full irrigation) at 8.10 and 8.31 q/ha, and A5 (Hydrogel + Salicylic acid at pod formation) at 7.85 and 7.90 q/ha, respectively. Moderate values were observed for A4, A1, A3, and A2, varying from 6.07 to 7.73 q/ha. The minimal oil yield was recorded in A7 (Restricted irrigation), at 5.28 q/ha in 2021–22 and 5.42 q/ha in 2022–23, representing decreases of 38.6% and 38.1%, respectively, compared to A6. The interaction effects of sulphur sources and agrochemical treatments on oil yield (q/ha) in Gobhi Sarson *(Brassica napus* L.) were statistically significant throughout both the 2021-22 and 2022-23 periods. The data in Table 4.4.4.2 illustrate the varying effects of sulphur sources and moisture-retaining treatments, highlighting the significance of their combined use in enhancing oil yield. From the three sulphur sources, the maximum oil yield was seen under S1A6, with the value of 10.35 q/ha in 2021–22 and 10.60 q/ha in 2022–23. S1A0 (Gypsum + irrigation as required) and S1A5 (Gypsum + Salicylic acid) subsequently produced yields of 9.76 and 9.91 q/ha, and 9.46 and 9.57 q/ha, respectively, throughout the corresponding years. The results demonstrate the superiority of gypsum-based treatments under restricted and normal irrigation and agrochemical application. The minimum oil yield was recorded in S3A7 (Elemental sulphur + limited irrigation), at 4.01 q/ha in 2021–22 and 4.10 q/ha in 2022– 23. In contrast, S1A6 had a significant enhancement of 157.9% in 2021–22 and 158.5% in 2022–23. Most treatments utilizing elemental sulphur (S3 series), especially under conditions of water stress, consistently exhibited reduced oil yields across both years.

Gypsum outperformed bentonite sulphur and elemental sulphur, but the incorporation of hydrogel and salicylic acid further enhanced oil buildup and translocation efficiency, presumably by enhancing water and nutrient availability. The combined use of Hydrogel and Salicylic Acid (A6) markedly increases oil yield, especially in sufficient moisture conditions. Water stress (A7) significantly reduces oil yield, highlighting the necessity for moisture conservation techniques in rapeseed agriculture. Optimization of sulphur application and agrochemical treatments is essential for maximizing oil yield in Gobhi Sarson. These findings correspond with prior research demonstrating that sulphur is essential for oil biosynthesis by facilitating fatty acid metabolism, while moisture- retaining additions enhance food availability and stress resilience.

The observed variations in oil yield can be elucidated through physiological, biochemical, and agronomic causes, corroborated by pertinent scientific research. Sulphur is a vital ingredient for oilseed crops, significantly contributing to fatty acid production, protein metabolism, and enzymatic activity. Of the three sulphur sources employed, Gypsum (S1) had the highest oil output, succeeded by Bentonite Sulphur (S2) and Elemental Sulphur (S3). The exceptional efficacy of Gypsum (S1) is due to its accessible sulphate (SO_4^{2-}) form, which is directly assimilated by the plant, hence augmenting enzyme activity and facilitating effective lipid production. Bentonite Sulphur (S2) experiences gradual oxidation to sulphate, resulting in moderate sulphur availability and, therefore, an intermediate oil yield. Elemental Sulphur (S3) necessitates microbial oxidation to transform into a plant-accessible form, a process that is gradual and contingent upon temperature and moisture levels, leading to reduced oil yield relative to alternative sulphur sources. A multitude of investigations have corroborated these conclusions. A study indicates that sulphate-based sulphur sources, such as gypsum, improved oil yield in rapeseed due to their rapid availability to plants. Similarly, another study revealed that slow-release sulphur sources, such as Bentonite Sulphur, enhanced oil yield but were less effective than readily available sulphates in short-duration crops. Furthermore, Elemental Sulphur considerably underperforms compared to sulphate-based sources in enhancing oil yield, due to the impact of environmental variables on microbial oxidation. The use of agrochemicals, alongside sulphur sources, greatly affected oil output (Nabati et al., 2025; Padma et al., 2018; Patel et al., 2024; Rameeh et al., 2021) Treatments with Hydrogel and Salicylic Acid (SA) (A6, A5, A4) produced greater oil yield, but control conditions (A0) and limited irrigation (A7) exhibited comparatively lower oil yield. The identified tendencies can be elucidated by the advantageous impacts of these treatments on moisture retention, stress alleviation, and metabolic control. Hydrogel is a superabsorbent polymer that absorbs soil moisture and gradually releases it, alleviating water stress and enhancing nutrient availability. The increased oil yield in A6, A5, and A4 is due to Hydrogel's capacity to retain soil moisture and boost sulphur uptake, therefore promoting seed fullness and oil biosynthesis. This corresponds with the findings of (Calcagno et al., 2023) who indicated that the application of Hydrogel in oilseed crops enhanced oil yield by 15-20% in semi-arid conditions, attributed to improved water retention and nutrient uptake. Likewise, Patra et al., (2022) discovered that Hydrogel-treated plants had increased lipid accumulation and seed weight, corroborating the findings of the current study. Salicylic Acid (SA) is a phytohormone implicated in stress resilience and metabolic control. The notable rise in oil yield in treatments with SA applied during the 50% flowering and pod formation stages (A6, A5, A4) can be attributed to its capacity to augment antioxidant enzyme activity, enhance photosynthetic efficiency, and facilitate seed development. Furthermore, SA promotes the activation of fatty acid desaturase enzymes, resulting in enhanced synthesis of unsaturated fatty acids, essential for oil buildup (Ghassemi-Golezani & Farhangi-Abriz, 2018). Research conducted by (Zaid et al., 2022) corroborates these findings, demonstrating that the exogenous injection of salicylic acid during reproductive phases increases oil content by activating lipid biosynthesis enzymes. SA-treated oilseed crops exhibited enhanced stress tolerance and improved seed filling, leading to greater oil yield. The minimal oil yield occurred in the restricted irrigation treatment (A7), aligning with the detrimental effect of water stress on lipid metabolism. Water scarcity diminishes stomatal conductance, carbon uptake, and enzymatic activity, hence constraining oil biosynthesis. (Hatzig et al., 2018) established that water stress during seed development diminishes oil output in Brassica species by disrupting fatty acid metabolism and inducing oxidative damage. Drought stress markedly diminished oil content in rapeseed owing to poor sulphur uptake and metabolic disturbances. The current findings underscore the significance of coordinated sulphur feeding and agrochemical application in maximizing oil yield in water-scarce conditions. The synergistic application of Hydrogel and Salicylic Acid shown efficacy in alleviating moisture stress, improving fertilizer utilization efficiency, and optimizing oil yield in Gobhi Sarson. The research demonstrates that sulphur sources and agrochemical applications substantially influence oil yield in *Brassica napus*. The maximum oil yield was seen with Gypsum (S1) owing to its accessible sulphur, while Hydrogel and Salicylic Acid treatments (A6, A5, A4) augmented oil yield by enhancing water retention, stress resilience, and lipid biosynthesis. Conversely, restricted irrigation (A7) resulted in the lowest oil output, highlighting the detrimental impact of water stress on oil accumulation. The results are substantiated by scientific literature, emphasizing the significance of effective sulphur control and stress alleviation measures in improving oil yield across diverse environmental conditions.

Table 4.4.4.1: The impact of treatments on oil yield (q/ha) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	Oil yield (q/ha) (2021-22)	Oil yield (q/ha) (2022-23)
Sulphur sources		
S1: Gypsum	8.50[a]	8.67[a]
S2: Bentonite Sulphur	7.31[b]	7.44[b]
S3: Elemental Sulphur	5.37[c]	5.43[c]
CV (Sulphur Sources)	6.02	5.97
CD (Sulphur Sources)	0.34	0.34
Agrochemical		
A0: Control (Irrigation as per requirement)	8.10[b]	8.31[b]
A1: Hydrogel (2.5 kg/ha) as basal application	6.60[d]	6.72[d]
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	6.07[e]	6.18[e]
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	6.35[d]	6.41[e]
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	7.63[c]	7.73[c]
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	7.85[bc]	7.90[c]
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	8.60[a]	8.76[a]
A7: Control (Restricted irrigation)	5.28[f]	5.42[f]
CD (Agrochemical)	0.28	0.27
CV (Sulphur Sources and agrochemical)	4.09	3.96

Table 4.4.4.2: The interaction impact of treatments on oil yield (q/ha) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	Oil yield (q/ha) (2021-22)	Oil yield (q/ha) (2022-23)
S1A0	9.76±0.17	9.91±0.24
S1A1	7.95±0.01	8.14±0.01
S1A2	7.32±1.20	7.50±1.22
S1A3	7.64±0.56	7.76±0.74
S1A4	9.19±0.02	9.36±0.20
S1A5	9.46±0.03	9.57±0.03
S1A6	10.35±0.04	10.60±0.04
S1A7	6.36±0.04	6.56±0.04
S2A0	8.35±0.40	8.74±0.14
S2A1	6.84±0.01	6.94±0.01
S2A2	6.28±0.32	6.38±0.17
S2A3	6.58±0.02	6.63±0.02
S2A4	7.91±0.02	7.99±0.02
S2A5	8.14±0.01	8.16±0.01
S2A6	8.91±0.22	9.05±0.01
S2A7	5.47±0.02	5.60±0.02
S3A0	6.18±0.10	6.27±0.10
S3A1	5.01±0.01	5.08±0.01
S3A2	4.60±0.01	4.67±0.01
S3A3	4.82±0.02	4.85±0.02
S3A4	5.79±0.02	5.85±0.02
S3A5	5.96±0.01	5.98±0.01
S3A6	6.53±0.01	6.62±0.01
S3A7	4.01±0.01	4.10±0.01
CV	4.09	3.96
CD	0.56	0.55

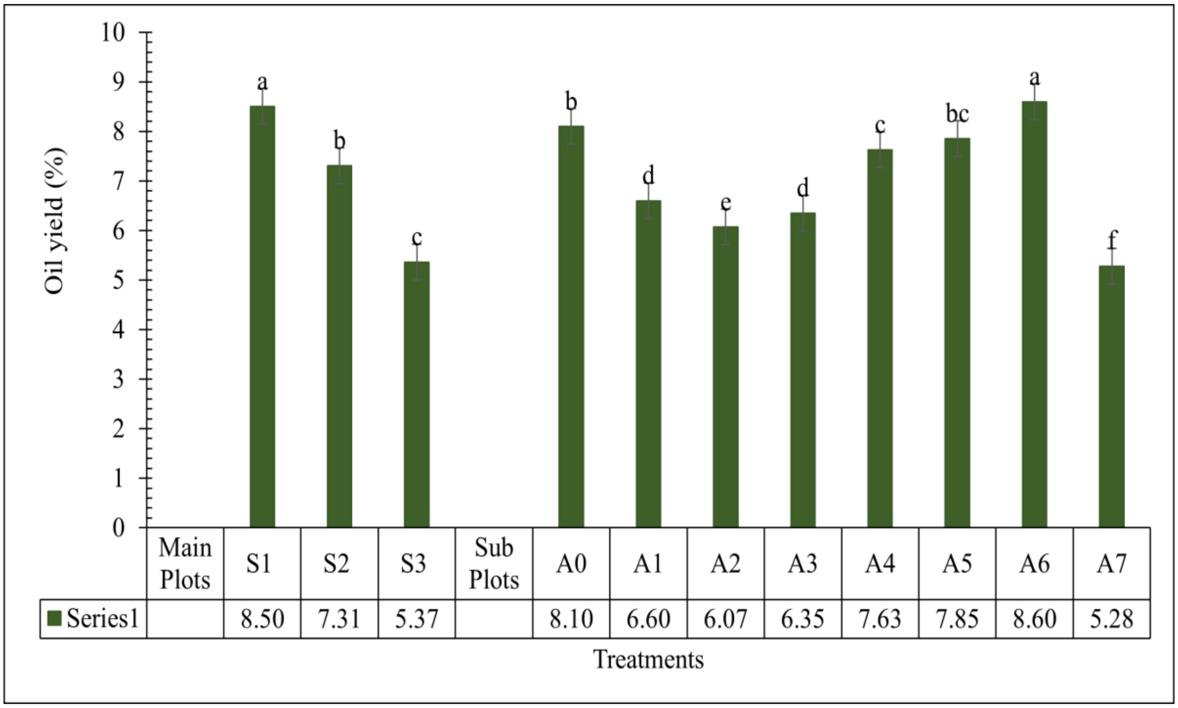


Fig:4.4.4.1(a): The impact of sulphur sources and agrochemical treatments on oil yield (q/ha) in the year 2021-2022

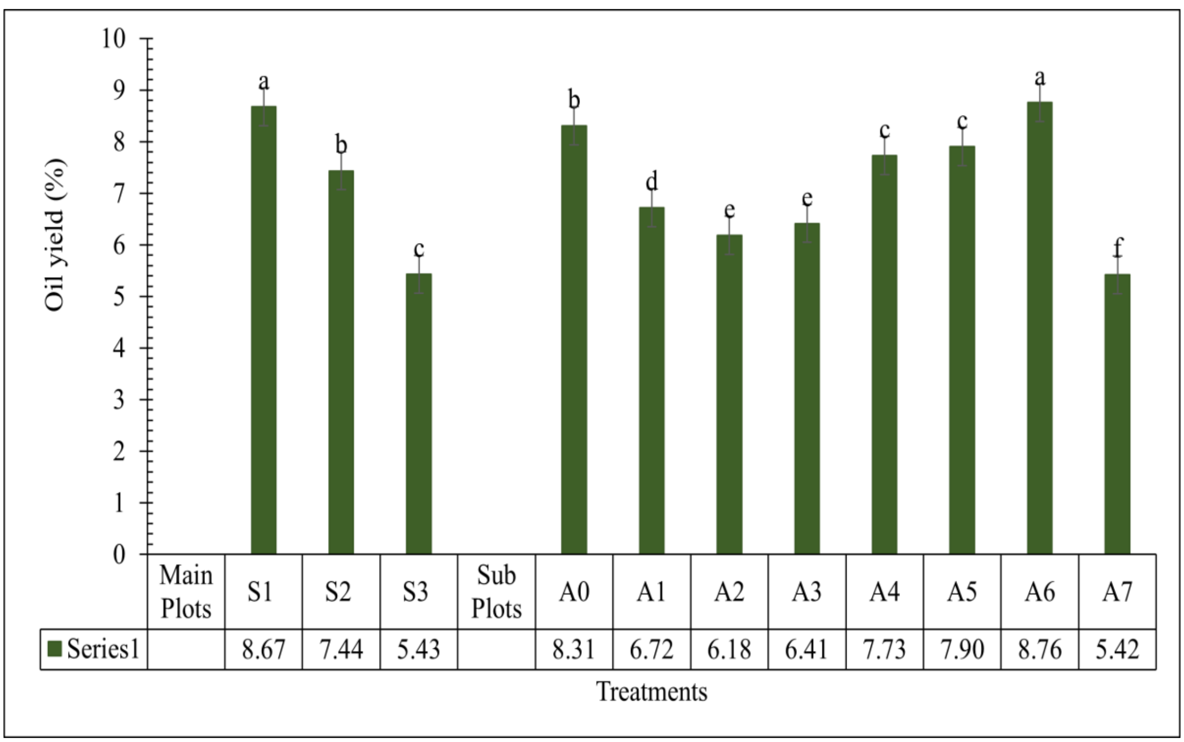


Fig:4.4.4.2(b): The impact of sulphur sources and agrochemical treatments on oil Yield (q/ha) in the year 2022-2023

4.4.5 Glucosinolate Content: The glucosinolate concentration in the GSC 7 variety of rapeseed exhibited considerable variation across several treatments implemented throughout the 2021-22 and 2022-23 growing seasons. As shown in Table 4.4.5.1 and Figure 4.4.5.1(a), 4.4.5.2(a), the study of sulphur sources and agrochemical usage indicated notable patterns in glucosinolate concentrations, essential for assessing the quality of oil intended for human consumption. Low glucosinolate levels are considered beneficial for human consumption, as excessive concentrations can provide a bitter flavor and disturb thyroid function. The glucosinolate content was markedly influenced by the sources of sulphur and agrochemical applications. The highest glucosinolate level among sulphur sources was observed with Elemental Sulphur (S3) at 26.7 µmol/g in 2021–22 and 26.9 µmol/g in 2022–23, closely succeeded by Bentonite Sulphur (S2) with 25.4 and 25.7 µmol/g, respectively. The minimal glucosinolate concentration was recorded under Gypsum (S1), measuring 22.2 and 22.4 µmol/g, which represents a reduction of 16.8% and 16.7% compared to Elemental Sulphur. The highest glucosinolate level in agrochemical treatments was observed in A7 (Restricted irrigation) at 27.4 and 27.6 µmol/g, followed by A1 (Hydrogel alone) at 27.1 and 26.9 µmol/g in both years. Moderate levels were recorded for A2, A3, and A5, varying from 24.0 to 26.0 µmol/g. The lowest glucosinolate level was seen in A6 (Hydrogel + Salicylic acid during flowering and pod development), measuring 21.3 µmol/g in 2021–22 and 21.6 µmol/g in 2022–23, representing reductions of 22.3% and 21.7%, respectively, compared to A7. In conclusion, Elemental Sulphur and Restricted irrigation markedly elevated glucosinolate levels, while the combination of Gypsum and A6 agrochemical treatment (Hydrogel + Salicylic acid at both stages) significantly diminished glucosinolate accumulation, establishing A6 as the most effective treatment for reducing glucosinolates over both years.

The interaction effect of various sulphate sources and agrochemical treatments on glucosinolate content in Gobhi Sarson (GSC 7) during the *rabi* seasons of 2021-22 and 2022-23 demonstrated significant variations among treatments shown in Table 4.4.5.2. During the 2021–22 period, the treatment S1A6 (Gypsum + Hydrogel at 2.5 kg/ha + Salicylic acid at 150 ppm) exhibited the lowest glucosinolate level at 19.3 µmol/g, followed by S1A0 (Gypsum + full irrigation) at 20.9 µmol/g, and S1A4 (Gypsum + Hydrogel) at 21.1 µmol/g. In 2022–23, similar trends were observed, with S1A6 recording the lowest value of 19.6 µmol/g, succeeded by S1A0 at 21.3 µmol/g and S1A4 at 21.4 µmol/g. The results demonstrate that gypsum, particularly in conjunction with hydrogel and salicylic acid, significantly diminished glucosinolate buildup under controlled irrigation conditions. Conversely, the maximum glucosinolate concentration was seen in S3A7 (Elemental sulphur + restricted irrigation), measuring 29.3 μmol/g in both years. S3A1 (28.9 and 28.6 μmol/g) and S2A7 (28.4 and 28.9 μmol/g) closely followed this. The treatments, including elemental or bentonite sulphur under water stress, resulted in elevated glucosinolate levels, likely due to stress-induced enhancement of secondary metabolite production. Treatment S1A6 yielded a glucosinolate content that was 34.1% and 33.1% lower in 2021–22 and 2022–23, respectively, compared to the peak value observed in S3A7. S1A6 (Gypsum + Hydrogel + Salicylic acid) emerged as the most efficacious treatment for diminishing glucosinolate levels in Gobhi Sarson over both years. Glucosinolates are sulphur- containing secondary metabolites mostly located in Brassica species. Although they aid in plant defense and impart distinctive flavor, elevated levels are regarded as anti- nutritional for humans due to their possible goitrogenic effects. Consequently, diminishing glucosinolate levels in oilseed crops such as Gobhi Sarson is advantageous for improving seed meal quality. The differences in glucosinolate levels among various sulphur sources can be ascribed to the variances in their availability and release dynamics in the soil. Elemental sulphur (S_3), exhibiting the highest glucosinolate concentration, undergoes microbial oxidation to transform into plant-available sulfate. This process transpires incrementally, guaranteeing a sustained and uniform supply of sulphur in the rhizosphere over the entire crop growth phase. The constant availability of sulphur facilitates the ongoing manufacture of glucosinolates, which are sulphur-rich secondary metabolites. Conversely, gypsum (S_1), exhibiting the minimal glucosinolate concentration, is a highly soluble and instantly accessible source of sulfate. Although it facilitates rapid sulphur absorption in the initial growth phases, its solubility renders it susceptible to leaching losses, particularly in sandy loam soils. This leads to a reduction in sulphur availability in the later phases of crop development, thereby restricting the substrate necessary for glucosinolate production. Consequently, owing to its ephemeral availability, gypsum mitigates the potential for excessive glucosinolate buildup, rendering it a more appropriate choice for the production of low-glucosinolate seeds that are safer and more acceptable for human consumption (Malhi et al., 2025; Manish Kumar Maurya et al., 2023; Van Dam et al., 2003; Verkerk et al., 2009).

The agrochemical treatment A6 resulted in the lowest glucosinolate concentration. This combination probably affected glucosinolate metabolism through many routes. Hydrogel aids in sustaining uniform soil moisture, hence diminishing abiotic stress indicators that frequently provoke the buildup of secondary metabolites (glucosinolates) as a defensive response. Salicylic acid (SA), a plant hormone implicated in stress signaling and defense modulation, is recognized for its role in modulating secondary metabolite pathways. Its application during reproductive phases may have altered plant metabolism to prioritize reproductive development and seed filling over the manufacturing of defense-related compounds such as glucosinolates. Conversely, Restricted irrigation (A7) induced water stress, a recognized promoter of glucosinolate production. In response to stress, plants allocate resources to protective chemicals, resulting in heightened glucosinolate accumulation as a component of their biochemical defense mechanism. The minimal glucosinolate content seen with Gypsum + A6 is due to the restricted sulphur availability from Gypsum and the downregulation of glucosinolate production, influenced by optimal moisture conditions and salicylic acid-mediated hormonal signaling. This treatment combination substantially inhibited glucosinolate buildup, rendering it the optimal choice for enhancing the nutritional quality of Gobhi Sarson for human consumption. (Ilahy et al., 2020; Kiddle et al., 1994; Verkerk et al., 2009; Yi et al., 2016). The study demonstrates that a balanced sulphate supply, sufficient moisture retention, and effective stress regulation significantly affect glucosinolate content. Notably, the combination of gypsum with hydrogel and salicylic acid (S1A6) is identified as the most effective treatment for enhancing the quality of edible oil.

Table 4.4.5.1: The impact of treatments on glucosinolate content (μmol/g) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	Glucosinolate content (μmol/g) (2021-22)	Glucosinolate content (μmol/g) (2022-23)
Sulphur sources		
S1: Gypsum	22.2^{b}	22.4^{b}
S2: Bentonite Sulphur	25.4^{a}	25.7^{a}
S3: Elemental Sulphur	26.7^{a}	26.9^{a}
CV (Sulphur Sources)	7	6.7
CD (Sulphur Sources)	1.4	1.3
Agrochemical		
A0: Control (Irrigation as per requirement)	23.0^{d}	23.4^{d}
A1: Hydrogel (2.5 kg/ha) as basal application	27.1^{ab}	26.9^{ab}
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	25.6^{c}	25.8^{bc}
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	25.9^{bc}	26.0^{bc}
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	23.7^{d}	24.0^{d}
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	24.0^{d}	24.6^{cd}
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	21.3^{e}	21.6^{e}
A7: Control (Restricted irrigation)	27.4^{a}	27.6^{a}
CD (Agrochemical)	1.4	1.5
CV (Sulphur Sources and agrochemical)	5.96	6.13

Table 4.4.5.2: The interaction impact of treatments on Glucosinolate (µmol/g) content of rapeseed During the *rabi* season of 2021-2022 & 2022-23

Treatments	Glucosinolate content (µmol/g) (2021-22)	Glucosinolate content (µmol/g) (2022-23)
S1A0	20.9±0.01	21.3±0.01
S1A1	24.3±0.49	24.2±0.00
S1A2	22.9±0.01	22.9±0.01
S1A3	23.2±0.01	23.2±0.00
S1A4	21.1±0.01	21.4±0.01
S1A5	21.3±0.01	21.7±0.01
S1A6	19.3±0.01	19.6±0.01
S1A7	24.6±0.01	24.7±0.01
S2A0	22.7±0.01	22.7±0.01
S2A1	28.2±0.59	27.8±0.29
S2A2	26.5±0.01	26.9±0.00
S2A3	26.8±0.01	27.1±0.00
S2A4	24.6±0.95	24.6±0.79
S2A5	24.9±0.00	25.7±0.01
S2A6	21.1±5.47	21.7±6.23
S2A7	28.4±0.00	28.9±0.01
S3A0	25.3±4.73	26.1±3.80
S3A1	28.9±0.53	28.6±0.43
S3A2	27.4±0.01	27.6±1.44
S3A3	27.7±0.01	27.8±0.01
S3A4	25.5±0.01	26.1±0.01
S3A5	25.8±0.01	26.4±0.01
S3A6	23.5±0.02	23.6±0.01
S3A7	29.3±0.01	29.3±0.01
CV	5.96	6.13
CD	2.4	2.5

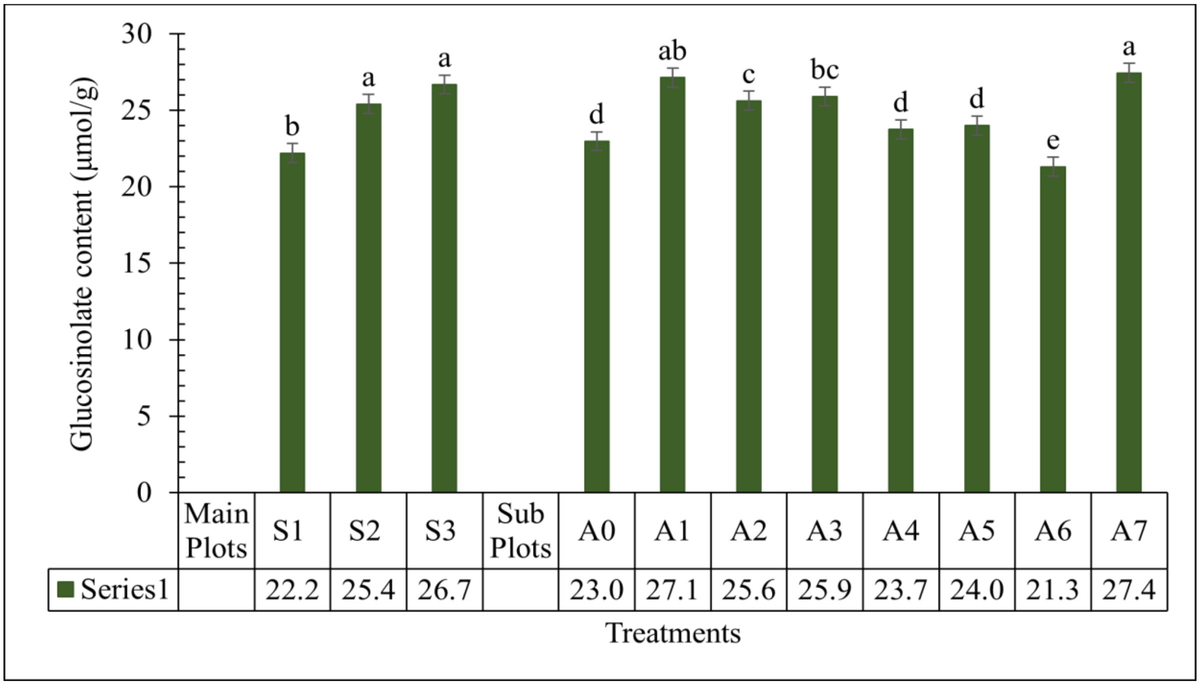


Fig. 4.4.5.1 (a): The impact of sulphur sources and agrochemical treatments on glucosinolate value (µmol/g) in the year 2021-2022

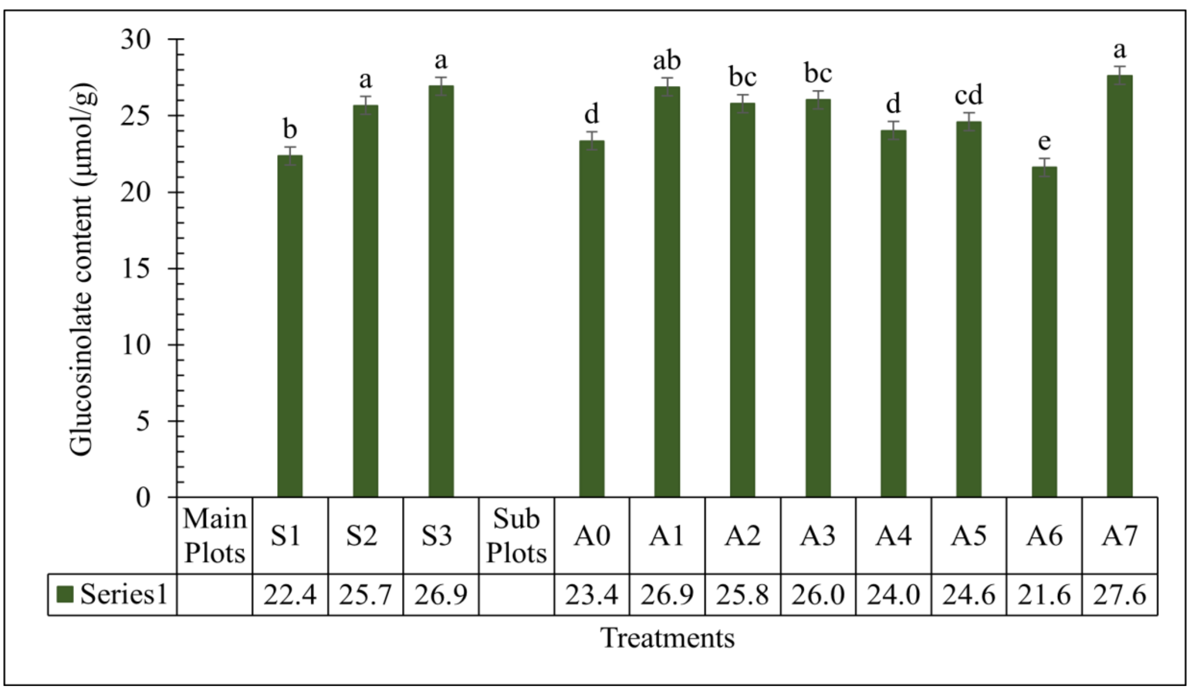


Fig. 4.4.5.2 (b): The impact of sulphur sources and agrochemical treatments on glucosinolate value (µmol/g) in the year 2022-2023

4.4.6 Erucic acid (%): Table 4.4.6.1 and Figure 4.4.6.1(a), 4.4.6.2(b) display the erucic acid concentration in Gobhi Sarson (*Brassica napus* L.) for the years 2021-22 and 2022-23, illustrating the impact of various sulphur sources and agrochemical applications. As products with reduced erucic acid levels are preferable for consumption, Gypsum (S1) is identified as the optimal sulphur source, exhibiting the lowest erucic acid content (0.9% in 2021-22 and 1.0% in 2022-23), followed by Bentonite Sulphur (S2) with 1.3% and 1.5%, whereas Elemental Sulphur (S3) displayed the highest concentrations (1.6% in both years), suggesting its ineffectiveness in diminishing erucic acid levels. Among agrochemical treatments, A6 (Hydrogel at 2.5 kg/ha combined with Salicylic acid at 150 ppm during 50% flowering and pod development) proved to be the most effective, decreasing erucic acid levels to 0.8% in 2021-22 and 0.9% in 2022-23, indicating a substantial reduction. A4 (Hydrogel + SA at flowering) recorded 1.0% in both years, whereas A5 (Hydrogel + SA at pod formation) exhibited somewhat higher amounts of 1.2% in both instances. Salicylic acid alone (A2, A3) showed efficacy, with A2 (50% flowering) decreasing it to 1.2% and 1.3%, while A3 (50% pod development) exhibited marginally elevated values of 1.4% and 1.5%. Hydrogel alone (A1) demonstrated modest efficacy (1.4% and 1.6%), while complete irrigation control (A0) yielded elevated levels of erucic acid (1.6% and 1.7%). The most adverse treatment was A7 (Restricted Irrigation), which exhibited the highest concentrations (1.7% and 1.8%), underscoring that water stress markedly enhances erucic acid development. Throughout the period of two years, the most successful treatments continuously reduced erucic acid levels, demonstrating that the combination of Gypsum with Hydrogel and Salicylic Acid during both flowering and pod formation is the optimal approach to improve oil quality.

The interaction effects of sulphur sources and agrochemical treatments on erucic acid concentration during two consecutive years (2021-22 and 2022-23) in Table 4.4.6.2 underscore the importance of these factors in modulating fatty acid metabolism in Gobhi Sarson (*Brassica napus* L.). Among all treatments, S1A6 (Gypsum + Hydrogel at 2.5 kg/ha + Salicylic Acid at 50% flowering and 50% pod formation) displayed the lowest erucic acid content (0.5% in 2021-22 and 0.7% in 2022-23), highlighting the efficacy of gypsum as a sulphur source, coupled with moisture retention and salicylic acid-mediated lipid metabolism regulation. Alternative gypsum-based treatments, including S1A4 and S1A5

(Hydrogel + SA applied in single stages), consistently yielded low erucic acid levels (0.8% in both years), albeit marginally higher than S1A6, thereby underscoring the significance of multiple-stage application. The peak amounts of erucic acid were recorded under S3A7 (Elemental Sulphur + Restricted Irrigation), attaining 2.0% in both years, demonstrating the adverse impact of moisture stress coupled with gradual sulphur release. Among all sulphur sources, gypsum-based treatments consistently produced the lowest levels of erucic acid, but elemental sulphur-based treatments maintained the highest levels due to the protracted conversion of elemental sulphur to plant-available sulphate. Among agrochemical treatments, S6 (Hydrogel + SA at both stages) consistently surpassed other combinations in diminishing erucic acid across sulphur sources, further highlighting the advantageous effects of moisture stabilization and hormone modulation on fatty acid desaturation. The data confirm that the use of gypsum in conjunction with hydrogel and SA during critical growth phases significantly reduces erucic acid accumulation, hence enhancing the quality of the obtained oil.

Erucic acid, a monounsaturated omega-9 fatty acid, has significant health risks in edible oils. The synthesis in *Brassica napus* L. is affected by multiple factors, including as moisture availability, nutrition supply, and hormone regulation. The study's findings indicate that sulphur sources, hydrogel, and salicylic acid (SA) treatments affected erucic acid buildup, with Gypsum (S1) and the combination of Hydrogel + SA (A6) being the most efficient in its reduction. Sulphur (S) is an essential element in fatty acid metabolism, especially in Brassica crops, as it contributes to enzyme activation and lipid production. S1 (Gypsum) had the lowest levels of erucic acid (0.9% in 2021-22, 1.0% in 2022-23) due to gypsum supplying sulphur in the form of sulphate (SO_4^{2-}), which is readily accessible to plants and effectively facilitates fatty acid desaturation. This facilitates the conversion of long-chain fatty acids into preferred shorter-chain fatty acids, hence diminishing erucic acid concentration. S2 (Bentonite Sulphur) exhibited a moderate reduction of 1.3% and 1.5%, as bentonite necessitates microbial oxidation to liberate sulphate, rendering it less immediately efficacious than gypsum. S3 (Elemental Sulphur) produced the greatest erucic acid levels (1.6% in both years) due to the necessity of microbial conversion to sulphate, a gradual process. This delay results in a transient sulphur deficit, hindering fatty acid metabolism and causing an increase in erucic acid buildup. (Chahal et al., 2020; Galanty et al., 2023; Narayan et al., 2023c; G. Singh et al., 2023)

The utilization of hydrogel and salicylic acid affected erucic acid concentrations via moisture management and hormonal signaling. A6 (Hydrogel at basal level combined with SA during flowering and pod development) exhibited the lowest erucic acid content (0.8% and 0.9%) attributable to the excellent moisture retention provided by the hydrogel and the influence of SA on lipid metabolism. SA regulates fatty acid desaturases, which transform long-chain fatty acids, such as erucic acid, into healthy polyunsaturated fatty acids. The synergistic effect improved fatty acid catabolism and reduced erucic acid buildup. A4 (Hydrogel + SA at flowering) significantly reduced erucic acid (1.0% in both years), while it was marginally less efficient than A6, as SA was given solely during flowering, neglecting the influence of the additional pod development stage on lipid metabolism. A5 (Hydrogel + SA at pod formation) exhibited 1.2% in both years, indicating that SA application at pod formation was advantageous but less effective than the dual-stage treatment (A6). A2 (SA during flowering) and A3 (SA at pod formation) independently decreased erucic acid levels (1.2%–1.5%), indicating that SA affects lipid biosynthesis; however, its impact is enhanced when used in conjunction with hydrogel, which improves nutrient uptake and stability. A1 (Hydrogel alone, 1.4% and 1.6%) demonstrated moderate efficacy, as moisture retention facilitated nutrient uptake; however, in the absence of SA, lipid metabolism regulation was diminished, resulting in elevated erucic acid levels compared to A4, A5, and A6. A0 (Full irrigation control) sustained higher erucic acid concentrations (1.6% and 1.7%) because, although adequate water supports fatty acid composition, it does not actively enhance lipid metabolism as SA and hydrogel do. A7 (Restricted irrigation) exhibited the highest levels of erucic acid (1.7% and 1.8%) as a result of moisture stress (Galanty et al., 2023; Narayan et al., 2023c). Water scarcity induces stress-related lipid peroxidation, elevating the production of long-chain fatty acids such as erucic acid, rendering it the least favorable treatment. Studies have shown that gypsum, providing accessible sulphate, significantly reduces erucic acid levels in rapeseed. A study indicated that gypsum application resulted in a substantial reduction of erucic acid levels, hence improving oil quality. Elemental sulphur necessitates microbial oxidation to transform into plant-accessible sulphate, leading to a delayed impact. The diminished availability may result in a less efficient elimination of erucic acid relative to gypsum. The dual application of hydrogel and SA during important growth phases (flowering and pod formation) has demonstrated a synergistic reduction in erucic acid concentration. Hydrogel enhances soil moisture retention, promoting nutrient uptake, while SA affects lipid metabolism, together improving oil quality. The SA application has been shown to beneficially influence fatty acid composition by regulating enzyme activity related to lipid production, resulting in decreased erucic acid levels. Although hydrogel contributes to soil moisture retention, its exclusive use without SA exhibits a diminished impact on the decrease of erucic acid. The synergy with SA is more efficacious due to the hormonal modulation of lipid metabolism. (Ayala et al., 2014; Gigon et al., 2004; Hartina et al., 2025; Kulczycki, 2021; Mitra & Begum, 2023)

The findings clearly demonstrate that Gypsum (S1) is the superior source of sulphur due to its prompt availability and its function in fatty acid desaturation, whereas A6 (Hydrogel + SA during flowering and pod formation) is the optimal agrochemical treatment, as it maximizes moisture retention and improves the enzymatic regulation of fatty acids. The results highlight that integrating moisture management, sulphur supplementation, and hormone regulation is essential for decreasing erucic acid levels, hence enhancing oil quality and nutritional advantages.

Table 4.4.6.1: The impact of treatments on Erucic acid (%) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	Erucic acid (%) (2021-22)	Erucic acid (%) (2022-23)
Sulphur sources		
S1: Gypsum	0.9^{c}	1.0^{c}
S2: Bentonite Sulphur	1.3^{b}	1.5^{b}
S3: Elemental Sulphur	1.6^{a}	1.6^{a}
CV (Sulphur Sources)	6.41	3.31
CD (Sulphur Sources)	0.07	0.04
Agrochemical		
A0: Control (Irrigation as per requirement)	1.6^{b}	1.7^{b}
A1: Hydrogel (2.5 kg/ha) as basal application	1.4^{c}	1.6^{c}
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	1.2^{d}	1.3^{e}
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	1.4^{c}	1.5^{d}
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	1.0^{e}	1.0^{g}
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	1.2^{d}	1.2^{f}
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	0.8^{f}	0.9^{h}
A7: Control (Restricted irrigation)	1.7^{a}	1.8^{a}
CD (Agrochemical)	0.06	0.04
CV (Sulphur Sources and agrochemical)	5.3	3.28

Table 4.4.6.2: The interaction impact of treatments on Erucic acid (%) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	Erucic acid (%) (2021-22)	Erucic acid (%) (2022-23)
S1A0	1.2±0.11	1.2±0.03
S1A1	1.0±0.00	1.1±0.03
S1A2	0.8±0.01	0.9±0.03
S1A3	1.0±0.00	1.0±0.03
S1A4	0.8±0.01	0.8±0.03
S1A5	0.8±0.00	0.8±0.03
S1A6	0.5±0.00	0.7±0.03
S1A7	1.3±0.01	1.5±0.03
S2A0	1.7±0.14	1.8±0.03
S2A1	1.5±0.00	1.8±0.04
S2A2	1.2±0.18	1.5±0.02
S2A3	1.4±0.00	1.6±0.03
S2A4	1.0±0.12	1.0±0.10
S2A5	1.3±0.00	1.4±0.08
S2A6	0.9±0.01	1.0±0.05
S2A7	1.8±0.00	1.9±0.02
S3A0	1.9±0.10	1.9±0.05
S3A1	1.7±0.00	1.9±0.03
S3A2	1.5±0.01	1.6±0.03
S3A3	1.7±0.01	1.7±0.05
S3A4	1.4±0.00	1.2±0.05
S3A5	1.4±0.00	1.4±0.04
S3A6	1.1±0.00	1.1±0.03
S3A7	2.0±0.00	2.0±0.03
CV	5.3	3.28
CD	0.11	0.07

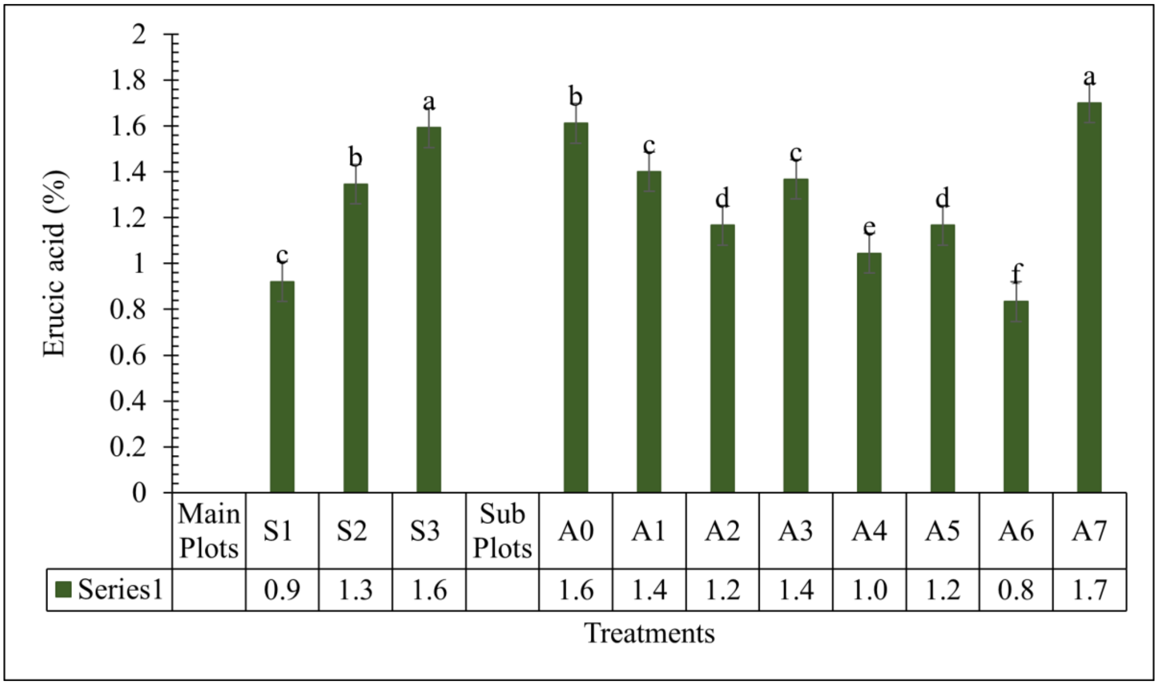


Fig:4.4.6.1(a): The impact of sulphur sources and agrochemical treatments on Erucic acid (%) in the year 2021-2022

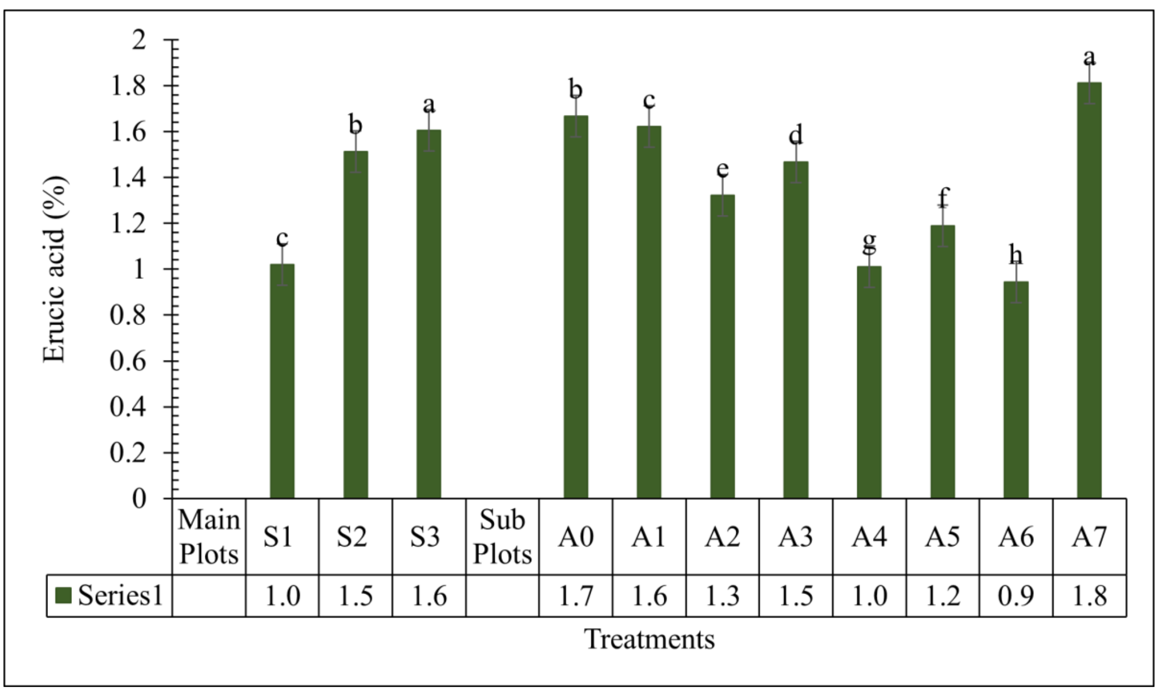


Fig:4.4.6.2(b): The impact of sulphur sources and agrochemical treatments on Erucic acid (%) in the year 2022-2023

4.4.6 Iodine Value (gm/100 g): During the 2021-22 growing season, the iodine value of rapeseed oil showed considerable variation across treatments shown in Table 4.4.7.1 and Figure 4.4.7.1(a) and 4.4.7.2(b). A higher iodine value is favored in edible oils as it signifies increased unsaturation, correlating with superior nutritional quality and health advantages. The iodine value of Gobhi Sarson oil was markedly affected by various sulphur sources and agrochemical treatments during both years. The highest iodine value among the sulphur sources was recorded for Gypsum (S1) at 105.75 in 2021–22 and 105.79 in 2022–23, closely followed by Bentonite Sulphur (S2) with values of 103.90 and 104.18, respectively. The minimum iodine value was seen with Elemental Sulphur (S3) at 95.86 and 96.46, representing reductions of 9.35% and 8.83% compared to Gypsum, respectively. The highest iodine value for agrochemical treatments was observed in A6 (Hydrogel + Salicylic acid during flowering and pod formation) with values of 106.42 and 106.84 across both years. This was closely followed by A0 (Irrigation as required) with values of 105.91 and 105.83, and A4 (Hydrogel + Salicylic acid during flowering) with values of 104 and 104.32. Gypsum served as a sulphur source, and A6 agrochemical treatment markedly improved the iodine value of the oil, with A6 showing to be the most effective treatment across both years for enhancing oil quality regarding unsaturation. The lowest iodine value, recorded under A7 (Restricted irrigation), was 95.31 and 95.99, indicating a reduction of 10.43% and 10.16% relative to A6, highlighting the detrimental effect of water scarcity on oil quality. The elevated iodine values in the treatments involving gypsum and the combination application of hydrogel and salicylic acid were likely attributable to their enhancement of plant physiological responses under stress, which includes improved hydration, sulphur uptake, and the synthesis of unsaturated fatty acids. In contrast, the limited irrigation treatment resulted in reduced iodine values, presumably due to compromised metabolic activity and fatty acid desaturation under conditions of water stress. (Khatami et al., 2022)

In interaction treatments (Table 4.4.7.2) during the 2021-22 and 2022-23 growing season, the iodine value of rapeseed oil exhibited considerable variation across different combinations of sulphur sources and agrochemical treatments. During the 2021–22 period, the greatest iodine value was recorded for S1A6 (Gypsum + Hydrogel at 2.5 kg/ha + Salicylic acid at 150 ppm) at 110.38, followed closely by S1A0 (Gypsum + full irrigation) at 109.72, and S2A6 (Bentonite sulphur + Hydrogel + Salicylic acid) at 108.87. In 2022–23, S1A6 exhibited the highest iodine value of 110.49, followed by S1A0 at 109.57 and S2A6 at 109.21. This demonstrates that the combination of gypsum with hydrogel and salicylic acid efficiently maintains the unsaturation of oil, hence improving its quality. The lowest iodine value was seen in S3A7 (Elemental sulphur + restricted irrigation) at 89.57 in 2021–22 and 90.58 in 2022–23, followed by S3A2 (93.15 and 93.72) and S3A3 (94.11 and 95.01). These treatments, conducted under limited irrigation and with elemental sulphur, typically exhibited reduced iodine values, presumably due to elevated stress levels that adversely impacted oil quality. The iodine value enhancement under S1A6 compared to S3A7 was 23.3% in 2021–22 and 22.0% in 2022–23, indicating a steady advancement in oil unsaturation levels with the optimal treatment. Consequently, S1A6 (Gypsum + Hydrogel + Salicylic acid) had the highest efficacy in augmenting the iodine value of oil, signifying superior quality and elevated unsaturation levels over both years. The notable enhancements in iodine values with gypsum and bentonite sulphur under treatments incorporating Hydrogel and salicylic acid can be ascribed to increased nutritional availability, augmented water retention, and superior physiological stress management. On the other hand, elemental sulphur showed somewhat lower values throughout treatments, perhaps due to its slower oxidation and assimilation in the soil (A. Sharma et al., 2020).

The variations in iodine value among different sulphur sources and agrochemical treatments can be understood through the complex physiological and biochemical mechanisms that regulate oil synthesis in rapeseed. Sulphur is an essential macronutrient that facilitates the manufacture of amino acids such as cysteine and methionine, which serve as precursors to glucosinolates and fatty acids. These chemicals are essential in assessing oil quality, namely the level of unsaturation, as indicated by the iodine value (Dhaliwal et al., 2024). Among the examined sulphur sources, gypsum consistently exhibited the highest iodine values owing to its high solubility, which guarantees a fast and persistent supply of sulphate (SO_4^{2-}), the bioavailable form of sulphur. Sulphate directly affects enzyme function, including acetyl-CoA carboxylase and fatty acid desaturase, which are essential for unsaturated fatty acid synthesis (Seeda et al., 2020; Zenda et al., 2021). Research by Scherer (2001) indicates that sulphur deficit constrains enzymatic activity, resulting in diminished fatty acid desaturation and a decreased iodine value, a pattern supported by the suboptimal performance of elemental sulphur (S3) in the present investigation. The postponed oxidation of elemental sulphur to sulphate due to microbial activity, affected by soil pH, moisture, and temperature, likely limited its availability during crucial phases of crop development, hence underscoring the advantages of gypsum and bentonite sulphur. Agrochemical treatments, including Hydrogel and salicylic acid, significantly affected iodine values, indicating their contributions to improving stress tolerance and physiological performance under different irrigation conditions. Hydrogel, a superabsorbent polymer, enhances soil moisture retention and ensures a steady supply of water to plants. This alleviates water stress, ensuring continuous photosynthesis and nutrient uptake, both of which are necessary for fatty acid production. Salicylic acid (SA) functions as a signaling molecule that activates antioxidant processes and stabilizes membranes during stress conditions (Ghobashy et al., 2024; Oladosu et al., 2022c). Research by Khan et al. (2015) indicates that SA strengthens resistance to lipid peroxidation and boosts the activity of fatty acid desaturases, resulting in a higher proportion of unsaturated fatty acids. The current investigation observed the greatest iodine values with the combined application of Hydrogel and salicylic acid (A6), suggesting a synergistic impact. Hydrogel provided adequate hydration, while salicylic acid improved stress resilience, thereby creating excellent conditions for oil synthesis. These findings correspond with the research conducted by Farooq et al., 2009, which indicated that the integration of soil moisture management with plant growth regulators markedly enhances crop quality under abiotic stress. The year-over-year consistency in treatment efficacy, despite minor fluctuations in iodine levels, further substantiates the reliability of treatments. The synergistic impact of sulphur and agrochemicals was particularly evident with gypsum and bentonite sulphur sources, underscoring the significance of timely sulphur availability in conjunction with stress alleviation.

Restricted irrigation treatments (A7) consistently produced the lowest iodine readings, possibly attributable to diminished carbon uptake and compromised fatty acid metabolism under water stress, corroborated Sabagh et al., 2019, who outlined the adverse impacts of drought on oilseed quality. The study underlines the significance of aligning sulphur nutrition with agrochemical interventions to enhance oil quality in rapeseed. The results recommend gypsum as an optimal sulphur source and the incorporation of hydrogel and salicylic acid to alleviate abiotic stress and promote unsaturated fatty acid production. This comprehensive method establishes a scientific foundation for enhancing oil quality in rapeseed, especially under fluctuating irrigation conditions, presenting a significant strategy for sustainable oilseed cultivation.

Table 4.4.7.1: The impact of treatments on iodine value (gm) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	Iodine Value (2021-22)	Iodine Value (2022-23)
Sulphur sources		
S1: Gypsum	105.75^{a}	105.79^{a}
S2: Bentonite Sulphur	103.90^{a}	104.18^{a}
S3: Elemental Sulphur	95.86^{b}	96.46^{b}
CV (Sulphur Sources)	4.81	6.65
CD (Sulphur Sources)	3.93	5.44
Agrochemical		
A0: Control (Irrigation as per requirement)	105.91^{a}	105.83^{ab}
A1: Hydrogel (2.5 kg/ha) as basal application	101.92^{bc}	102.12^{cd}
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	98.04d^{e}	98.22^{ef}
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	100.14^{cd}	100.69^{de}
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	104.00^{ab}	104.32^{abc}
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	102.95^{bc}	103.15^{bcd}
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	106.42^{a}	106.84^{a}
A7: Control (Restricted irrigation)	95.31^{e}	95.99^{f}
CD (Agrochemical)	2.83	3.16
CV (Sulphur Sources and agrochemical)	2.92	3.26

Table 4.4.7.2: The interaction impact of treatments on iodine value (gm) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	Iodine Value (2021-22)	Iodine Value (2022-23)
S1A0	109.72±0.38	109.57±0.38
S1A1	105.71±0.01	105.61±0.01
S1A2	102.81±10.00	102.72±10.00
S1A3	103.87±10.01	104.13±10.01
S1A4	107.87±0.01	107.89±10.00
S1A5	106.78±0.01	106.67±2.01
S1A6	110.38±0.01	110.49±0.01
S1A7	98.86±0.02	99.27±0.02
S2A0	108.28±0.37	108.49±0.45
S2A1	104.26±0.00	104.38±0.00
S2A2	98.15±6.22	98.24±6.18
S2A3	102.44±1.00	102.92±1.00
S2A4	106.39±0.00	106.63±0.00
S2A5	105.31±0.00	105.44±0.00
S2A6	108.87±0.00	109.21±0.00
S2A7	97.50±0.00	98.12±0.00
S3A0	99.73±0.22	99.43±0.33
S3A1	95.78±0.01	96.36±0.01
S3A2	93.15±0.01	93.72±0.01
S3A3	94.11±0.00	95.01±0.00
S3A4	97.74±0.00	98.44±0.00
S3A5	96.75±0.01	97.34±0.01
S3A6	100.01±0.01	100.82±0.01
S3A7	89.57±0.01	90.58±0.01
CV	2.92	3.26
CD	5.96	7.38

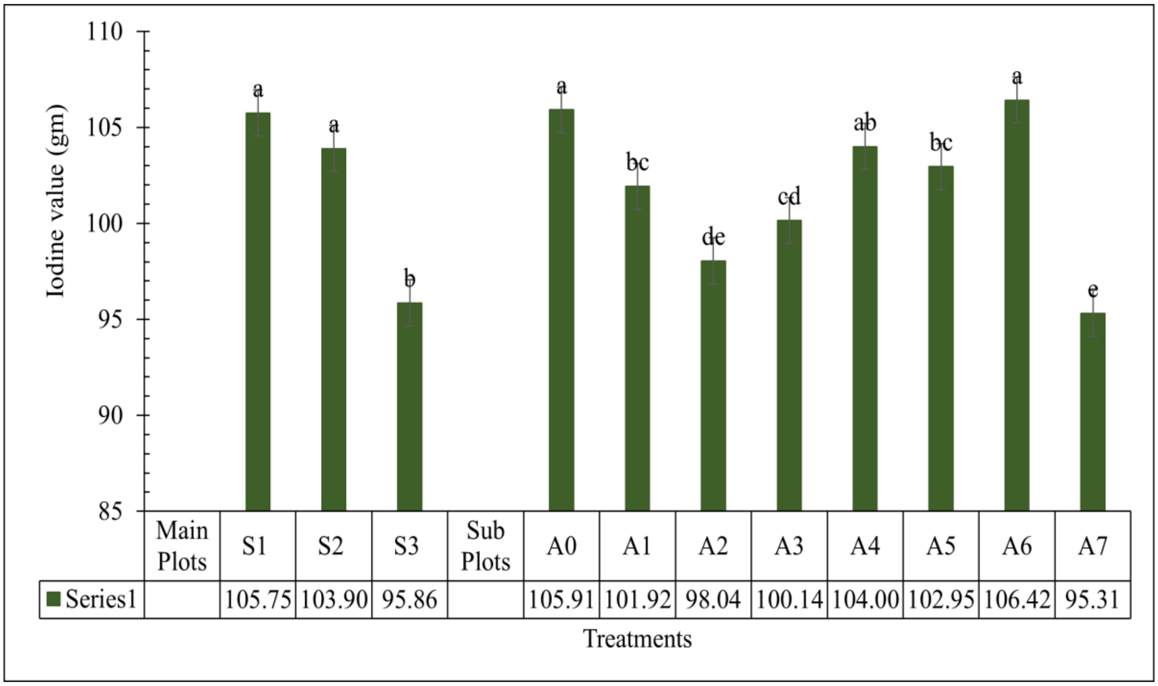


Fig 4.4.7.1(a): The impact of sulphur sources and agrochemical treatments on iodine value in the year 2021-2022

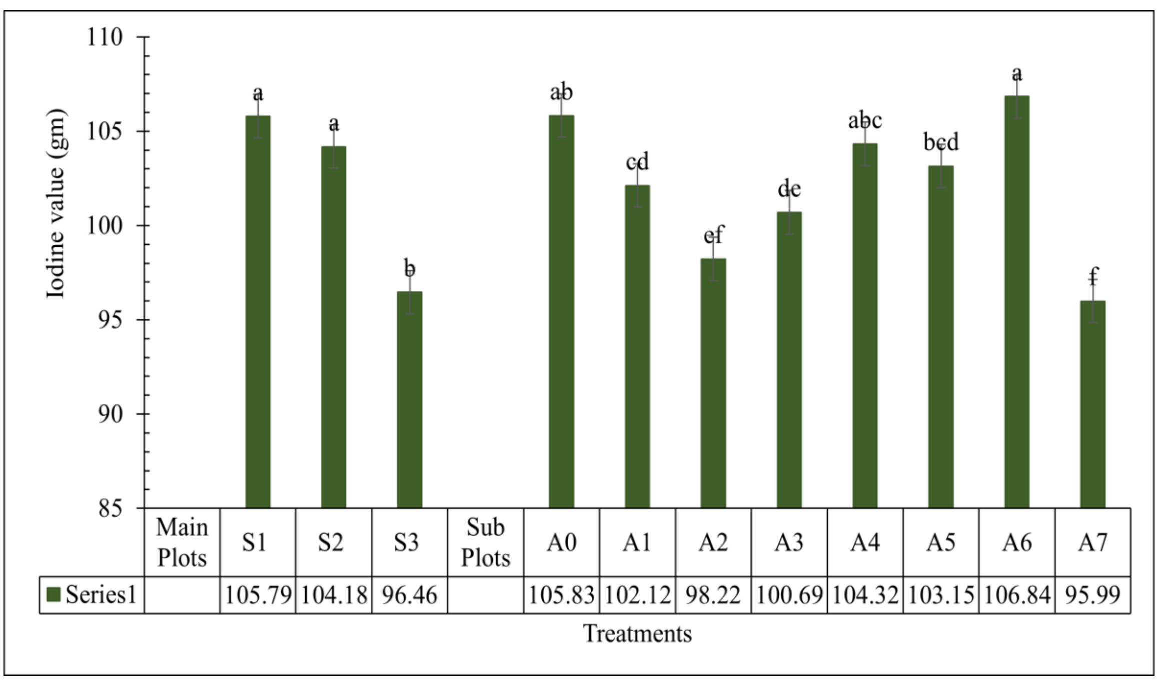


Fig 4.4.7.2(b): The impact of sulphur sources and agrochemical treatments on iodine value in the year 2022-2023

4.4.8 Saponification value (mg KOH/g): Table 4.4.8.1 and Figure 4.4.8.1(a) and 4.4.8.2(b) displays the impact of various sulphur sources and agrochemical treatments on the saponification value (mg KOH/g) of Gobhi Sarson (*Brassica napus* L.) during the *rabi* seasons of 2021-22 and 2022-23. The saponification value quantifies the average molecular weight of the fatty acids present, with a lower value being preferable for human consumption since it signifies a higher amount of healthy, long-chain fatty acids. The findings indicated that both sulphur sources and agrochemical applications markedly affected the saponification value of oil in Gobhi Sarson over both years of the study. Gypsum (S1) exhibited the lowest saponification values among the sulphur sources, recording 168.32 in 2021–22 and 168.82 in 2022–23. In comparison to elemental sulphur (S3), which exhibited peak values of 175.50 and 175.95, gypsum resulted in a decrease of 4.10% and 4.05% in saponification value, respectively. Bentonite sulphur (S2) had intermediate levels, demonstrating a reduction of 1.56% and 1.52% relative to elemental sulphur over the two years. The application of hydrogel and salicylic acid during both the 50% flowering and 50% pod formation stages (A6) yielded the lowest saponification values (167.51 and 168.31), reflecting reductions of 4.93% and 4.67% relative to the restricted irrigation control (A7), which exhibited the highest values of 176.19 and 176.57. Treatments A4 and A5 similarly resulted in diminished values, with drops of around 3.59% and 3.14% relative to A7. Conversely, control treatments under both full irrigation (A0) and restricted irrigation (A7) had the highest saponification values, signifying oil with comparatively shorter-chain fatty acids and diminished appropriateness for human consumption. Consequently, utilizing gypsum as a sulphur source with the concurrent application of hydrogel and salicylic acid during the flowering and pod formation stages is advised to enhance oil quality by reducing saponification value.

The interaction effect of various sulphur sources and agrochemical treatments on the saponification value (mg KOH/g) of Gobhi Sarson (*Brassica napus* L.) during the *rabi* seasons of 2021-22 and 2022-23 is displayed in Table 4.4.8.2. The interaction effects of sulphur sources and agrochemical treatments shown notable differences in the saponification value of *Brassica napus* L. oil during the two years. In the context of gypsum administration (S1), the synergistic treatment of hydrogel and salicylic acid administered during both flowering and pod formation stages (S1A6) exhibited the lowest saponification values, reflecting a 4.3% reduction in 2021–22 and a 4.2% reduction in 2022–23 relative to the complete irrigation control (S1A0). This signifies the combined impact of greater water retention and improved metabolic regulation on oil quality. Likewise, combinations S1A4 and S1A5 exhibited significant decreases of roughly 2.7–3.2% in saponification values compared to the control. In the presence of bentonite sulphur (S2), S2A6 decreased the saponification value by approximately 4.3% in 2021–22 and 4.4% in 2022–23 compared to S2A0. Elemental sulphur treatments (S3) consistently shown elevated saponification values, with the control under limited irrigation (S3A7) attaining the highest value in both years. Despite S3A6 exhibiting a marginal decrease of 4.8% in saponification value during 2021–22 relative to S3A0, it nevertheless surpassed the values observed in similar treatments involving gypsum and bentonite sulphur. The results indicate that gypsum, when combined with integrated agrochemical treatments, was most successful in reducing the saponification value, thereby improving oil quality.

The saponification value, which reflects the average molecular weight of fatty acids in oils, is affected by many agronomic practices, especially the use of diverse sulphur sources and agrochemicals. Sulphur is an essential nutrient in oilseed crops such as *Brassica napus* L. (Gobhi Sarson), significantly contributing to synthesizing sulphur-containing amino acids like cysteine and methionine, which are vital for protein and lipid metabolism. Proper sulphur nutrition promotes the synthesis of glycerol esters with lower molecular weight fatty acids, thereby elevating the saponification value of the oil. The saponification value, indicative of the average molecular weight of fatty acids in oil, is crucial in assessing oil quality. Reduced saponification values are deemed advantageous, since they signify the presence of longer-chain fatty acids, which are more favorable for human health owing to their lower reactivity and superior nutritional profile. The findings of this study indicate that gypsum (S1), utilized as a sulphur source, yielded the lowest saponification values over both years, establishing it as the most effective treatment for enhancing oil quality in *Brassica napus* L. (Gobhi Sarson). Gypsum, being a highly soluble source of sulphur, supplies sulphate ions that are rapidly absorbed by plants, enhancing sulphur assimilation and metabolic processes. The prompt availability of sulphur facilitates the synthesis of longer-chain fatty acids, which exhibit less reactivity during saponification, resulting in diminished saponification values. This is especially advantageous for human consumption, as oils with reduced saponification values are healthier and less susceptible to oxidation. The results indicate that gypsum's fast release of sulphate enhances lipid metabolism, promoting the synthesis of long-chain fatty acids and so improving oil quality. Elemental sulphur, upon microbial oxidation, yields sulphate in a gradual and delayed manner. The postponed nutrient availability probably enhances the production of shorter-chain fatty acids, resulting in elevated saponification values. Bentonite sulphur, due to its gradual sulphate release, promotes the buildup of additional short-chain fatty acids, leading to considerably increased saponification values compared to gypsum. Agrochemical treatments with hydrogel and salicylic acid were observed to impact oil quality by altering the plant's metabolic activities. The utilization of hydrogel improves soil moisture retention, guaranteeing a steady provision of water and nutrients to the plants. Salicylic acid functions as a growth regulator and stress alleviator, enhancing metabolic activities such as lipid production, which likely led to the decrease in saponification values. The complete irrigation control treatment (A0) yielded the greatest saponification values, suggesting that unlimited water availability promotes excessive vegetative growth and accelerates fatty acid turnover, hence enhancing the production of short-chain fatty acids. This process elevates the saponification value, rendering it less advantageous for human health. Conversely, the restricted irrigation treatment (A7), although resulting in elevated saponification values relative to gypsum, presumably induced water stress, hence intensifying the turnover of shorter-chain fatty acids. In conclusion, the gypsum treatment proved to be the most effective method for attaining reduced saponification values and, therefore, enhanced oil quality. The quick availability of sulphate from gypsum facilitates the synthesis of longer-chain fatty acids, which possess greater nutritional value. This outcome highlights the significance of sulphur management in enhancing oil quality in oilseed crops, especially for the attainment of a desirable fatty acid profile advantageous to human health. The simultaneous use of hydrogel and salicylic acid, especially during essential growth phases such as flowering and pod development, enhances oil quality metrics synergistically. Recent research indicates that this combination enhances seed output and improves oil qualities in *Brassica napus* L. (Chahal & Singh, 2018; Guvvali & Thirupathaiah Guvvali, 2019; Ivanova et al., 2022; M et al., 2020; Safdar et al., 2023; Sroka & Sroka, 2024; Xiao et al., 2021; Yusuf et al., 2023).

The study underscores the substantial influence of sulphur sources and agrochemical treatments on the saponification value of *Brassica napus* L. oil. Gypsum, serving as a sulphur source, demonstrated the highest efficacy in reducing the saponification value, hence enhancing oil quality for human consumption. The timely availability of sulphur and effective agronomic management are crucial for enhancing the fatty acid profile of the oil. These findings underscore the significance of strategic sulphur control in improving the nutritional content of oilseed crops.

Table 4.4.8.1: The impact of treatments on Saponification value (mg KOH/g) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	Saponification value (2021-22)	Saponification value (2022-23)
Sulphur sources		
S1: Gypsum	168.32^{c}	168.82^{b}
S2: Bentonite Sulphur	172.80^{b}	173.30^{ab}
S3: Elemental Sulphur	175.50^{a}	175.95^{a}
CV (Sulphur Sources)	1.01	3.95
CD (Sulphur Sources)	1.40	5.47
Agrochemical		
A0: Control (Irrigation as per requirement)	175.32^{a}	175.83^{a}
A1: Hydrogel (2.5 kg/ha) as basal application	173.50^{ab}	173.91^{ab}
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	171.07^{bc}	171.44^{bcd}
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	173.24^{ab}	173.69^{ab}
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	169.86^{cd}	170.24^{cd}
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	170.96^{bc}	171.52^{bc}
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	167.51^{d}	168.31^{d}
A7: Control (Restricted irrigation)	176.19^{a}	176.57^{a}
CD (Agrochemical)	3.11	3.14
CV (Sulphur Sources and agrochemical)	1.9	1.91

Table 4.4.8.2: The interaction impact of treatments on Saponification value (mg KOH/g) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	Saponification value (2021-22)	Saponification value (2022-23)
S1A0	171.29±0.02	172.00±0.02
S1A1	169.12±0.00	169.81±0.00
S1A2	167.25±0.01	167.56±0.01
S1A3	169.05±0.00	169.43±0.00
S1A4	166.62±0.01	166.95±0.01
S1A5	166.80±0.00	167.35±0.00
S1A6	163.98±0.01	164.70±0.01
S1A7	172.42±0.00	172.76±0.00
S2A0	175.86±0.44	176.61±0.53
S2A1	174.71±0.01	174.99±0.01
S2A2	171.60±0.01	172.00±0.01
S2A3	174.24±10.01	174.69±0.00
S2A4	168.89±0.01	169.43±0.01
S2A5	171.96±1.00	172.54±1.00
S2A6	168.27±5.88	168.82±6.15
S2A7	176.91±0.00	177.34±0.00
S3A0	178.82±0.53	178.89±0.65
S3A1	176.66±0.01	176.94±10.00
S3A2	174.36±0.00	174.76±10.01
S3A3	176.42±0.01	176.93±2.01
S3A4	174.06±10.00	174.35±10.00
S3A5	174.11±0.00	174.68±0.00
S3A6	170.29±0.15	171.39±0.22
S3A7	179.25±0.01	179.62±0.01
CV	1.9	1.91
CD	5.21	7.38

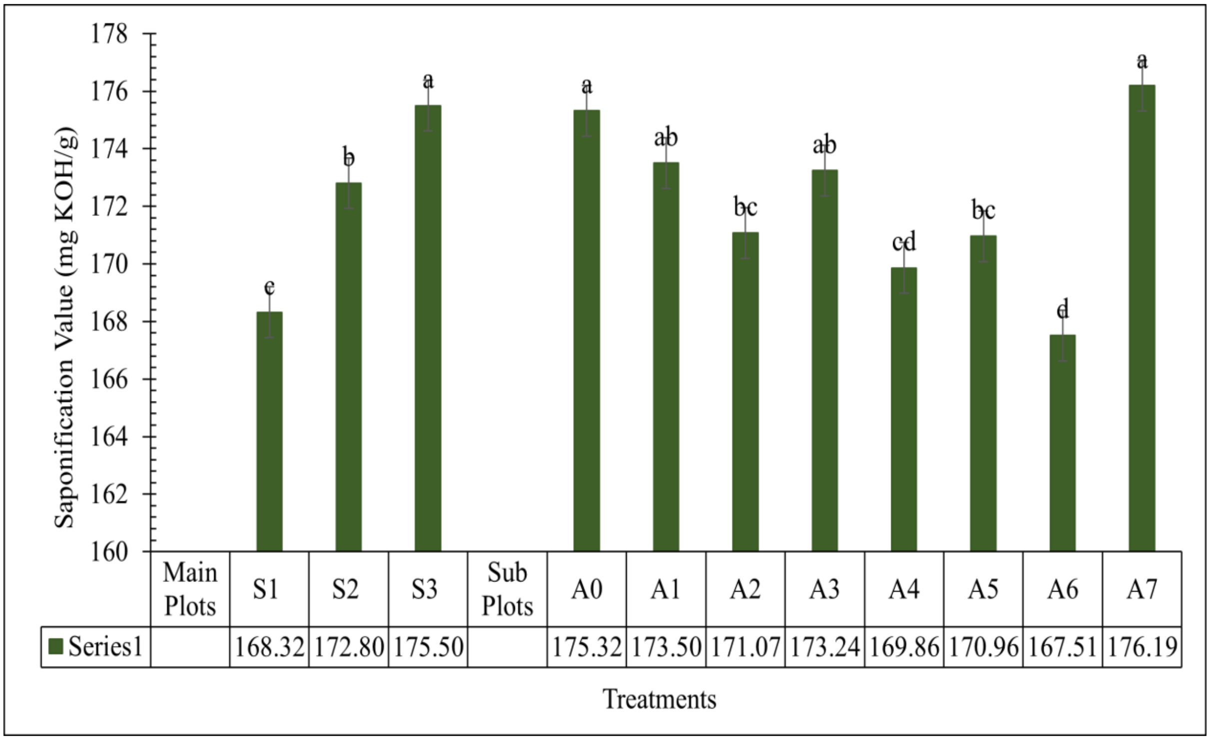


Fig. 4.4.8.1 (a): The impact of sulphur sources and agrochemical treatments on Saponification value in the year 2021-2022

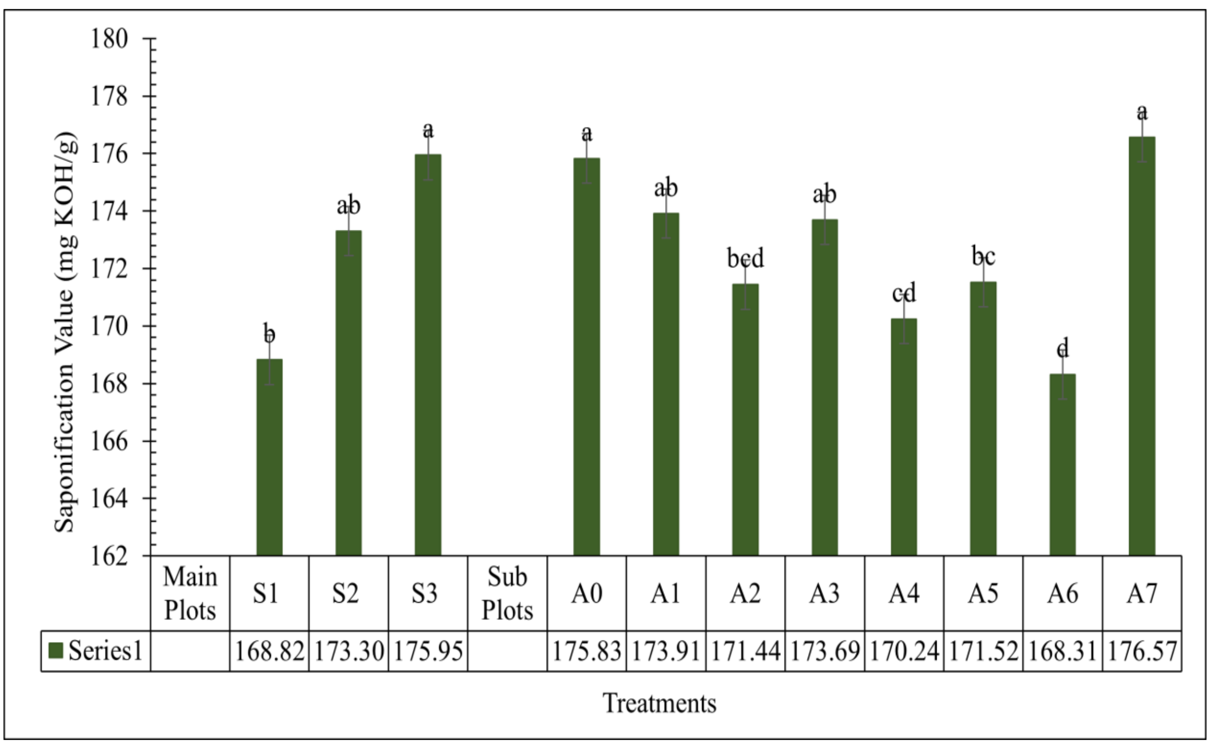


Fig. 4.4.8.2 (b): The impact of sulphur sources and agrochemical treatments on Saponification value in the year 2022-2023

4.4.9 Peroxide Value (meq/kg): The research demonstrated notable discrepancies in peroxide value across several treatments, highlighting the influence of sulphur sources and agrochemicals on the quality of Gobhi Sarson (Brassica napus L.) oil shown in Table 4.4.9.1, Figure 4.4.9.1(a),4.4.9.2(b). A diminished peroxide number is preferable for superior oil quality, as it indicates decreased oxidative degradation. A lower peroxide amount is preferable as it signifies enhanced oxidative stability and freshness of the oil, important for shelf life and safe human ingestion. The peroxide value of Gobhi Sarson oil was markedly affected by both sulphur sources and agrochemical treatments throughout the years 2021–22 and 2022–23. The lowest peroxide value among sulphur sources was observed in Gypsum (S1) at 4.17 and 4.19 meq/kg, followed by Bentonite Sulphur (S2) at 5.20 and 5.28 meq/kg. The highest value was recorded for Elemental Sulphur (S3) at 5.64 and 5.70 meq/kg, indicating a 35.2% and 36.0% increase, respectively, compared to Gypsum. The lowest peroxide value for agrochemical treatments was seen in A6 (Hydrogel + Salicylic acid during flowering and pod development) at 4.22 and 4.33 meq/kg, followed closely by A4 at 4.56 and 4.60, and A5 at 4.61 and 4.66. The highest peroxide values were recorded in A1 (Hydrogel alone) and A7 (Restricted irrigation) at 5.61 & 5.72 and 5.68 & 5.76 meq/kg, respectively. The peroxide value for A6 was 24.8%, which is 24.8% lower than that of A7 in the corresponding years. Thus, the integration of Gypsum as a sulphur source and A6 agrochemical treatment shows optimal efficacy in preserving oil quality by reducing peroxide generation, signifying enhanced oxidative stability and extended shelf life.

The interaction between sulphur sources and agrochemical applications significantly affected the peroxide value of Gobhi Sarson (*Brassica napus* L.) oil, a crucial determinant of oil quality and oxidative stability. During the 2021–22 period, the lowest peroxide value was seen in S1A6 (Gypsum + Hydrogel at 2.5 kg/ha + Salicylic acid at 150 ppm) at 3.53 meq/kg, followed by S1A4 (3.82) and S1A5 (3.85), indicating improved oil stability under these treatments. A comparable pattern was observed in 2022–23, with S1A6 displaying the lowest value of 3.59, succeeded by S1A4 at 3.82 and S1A5 at 3.87. The results demonstrate that the use of hydrogel and salicylic acid in conjunction with gypsum under controlled irrigation mitigates oxidative degradation of oil. The highest peroxide value was observed in S3A7 (Elemental sulphur + restricted irrigation) at 6.44 meq/kg in

2021–22 and 6.49 meq/kg in 2022–23, followed by S3A1 (6.38 and 6.43) and S3A3 (6.13 and 6.21), all under elemental sulphur with restricted irrigation, signifying a significant deterioration in oil quality under stress. The decrease in peroxide value under S1A6 relative to S3A7 was 45.2% in 2021–22 and 44.7% in 2022–23, indicating enhanced oxidative stability attained with the combined use of gypsum, hydrogel, and salicylic acid. Consequently, S1A6 proved to be the most efficacious treatment in reducing peroxide value, thereby prolonging oil shelf life and preserving quality over both years.

The use of treatments including gypsum, hydrogel, and salicylic acid (SA) considerably affects the peroxide values in Gobhi Sarson (*Brassica napus* L.) oil via regulating plant metabolic processes and improving stress responses. Gypsum, a source of calcium sulphate, supplies easily available sulphate ions crucial for the synthesis of sulphur-containing amino acids such as cysteine and methionine. These amino acids are essential for the synthesis of antioxidant molecules like glutathione, which alleviate oxidative stress by neutralizing reactive oxygen species (ROS), thereby diminishing lipid peroxidation and lowering peroxide values in the oil. Research has shown that sulphur assimilation bolsters the plant's antioxidant defense mechanism, leading to enhanced oil quality. (Mukwevho et al., 2014).

Hydrogels, recognized for their superabsorbent characteristics, enhance soil moisture retention, thereby providing a reliable water supply to plants. This continuous hydration mitigates drought-induced oxidative stress, a recognized contributor to heightened lipid peroxidation. By sustaining adequate hydration levels, hydrogels enhance cell membrane integrity and inhibit the buildup of reactive oxygen species, hence reducing peroxide values in the oil. Studies demonstrate that the use of hydrogel under drought conditions improves soil moisture levels, resulting in enhanced plant development and less oxidative damage (Teng et al., 2024). Salicylic acid, a phytohormone, is crucial for initiating the plant's defense responses to environmental stressors. The external application of salicylic acid (SA) has been demonstrated to enhance the activity of antioxidant enzymes, including superoxide dismutase (SOD), catalase (CAT), and ascorbate peroxidase (APX). These enzymes are essential for scavenging reactive oxygen species (ROS), hence diminishing lipid peroxidation and lowering peroxide values in the oil. Research indicates that SA treatments augment the activity of antioxidant enzymes, hence strengthening the plant's resistance to oxidative stress (Liu et al., 2022b). The concurrent use of hydrogel and salicylic acid has a synergistic impact, combining the advantages of increased soil moisture retention and improved antioxidant protection. Hydrogels sustain uniform soil moisture, alleviating drought-related stress, whilst SA triggers internal plant defense systems against oxidative harm. This combination efficiently diminishes lipid peroxidation, leading to decreased peroxide levels in the oil. Research on Indian mustard under limited irrigation conditions revealed that the synergistic use of hydrogel and salicylic acid markedly enhanced yield and oil quality by alleviating oxidative stress (Meena et al., 2020a).

The strategic use of gypsum, hydrogel, and salicylic acid improves oil quality in Gobhi Sarson by lowering peroxide levels. These treatments operate via processes that enhance sulphur feeding, preserve soil moisture, and strengthen the plant's antioxidant defense system, collectively reducing lipid peroxidation and improving oil stability.

Table 4.4.9.1: The impact of treatments on the Peroxide value (meq/kg) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	Peroxide value (meq/kg) (2021- 22)	Peroxide value (meq/kg) (2022-23)
Sulphur sources		
S1: Gypsum	4.17^{c}	4.19^{c}
S2: Bentonite Sulphur	5.20^{b}	5.28^{b}
S3: Elemental Sulphur	5.64^{a}	5.70^{a}
CV (Sulphur Sources)	3.2	5.5
CD (Sulphur Sources)	0.13	0.22
Agrochemical		
A0: Control (Irrigation as per requirement)	4.75^{d}	4.79^{d}
A1: Hydrogel (2.5 kg/ha) as basal application	5.61^{a}	5.68^{a}
A2: Salicylic acid (150 ppm) foliar spray at 50% flowering stage	5.10^{c}	5.14^{c}
A3: Salicylic acid (150 ppm) foliar spray at stage of 50% pod formation	5.45^{b}	5.51^{b}
A4: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% flowering stage	4.56^{e}	4.60^{e}
A5: Hydrogel (2.5 kg/ha) as basal application + salicylic acid (150 ppm) foliar spray at 50% pod formation stage	4.61^{de}	4.66^{de}
A6: Basal application of 2.5 kg/ha hydrogel along with foliar spray of 150 ppm SA during the stages of 50% flowering and 50% pod formation	4.22^{f}	4.33^{f}
A7: Control (Restricted irrigation)	5.72^{a}	5.76^{a}
CD (Agrochemical)	0.16	0.17
CV (Sulphur Sources and agrochemical)	3.27	3.51

Table 4.4.9.2: The interaction impact of treatments on Peroxide value (meq/kg) of rapeseed during the *rabi* season of 2021-2022 & 2022-23

Treatments	Peroxide value (2021-22)	Peroxide value (2022-23)
S1A0	3.98±0.00	3.98±0.00
S1A1	4.57±0.05	4.68±0.05
S1A2	4.27±0.00	4.27±0.00
S1A3	4.56±0.00	4.57±0.00
S1A4	3.82±0.01	3.82±0.01
S1A5	3.85±0.00	3.87±0.00
S1A6	3.53±0.00	3.59±0.00
S1A7	4.79±0.00	4.78±0.00
S2A0	4.93±0.00	5.00±0.00
S2A1	5.87±0.00	5.94±0.04
S2A2	5.29±0.04	5.36±0.00
S2A3	5.66±0.00	5.75±0.00
S2A4	4.73±0.00	4.80±0.00
S2A5	4.78±0.00	4.86±0.00
S2A6	4.38±0.00	4.52±0.00
S2A7	5.93±0.01	6.01±0.01
S3A0	5.35±0.00	5.40±0.00
S3A1	6.38±0.05	6.43±0.39
S3A2	5.74±0.80	5.79±0.80
S3A3	6.13±0.01	6.21±0.01
S3A4	5.13±0.01	5.18±0.01
S3A5	5.19±0.01	5.25±0.01
S3A6	4.75±0.00	4.88±0.00
S3A7	6.44±0.00	6.49±0.30
CV	3.27	3.51
CD	0.28	0.35

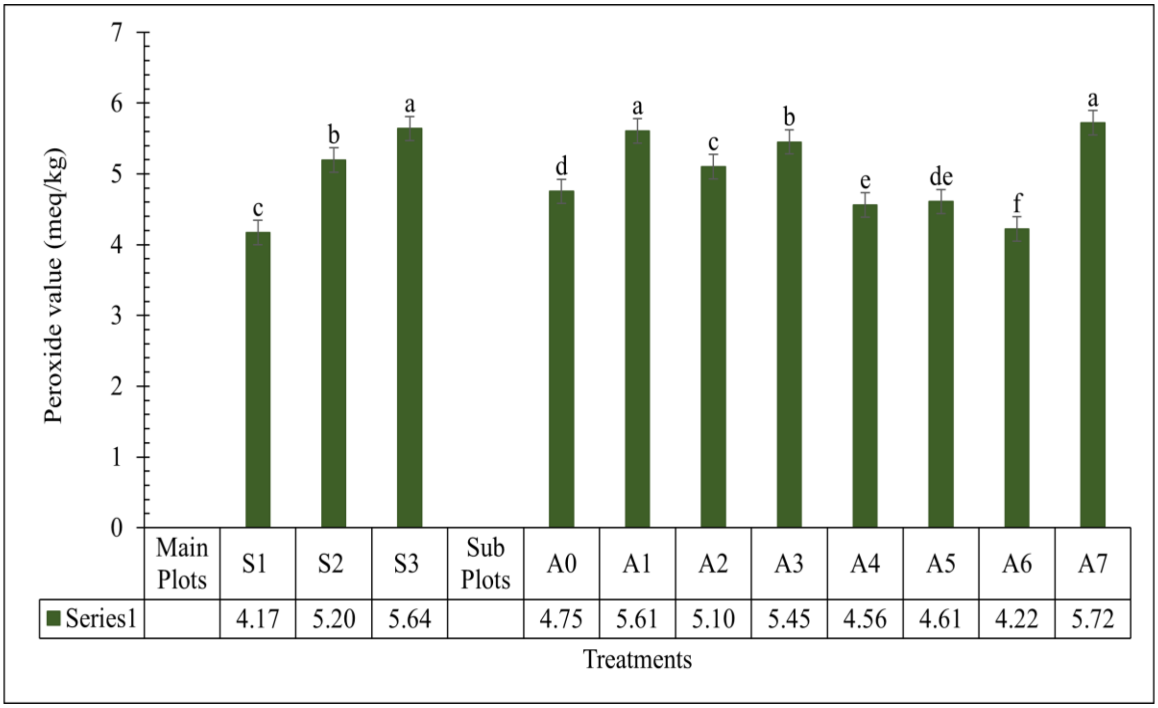


Fig. 4 .4.9.1 (a) The impact of sulphur sources and agrochemical treatments on Peroxide value (meq/kg) in the year 2021-2022

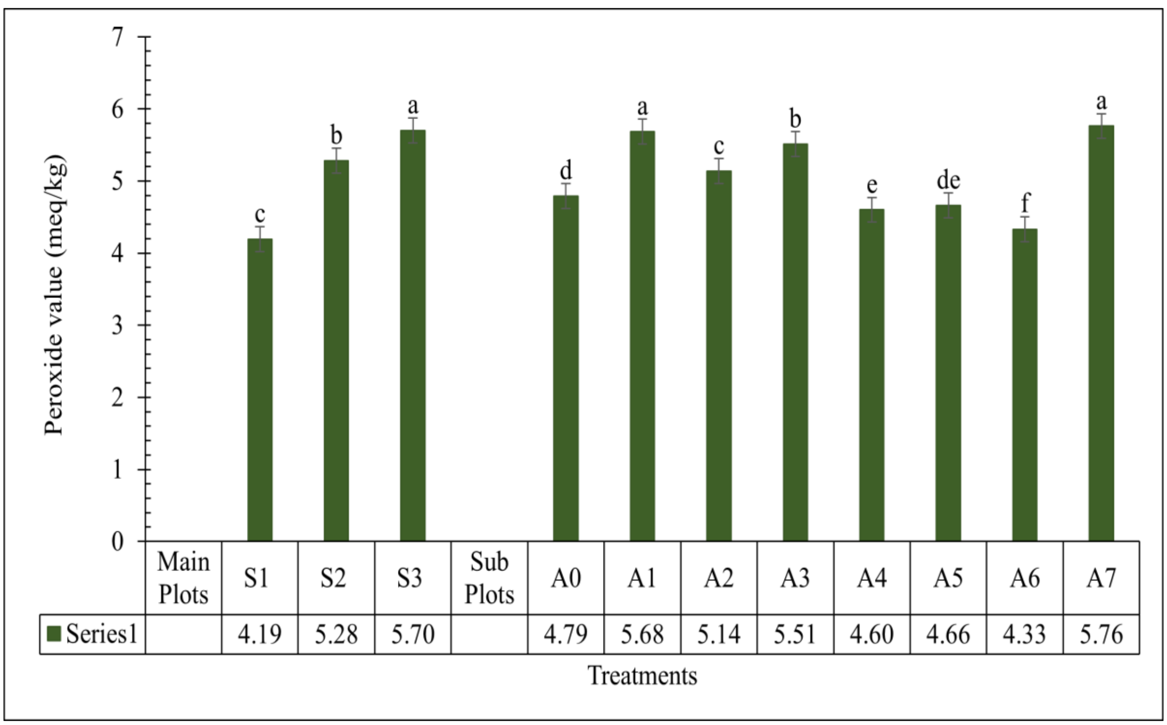


Fig. 4 .4.9.2 (b) The impact of sulphur sources and agrochemical treatments on Peroxide value (meq/kg) in the year 2021-2022

4.5 Economic Analysis

4.5.1 Cost of Cultivation (Rs/ha)

The cost of cultivation represents the total expenditure incurred in growing Gobhi Sarson under different treatment combinations during the *rabi* seasons of 2021–22 and 2022–23. The total cost varies across treatments due to differences in inputs such as fertilizers, superabsorbent polymers, and salicylic acid application. In the first year (2021–22), the cost of cultivation ranged from Rs. 28,600/ha (S1A7) to Rs. 34,100/ha (S3A6), while in the second year (2022–23), it ranged from Rs. 29,000/ha (S1A7) to Rs. 38,000/ha (S3A6). The variations in cost reflect the influence of different combinations of sulphur sources, hydrogel, and salicylic acid, which impact the overall input requirement.

4.5.2 Gross Return

Gross return is the total revenue generated from the yield produced under each treatment. It is calculated based on the minimum support price (MSP) of Gobhi Sarson for the respective years (Rs. 4,650/q in 2021–22 and Rs. 5,050/q in 2022–23). The highest gross return in 2021–22 was Rs. 107,787/ha (S1A6), while in 2022–23, it was Rs. 119,584/ha (S1A6). On the other hand, the lowest gross return was recorded in treatment S3A7, with Rs. 52,452/ha in 2021–22 and Rs. 57,772/ha in 2022–23. These values indicate that treatments incorporating appropriate inputs, particularly hydrogel and salicylic acid, resulted in higher yields, thereby increasing gross returns.

4.5.3 Net Returns

Net return is derived by subtracting the cost of cultivation from the gross return. A higher net return indicates better profitability from a given treatment. In 2021–22, the highest net return was observed in treatment S1A6 (Rs. 107,764/ha), while the lowest was in S3A7 (Rs. 52,441/ha). Similarly, in 2022–23, the highest net return was recorded in S1A6 (Rs. 119,560/ha), whereas S3A7 recorded the lowest at Rs. 57,761/ha. The trend suggests that treatments involving hydrogel and salicylic acid significantly improved crop performance, enhancing net profitability. Conversely, treatments with lower inputs resulted in reduced returns due to lower yield output.

4.5.4 Benefit-Cost (B:C) Ratio

The B:C ratio is an essential indicator of economic efficiency, representing the return per unit of investment. A higher B:C ratio signifies better profitability. Across both years, the highest B:C ratio was recorded for treatment S1A0 and S1A6 at 3.3 in 2021–22 and 3.4 in 2022–23, indicating these treatments provided the highest economic benefit per rupee spent. In contrast, the minimum B:C ratio was found in treatment S3A7 at 1.8 in 2021–22 and 1.9 in 2022–23, suggesting that the input investment in this treatment did not generate a sufficiently high return. The increase in MSP in 2022–23 further improved the B:C ratio across all treatments compared to the previous year.

Conclusion

The economic analysis highlights that treatments incorporating superabsorbent polymer (hydrogel) and salicylic acid, particularly S1A6, resulted in the best economic returns due to enhanced yield potential. Treatments with minimal inputs, such as S3A7, were less profitable. The findings suggest that optimizing inputs—especially hydrogel and salicylic acid—along with appropriate sulphur sources, can significantly improve yield, profitability, and economic viability in Gobhi Sarson cultivation under controlled irrigation.

Table 4.5.1.1 Interaction effect of sulphur and agrochemicals on rapeseed economics (*Rabi* 2021–22 & 2022–23)

	(2021-2022)				(2022-2023)			
Treatments	**Total Cost (Rs/ha)**	**Gross Return**	**Net Returns**	**B: C Ratio**	**Total Cost (Rs/ha)**	**Gross Return**	**Net Returns**	**B: C Ratio**
S1A0	30800	102021	101999	3.3	32,950	112733	112711	3.4
S1A1	32450	88862	88842	2.7	32,750	98475	98456	3.0
S1A2	29975	82615	82597	2.8	30,400	91792	91774	3.0
S1A3	29975	86087	86068	2.9	30,400	94553	94534	3.1
S1A4	32725	97976	97954	3.0	33,250	107919	107897	3.2
S1A5	32725	101324	101302	3.1	33,250	110949	110927	3.3
S1A6	33000	107787	107764	3.3	34,800	119584	119560	3.4
S1A7	28600	74214	74198	2.6	29,000	82618	82602	2.8
S2A0	31350	91311	91291	2.9	34,950	104754	104733	3.0
S2A1	33000	80259	80242	2.4	34,750	88123	88105	2.5
S2A2	30525	74586	74570	2.4	30,950	82164	82147	2.7
S2A3	30525	77733	77716	2.5	30,950	84588	84571	2.7
S2A4	33275	88443	88424	2.7	35,050	96556	96537	2.8
S2A5	33275	91466	91446	2.7	35,050	99283	99263	2.8
S2A6	33550	97340	97319	2.9	36,250	107026	107005	3.0
S2A7	29150	67007	66992	2.3	29,500	73949	73934	2.5
S3A0	31900	73036	73020	2.3	32,500	79268	79252	2.4
S3A1	33550	62729	62715	1.9	36,250	68882	68868	1.9
S3A2	31075	58311	58298	1.9	31,750	64186	64173	2.0
S3A3	31075	60776	60762	2.0	31,750	66105	66091	2.1
S3A4	33825	69146	69131	2.0	36,750	75498	75483	2.1
S3A5	33825	71517	71502	2.1	36,750	77619	77603	2.1
S3A6	34100	76121	76104	2.2	38,000	83628	83611	2.2
S3A7	29700	52452	52441	1.8	30,250	57772	57761	1.9

SUMMARY AND CONCLUSION

Agriculture remains the cornerstone of India's economy, sustaining a vast population through food production and rural employment. Water scarcity, however, has become a significant obstacle to agricultural output, especially in Punjab, which, in spite of its reputation as the "Granary of India," suffers from severe groundwater depletion as a result of intensive irrigation methods. Rapeseed, particularly Gobhi Sarson (*Brassica napus* L.), is a highly prized oil crop among *rabi* oilseeds, but it is also susceptible to nutritional imbalances and deficiencies in soil moisture. Therefore, sustaining this crop's production, profitability, and sustainability depends on enhancing water and nutrient management through integrated agronomic interventions.

Using a split-plot design, the current study was conducted during the 2021–22 and 2022–23 *rabi* seasons to evaluate the combined effects of foliar salicylic acid application, a superabsorbent polymer (hydrogel), and various sulphur sources on the growth, yield, quality, and economics of Gobhi Sarson under controlled irrigation. The results clearly revealed that the integrated treatment of gypsum (S_1) as the sulphur source, along with hydrogel and salicylic acid applied at 50% flowering and pod development phases (A_6), consistently outperformed all other treatments. Indicating robust vegetative development and excellent source-sink connections, this combination significantly increased plant height, dry matter accumulation, and leaf area index. The highest values of seed yield, oil yield, and harvest index were obtained under this treatment, proving that S_1A_6 is the most efficient combination for improving both productivity and quality. Increased nutrient uptake, especially nitrogen, phosphorus, and potassium, which are crucial for photosynthesis, protein synthesis, and enzymatic activity, was facilitated by improved physiological efficiency from salicylic acid and enhanced soil moisture retention through hydrogel.

Because of its instant availability and quick nutrient release, gypsum outperformed elemental sulphur and bentonite sulphur. In contrast, elemental sulphur had the least efficiency because of its slow microbial decomposition, while bentonite sulphur had delayed effects. By adding hydrogel, the adverse impacts of water stress were lessened, nutrient leaching losses were controlled, and ideal soil moisture conditions were maintained. By regulating physiological and biochemical processes, such as the actions of antioxidant enzymes and hormonal balance, salicylic acid further helped plants withstand drought and other abiotic stresses. The synergistic potential of integrated soil–plant–water management strategies was demonstrated by the combined usage of these components, which improved seed size uniformity, oil content, and overall quality in addition to growth and production.

Economic study further demonstrated the integrated S_1A_6 treatment's distinct advantage, as it produced the highest benefit-cost (B: C) ratio and net returns of any treatment. The yield improvement and better oil recovery that followed provided higher profitability even when inputs like hydrogel and salicylic acid raised the initial cost. Due to inadequate nutrient availability and subpar growth performance, elemental sulphur treatments with limited irrigation (S_3A_7) yielded the lowest economic returns. Overall, the results demonstrated that effective nutrient management and moisture conservation techniques increase output and profitability, making such integrated approaches financially viable in water-limited environments.

Future studies should concentrate on finding specific ways to get around these limitations. Trials conducted at multiple locations and during multiple seasons are required to confirm treatment consistency in a variety of settings. To comprehend the lingering effects on soil health, moisture dynamics, and nutrient cycling, long-term research should be done. These solutions' economic viability should also be assessed, taking into consideration labor needs, input prices, and farmer attitudes. The processes by which salicylic acid and hydrogel enhance stress tolerance and reproductive effectiveness can be clarified with the use of physiological and molecular research. Furthermore, assessing their impact on later crops in the rotation would offer a more thorough comprehension of their role in the sustainability of the system as a whole.

By enhancing soil moisture retention, physiological efficiency, and nutrient assimilation, the combination application of hydrogel, salicylic acid, and gypsum significantly improved Gobhi Sarson growth, yield, and quality attributes, according to the study's findings. With appreciable improvements in the absorption of nitrogen, phosphate, and potassium, the combined therapy markedly improved nutrient uptake, and nutrient-use efficiency. Additionally, the economic analysis verified that the gypsum-based integrated treatment (S_1A_6)

produced the highest net returns and benefit-cost ratio, proving that gypsum combined with hydrogel and salicylic acid is agronomically and financially feasible. In particular, SDG 2 (Zero Hunger) by increasing crop productivity and nutritional quality, SDG 6 (Clean Water and Sanitation) by conserving water and moisture, and SDG 12 (Responsible Consumption and Production) by encouraging resource-efficient and sustainable agricultural practices are all closely aligned with the study's findings. Furthermore, the findings indirectly support SDGs 13 (Climate Action) and 15 (Life on Land) by increasing farmers' profitability and resilience to water stress. This is achieved through sustainable management of soil and water resources, which guarantees long-term agricultural sustainability and food security.

Final Conclusion:

The study found that by enhancing soil moisture retention, physiological efficiency, and nutrient assimilation, the combination application of gypsum, hydrogel, and salicylic acid (S_1A_6) greatly increased Gobhi Sarson growth, yield, and quality. In addition to achieving the highest net returns and benefit-cost ratio, this integrated treatment enhanced the uptake of nitrogen, phosphorus, and potassium, making it both agronomically and financially feasible. The results support SDG 12 (Responsible Consumption and Production) by encouraging sustainable practices, SDG 6 (Clean Water and Sanitation) by improving water consumption, and SDG 2 (Zero Hunger) by boosting production. For optimal results, farmers are advised to use gypsum as a source of sulphur in conjunction with hydrogel to preserve moisture and salicylic acid sprays throughout the blooming and pod stages. This method improves oil quality, profitability, and stress tolerance. To support suggestions for widespread adoption, future research should confirm these findings in various locales and at various seasons.

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