

EFFECT OF SEED PRIMING, HUMIC ACID AND SULPHUR APPLICATION ON GROWTH, YIELD AND OIL QUALITY OF LINSEED UNDER DIFFERENT IRRIGATION INTERVALS

Thesis Submitted for the Award of the Degree of

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Agronomy

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2026



DECLARATION

I, hereby declared that the presented work in the thesis entitled “**Effect of seed priming, humic acid and sulphur application on growth, yield and oil quality of linseed under different irrigation intervals**” in fulfilment of degree of **Doctor of Philosophy (Ph. D.)** is outcome of research work carried out by me under the supervision of **Dr. Anaytullah Siddique**, working as an 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 acknowledgements have been made whenever work described here has been based on findings of other investigators. This work has not been submitted in part or 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 seed priming, humic acid and sulphur application on growth, yield and oil quality of linseed under different irrigation intervals**” submitted in fulfillment of the requirement for the reward of degree of **Doctor of Philosophy (Ph. D.)** in the **Department of Agronomy, School of Agriculture**, is a research work carried out by **Gumpi Kabak, Registration no.: 12116721**, 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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CERTIFICATE II

This is to certify that thesis entitled "**Effect of seed priming, humic acid and sulphur application on growth, yield and oil quality of linseed under different irrigation intervals**" submitted by **Gumpi Kabak (Registration number: 12116721)** to lovely Professional University, Phagwara, Punjab in fulfilment of the award of degree **Doctor of Philosophy** in **Agronomy** is a bonafide research work which has been approved by the committee after an oral evaluation in the presence of an external examiner, no part of the thesis has been submitted for any other degree or diploma.



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Abbreviations

%	Percent
µm	Micrometer
HDPE	High-density polyethylene
LDPE	Low-density polyethylene
BOPP	Bi-axially oriented polypropylene
cm	Centimeter
PLW	Physiological loss of weight
TSS	Total soluble solids
mg	Milligram
mL	Milliliter
nm	Nanometer
/	Per
°	Degree
No.	Number
ppm	Parts per million
HA	Humic acid
KNO ₃	Potassium nitrate
SA	Salicylic acid
DAS	Days After Sowing
ppm	Parts per million
HCL	Hydrochloric acid
RDF	Recommended dose of fertilizer
N	Nitrogen
P	Phosphorus
K	Potassium
MY	Marketing year
COC	Cost of cultivation
MT	Metric ton
Kg/ha	Kilogram per hectare
Approx.	Approximately
Rs.	Rupees

SA	Salicylic acid
SDS	Sodium dodecyl sulphate
SEM	Scanning electronic microscope
sp.	Species
SPAD	Soil plant analysis development
T	Treatment
TEM	Transmission electronic microscope
V	Volume
W	Weight
WP	Water potential

Abstract

The present study entitled “*Effect of Seed Priming, Humic Acid and Sulphur Application on Growth, Yield and Oil Quality of Linseed (*Linum usitatissimum*) under different irrigation intervals*” investigated the effect of priming and application of humic acid and sulphur on the performance of linseed. Two consecutive field experiments were conducted at the Research Farm of Agronomy, School of Agriculture at Lovely Professional University in Phagwara, Punjab, India, during the *Rabi* seasons in 2022-2023 and 2023-24. The study focused on identifying the optimal nutrient management strategies in varying irrigation regimes. The experiment was laid out in a split-plot design (SPD) with 21 treatments and 3 replications. The irrigation regimes applied at critical stages included no post-sowing irrigation (I₀), one post-sowing irrigation at the vegetative stage (I₁), two irrigations at the vegetative and flowering stages (I₂), meanwhile nutrient management treatments consisted of control (T₀), seed priming with KNO₃ (T₁), sulphur application (T₂), humic acid (T₃), combined application of KNO₃ and sulphur (T₄), combined application of KNO₃ and humic acid (T₅), combined application of sulphur and humic acid (T₆). Two post-sowing irrigation (I₂) and combined KNO₃ and humic acid application (T₅), *i.e.*, I₂T₅, had a significant impact on growth parameters such as plant height, fresh and dry biomass, leaf number and area, and phenological traits like days to emergence, branching, 50% flowering, and maturity. Growth analysis metrics, such as leaf area index (LAI). Crop growth rate (CGR), relative growth rate (RGR), and net assimilation rate (NAR) were computed to quantify plant performance. The lowest LAI values were recorded in the I₀ treatment, with measurements of 0.12 at 30 days after sowing (DAS), 0.14 at 60 DAS, and 0.14 at 90 DAS during the 2022-23 season.

A similar trend was observed in the following year. Similarly, the moisture content at harvest ranged from 76.00 (I₀) to 83.29 mm (I₂) in 2022-23 and 72.43 mm (I₀) to 84.56 mm (I₂). The highest CGR (0.020 g m⁻² day⁻¹) was observed in the I₂T₅ combination, and the lowest (0.015 g m⁻¹ day⁻¹) in I₀T₀. Physiological measurements, such as relative water content (RWC), membrane injury index (MII), and membrane stability index (MSI), and biochemical indicators like chlorophyll content and proline, were recorded to evaluate stress responses. The I₂T₅ treatment achieved the highest MSI at 58.23%, while the I₀T₀ treatment recorded the lowest MSI at 49.42% at 90 days after sowing in 2022-23. The treatment with I₂ consistently recorded the highest chlorophyll levels, with values of 3.10 and 24.20 mg g⁻¹ fresh weight (FW) at 90 DAS, in 2023-24. The lowest chlorophyll values were recorded in the control I₀ and T₀, with values of 1.15 mg g⁻¹ FW in 2022-23 and 30.60 mg g⁻¹ FW in 2023-24.

Yield and yield attributes, including number of primary and secondary branches, no of capsule seed yield, biological yield, and test weight, were measured at harvest. The interaction between irrigation regimes and nutrient management positively influenced linseed yield characteristics, with the highest values for capsule number, test weight, seed yield, and oil yield recorded under the I2 treatment, with average number of capsules of 162.46 (2022-23) and 142 (2023-24) plant⁻¹, test weight of 7.31 g, seed yield of kg ha⁻¹, and oil yield at 5.19%. In contrast, the no irrigation I0T0 treatments showed the lowest value across these parameters. Soil moisture dynamics were monitored before and after harvest with irrigation at critical stages, resulting in the best yield of linseed across both years. This integrated approach is recommended for optimizing linseed production, enhancing oil quality, and improving resource use efficiency. The findings provide valuable insights into sustainable oilseed production, particularly in water-scarce regions, by optimizing nutrient and water management strategies for improved productivity and sustainability.

Keywords: Humic acid; Seed priming KNO₃; Sulphur; linseed; Irrigation

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INTRODUCTION

Oilseeds are energy-dense foods rich in oil, minerals, fiber, vitamins, and fatty acids. They are crucial not only for human nutrition but also for industrial applications, including the production of soaps, pharmaceuticals, and textiles. By-products like oilcakes and meals are valuable sources of animal feed and fertilizers. In India, oilseeds remain the second most important group of crops after cereals. According to recent estimates, oilseeds are cultivated over about 30 million hectares, with an average productivity of around 1,400 kg ha⁻¹, resulting in a total production of approximately 42–43 million tonnes during 2023–24. The growth in oilseed production has been remarkable over the long term, increasing from about 5.26 million metric tonnes in the marketing year (MY) 1949–50 to over 42 million metric tonnes in recent years, driven by expansion in area, improved varieties, and better crop management practices (Directorate of Economics and Statistics, 2024; FAOSTAT, 2023). Moreover, plant fibers have a significantly lower environmental footprint compared to synthetic options, fostering sustainability through their biodegradability and minimal resource consumption. India continues to be one of the major players in both oilseed and fiber production globally. It ranks as the fourth-largest producer of oilseeds in the world, accounting for about 20.8% of global oilseed cultivation area and approximately 10% of global oilseed production according to industry data published in 2025. According to the Third Advance Estimates of the Department of Agriculture and Farmers Welfare, the total oilseed area under cultivation increased to about 30.27 million hectares in 2024–25, up from earlier years, with total oilseed production reaching around 426.1 lakh tones (42.6 million t) a significant rise from about 275 lakh tones a decade ago. India also continues to play a significant role in global vegetable oil production, ranking among the top four countries alongside the USA, China, and Brazil in the edible oil market. The country's diverse agro-ecological conditions support the cultivation of the nine major annual oilseed crops i.e. groundnut, rapeseed-mustard, soybean, sunflower, sesame, safflower, niger seed, castor, and linseed which collectively contribute substantially to livelihoods, industrial raw materials, and edible oil availability domestically. Just behind Canada, India is the second-largest producer of linseed by area, accounting for 21.21% of all cultivated land in the world. India is the fourth-largest producer in the world, accounting for 8.20% of global linseed production, behind the United States, China, and Canada (10.89, 18.68, 40.51% respectively). Linseed is one of the most widely grown oilseeds, which is being cultivated for various purposes like nutrition, fiber, and various other industries. India possesses 1.7 lakh ha and produces approximately 1 lakh tones of

agricultural output, producing 574 kg ha⁻¹, out of 30.68 lakh tones produced in 32.23 lakh ha⁻¹ area worldwide (Dash *et al.*, 2017; Ministry of Agriculture, Government of India, 2020; Devi, 2023). It is a key oilseed crop, economically and nutritionally significant, boasting high protein, low carbohydrate content, and dietary fiber, making it suitable for weight loss diets. Its seed contains about 35- 47% oil and is rich in dietary fiber, protein, ash, carbohydrates, and fats (28, 21, 4%, 6%, and 40% respectively) while major fatty acids present are as follows: linolenic (51.9- 55.2%), linoleic (14.2-22%), oleic (18.2-22%), stearic (3.4- 4.6%) palmitic acid (about 7%). It is also rich in micronutrients like Cu, Zn, and Mn (Yang, 2016). It is also rich in α -linolenic acid (35-70%), an essential omega-3 fatty acid known for its cardiovascular benefits, including the reduction of blood cholesterol levels. It is also used for its fibers, which are characterized by strength and durability, and can be used to manufacture low-cost roofing tiles from convertible polymers. For enhanced weather resistance and structural integrity, high-quality fibers should be extracted from the linseed stems (Galinousky *et al.*, 2020). Compared to rapeseed-mustard cake, linseed oil cake is a healthier feed additive for dairy cows and chickens. This oil cake contains approximately 20-25% protein and 40-45% fatty acids. Furthermore, it can serve as an organic fertilizer due to its rich nutrient content, including significant levels of nitrogen (N), phosphorus (P₂O₅), and potassium (K₂O₅) [5, 1.4%, and 1.8%, respectively], in addition to its oil content, which ranges from 33% to 47% (Halle and Schöne2013; Banerjee and Ghosh, 2016; Rakita *et al.*, 2023).

Despite showing considerable drought and salt tolerance up to 0.2% salinity, the crop is sensitive to moisture levels and, as per its photoperiod in concerned, it needs 14 hours of daylight to flower. The plant needs a relative water content of 60 to 80% and temperatures between 17 and 22°C. Nitrogen fertilization significantly enhances protein content in leaves by enhancing nitrogen uptake. Efficient use of N promotes grain yield and development stages in seed (Wang *et al.*, 2017 and Xie *et al.*, 2015). Proper nutrient management is essential for maximizing productivity and minimizing environmental impact. Excess nitrogen (N) supply beyond plant demand, i.e., 3.75 Kg N required for 100 Kg linseed seed, leads to inefficiency and environmental contamination (Xie *et al.*, 2015). To ensure sustainable agriculture, reducing N application during early growth stages, while keeping total N levels constant, is critical. Research shows that topdressing during the flowering stage meets peak N requirements, promoting nitrogen and assimilating accumulation (Guo *et al.*, 2020). Inadequate nutrient management has resulted in widespread sulphur deficiencies in soil, which were previously infrequent. These deficiencies can significantly impair the growth and yield of oilseed crops, leading to reductions of 10-30% due to insufficient nourishment (Basumatary *et al.*, 2019). Its short life cycle and adaptability to diverse agro-climatic

conditions and soil types, linseed can achieve optimal productivity through the provision of balanced sulphur nutrition (Kushwaha *et al.*, 2019). Among these, water availability, soil fertility, and the application of growth-promoting substances are particularly critical. The crop is sensitive to water stress due to its short stature and shallow tap root system, which can lead to reduced germination rates, poor plant establishment, and lower yields. Variable rainfall can significantly impact crop performance (Anastasiu *et al.*, 2016; Fila *et al.*, 2018; and Mirzaie *et al.*, 2020). Various stress mitigation strategies are involved in reducing stress and increasing productivity. Developing and promoting efficient water management practices can improve crop performance in water-scarce regions. Improving soil health through the application of balanced fertilizers and organic amendments is essential. Soil testing and targeted nutrient management practices can help address deficiencies and enhance soil health. Holistic Nutrient Management strategies, including the use of green manures and biological fertilizers, can also support sustainable soil fertility (Singh *et al.*, 2020; Meena and Reddy, 2021). Seed priming is a cost-effective hydration technique that effectively stimulates seed germination by activating pre-germinative metabolic processes, synchronizes germination, enhances seedling emergence, and maintains optimal plant populations across fields through controlled hydration and drying, thus reducing the use of fertilizers and increasing crop yield (Dawood *et al.*, 2018). Among various agents, potassium nitrate (KNO_3) stands out for its ability to support growth from germination to grain production, especially under water-limited conditions. Potassium is vital for photosynthesis and the transport of nutrients, and its application during moisture stress significantly improves water uptake, root development, and overall crop resilience (Mostofa *et al.*, 2022). Humic acid is a group of complex molecules that helps to hold moisture and manage nutrient release, retaining ionized nutrients and preventing leaching (Bhatt and Singh, 2022). To boost oil crop yields, both the cultivation of high-yielding varieties and the adoption of appropriate agricultural practices are important, alongside the application of the recommended sulphur doses (Rakesh and Banik, 2016, and Shakya *et al.*, 2023). Among the nutrients, sulphur has a significant effect on flaxseed, influencing both its quality and quantity by promoting fruit and seed formation (Zenda *et al.*, 2021).

Priming seeds with humic acid and applying sulphur are agronomic practices that will positively influence plant growth, yield and quality under water-stressed conditions. Humic acid (a component of the organic matter created from the decay of plants and animals), will improve soil structure, make nutrients more available to plants and allow for greater root development, hence improving the overall growth of crops. Sulphur is a plant macronutrient as it is required for protein synthesis, functioning of enzymes and the production of oils; thus, adequate supplies of sulphur can have a significant impact on crop yield and quality. Water availability is one of the

most crucial elements determining the potential for successful crop growth and the production of high-volume crops. Flood irrigation, which is the most widespread method of irrigating crops throughout the world, often results in significant losses of water due to evaporation and leaching (Yin *et al.*, 2020). The adverse effects of climate change through drought and irregular rainfall have also increased the importance of using efficient water-management systems. The use of optimized irrigation programs leads to an increase in the efficiency of the utilization of water, while at the same time, there is an improvement in crop yield. The timing of irrigating oilseed flax at the specific stages of plant development (during the budding stage and during flowering) can positively impact both grain yield and irrigation efficiency (Bauer *et al.*, 2015). It has also been found that utilizing several smaller irrigations will improve soil moisture retention and improve the water-use efficiency (Yan *et al.*, 2017). Other studies have suggested that seed priming with potassium nitrate can lead to a faster rate of germination and a quicker establishment of the plant by reducing stress during establishment (Farooq *et al.*, 2019). By using organic amendments for soil improvement and utilizing proper agricultural irrigation methods simultaneously, one can achieve improved soil fertility and crop yields (Zahir *et al.*, 2020). The productivity of linseed is still low and often inconsistent, despite the growing demand for and nutritional value associated with linseeds. The goal of the research plan, "*The Effect of Seed Priming, Humic Acid Treatment, and Sulfur Application on the Growth of Linseeds, Yield, and Quality of Oil produced under Different Irrigation Regimes*" will evaluate seed growth, yield, oil quality, and financial (ROI) return through evaluations using multiple irrigation methods (2022 - 2024) at Lovely Professional University, Punjab.

The objectives of the study are as follows:

- 1- To study the efficacy of seed priming, humic acid, and sulphur application on the growth and yield of linseed.
- 2- To evaluate the effect of different irrigation intervals on the growth, yield, and oil quality of linseed.
- 3- To work out the economics of different treatments

REVIEW OF LITERATURE

Linseed, also known as flax (*Linum usitatissimum* L.), is the oldest cultivated plant, since 7000 BC. This annual herbaceous plant can grow to a height of 20 to 110 cm and features glabrous stems, alternate linear-lanceolate leaves, and globose, mostly indehiscent capsules. Plants grown for seed production are typically shorter than those cultivated for fiber. Economically and nutritionally significant, linseed is an important oilseed crop, offering high protein content, low carbohydrates, and dietary fiber, making it an excellent choice for weight loss diets. There is a need to improve the yield and oil content of the seeds of linseed, as they are a rapidly growing crop in cultivation. Linseed is cultivated primarily for its seeds, which are rich in oil and protein. To enhance yield and other desirable attributes, several agronomic practices can be employed, including optimizing soil nutrient levels, particularly phosphorus and sulphur, as well as selecting suitable genotypes and implementing effective pest management strategies. Research has shown that adequate sulphur application can significantly improve oil content and seed yield (Choudhary *et al.*, 2016). Additionally, maintaining proper irrigation and adopting crop rotation can further contribute to increased productivity and sustainability in linseed cultivation (Sharma *et al.*, 2018). These practices not only boost yields but also enhance the nutritional profile of linseed, making it a valuable crop for both economic and health-related benefits.

2.1 Morpho-phenological parameters

2.1.1. Effect of seed priming on growth

Kumar *et al.*, (2016) investigated the effect of KNO₃ seed priming in late-sown sesame varieties (*Sesamum indicum*). The results indicated that KNO₃ treatment significantly enhanced shoot and root length and increased both fresh and dry weights of seedlings. Treatment containing 15 mM of KNO₃ yielded the best results for all varieties, indicating its effectiveness at higher concentrations.

Singh *et al.*, (2018) evaluated the effects of potassium nitrate (KNO₃) on seed germination, seedling vigor, growth, and field emergence of linseed (*Linum usitatissimum* L.). The results indicated that treatment with KNO₃ significantly improved total seedling length and shoot length.

Prasad *et al.*, (2021) worked on pre-treatment of seeds of *Brassica juncea* L. with different nutrients and plant growth regulators. Results concluded that seed priming with 0.5% KNO₃ resulted in improved plant height, followed by 25 ppm GA₃ and 0.1% Mg (NO₃)₂. Seeds treated with KNO₃ reached an impressive height.

Reddy *et al.*, (2023) conducted a field experiment on seed priming in flax seed and observed that soaking seeds in 150 ppm KNO₃ solution for 5 hours showed the best results for plant height. This shows KNO₃ is effective in increasing plant height in flaxseed.

Rehman *et al.*, (2024) researched on *Sinapis alba* seeds, wherein the priming treatment NaCl, CaCl₂, and KNO₃ @ 0.5% and moringa leaf extract 1:30 ratio, along with a control of treating the seed with distilled water and without soaking, were used. Results revealed that seeds treated with KNO₃ significantly increased plant height by 4.6% as compared to those without soaking seeds and all other treatments. Results underscore the effectiveness of KNO₃ in promoting robust seedling growth by improving root, shoot length, and overall plant height.

2.1.2 Effect of seed priming on dry matter accumulation, LAI, CGR, RGR, and NAR

Hamidi *et al.*, (2013) conducted an experiment that revealed both halo primed, and hydro primed wheat seeds exhibited enhanced performance concerning leaf area and LAI. The positive effects were associated with increased levels of KNO₃ and KH₂PO₄, along with a reduction in nitrogen (N) and phosphorus (P) concentrations.

Bose *et al.*, (2016) investigated the effects of seed hardening using water and nitrate salts (Mg(NO₃)₂ and KNO₃) on LAI, CGR, RGR, and net assimilation rate (NAR). The best results were achieved with seeds hardened in Mg(NO₃)₂, followed by those hardened with KNO₃ and distilled water. The enhancement in LAI, CGR, RGR, and NAR from hardened rice seeds was attributed to the effective utilization of photosynthates directed toward developing reproductive structures. The improved CGR likely stemmed from a vigorous and energetic start, which led to increased leaf number and larger leaf area, ultimately resulting in enhanced RGR and NAR.

Kumeera *et al.*, (2018) experimented with the SHUATS field in Allahabad during the *rabi* season of 2017-2018 examined the effects of inorganic seed priming on chickpea (*Cicer arietinum* L.) growth, yield, and physiological parameters under drought conditions. The variety Pusa-362 was subjected to seven treatments: KNO₃, NaCl₂, CaCl₂, KH₂PO₄, KCl at 2% each, water soaked for 8 hours, and a control (not soaked). Results showed that seeds primed with 2% CaCl₂ achieved the highest CGR and RGR, followed by 2% KNO₃.

In a study, leaf area at all growth stages was examined by Rehman *et al.*, (2024) and found a statistically higher value in seeds treated with KNO₃ with 0.5% concentration as compared to all other treatments in *S. alba* while the minimum leaf area at all growth stages was observed in control, showing the effectiveness of KNO₃ for increasing leaf area. Similarly, it showed the highest CGR and NARs, which are statistically at par with the seeds primed with water and moringa leaf extract.

2.1.3 Effect of seed priming on Days taken for emergence, 50% flowering, and days to maturity

Khan *et al.*, (2020d) worked on the effect of KNO₃ seed priming on mustard and found that a concentration of 0.3% reduced days to emergence compared to the control set of 12 days to 9 days, indicating a 25% improvement in emergence speed.

Rana *et al.*, (2021) conducted a study evaluating the significance of KNO₃ priming with 0.1%, 0.2%, and 0.3% on linseed germination. They observed that seeds primed with 0.2% KNO₃ significantly reduced the days taken to emergence from 10 days in the control to 7 days in the treated set, representing a 30% decrease.

Prasad *et al.*, (2021) evaluated the significance of seed priming, nutrients, and growth hormone on *B. juncea* and revealed that a superior treatment was potassium nitrate with 0.5% across the treatments. Potassium nitrate with 0.5% achieved maximum field emergence. This delay in flowering compensates for the gain in vegetative growth. The number of branches of plant⁻¹ increased in the KNO₃-treated set, corresponding to an enhancement in the yield of *Brassica juncea*.

Ahmed *et al.*, (2022) evaluated different concentrations of KNO₃, ranging from 0.2% to 0.4% on linseed and reported the impact of seed priming in improving the phenological traits of linseed. The priming with KNO₃ (0.2%) enhanced seedling emergence compared to the control set. Similarly, the concentration of 0.3% advanced flowering by 8 days compared to the control. Moreover, it also reduces the maturity of the crop up to 115 days compared to the control of 123 days. Therefore, the study suggested that priming with KNO₃ not only encourages the crop establishment but also reduces the maturity of the crop.

Jabbar *et al.*, (2023) studied the impact of KNO₃ priming on sunflower seeds and found that a treatment of 0.5% KNO₃ led to emergence.

Rehman *et al.*, (2024) experimented on seed priming treatment on *S. alba* seeds and concluded that the application of potassium nitrate markedly reduced days to 50% emergence. This reduction indicates a faster establishment of seedlings, which is beneficial for early crop performance.

Rana *et al.*, (2021) examined the effects of KNO₃ priming at concentrations of 0.1% and 0.2% on linseed. The study reported that seeds primed with 0.2% KNO₃ resulted in 50% flowering occurring in 85 days, compared to 90 days in the control group.

In this connection, Reddy *et al.*, (2023) also worked with seed priming of flaxseeds and demonstrated that five hours of duration of seed priming with 155 ppm significantly reduces the days to 50% flowering and maturity period of the linseed compared to the rest of the treatments, i.e., KCl and NAA. These results confirm the impact of seed priming with nutrients and hormones on the phenology of the linseed crop.

Jabbar *et al.*, (2023) reported that sunflower seeds treated with 0.5% KNO₃ flowered in 65 days, compared to 72 days for the control group, The time to maturity also improved, with treated plants maturing in 95 days instead of 102 days.

In their study of flaxseed, Reddy *et al.*, (2023) concluded that seed priming with 150 ppm of KNO₃ encourages branching plant⁻¹ and seed yield of linseed. the hardening treatment with KNO₃ is equally important to increase branches in plant⁻¹. These findings highlight the role of seed priming with KNO₃ in improving branching, capsule formation, and yield efficiency in flaxseed.

Rehman *et al.*, (2024) evaluated the number of branches in the KNO₃ treatment, increasing. This significant increase underscores the ability of KNO₃ to improve plant architecture, potentially leading to better light interception and higher overall productivity. Overall, KNO₃ not only hastens flowering but also promotes a more robust branching structure, contributing to enhanced plant vigor.

2.2 Yield and yield attributes

2.2.1 Effect of seed priming with KNO₃ on the number of capsules, seed yield, and test weight

Kumar *et al.*, (2016) experimented to know the significance of seed priming with KNO₃ on *S. indicum* and reported that 15 mM concentration of KNO₃ improved key yield attributes, including the number of capsules plant⁻¹, seed yield, and test weight (g) as compared to lower concentration along with the control set.

In connection with a previous study, Singh *et al.*, (2017) evaluated different priming in wheat crop to know the impact of KNO₃-based seed priming during the *rabi* seasons 2014-16. Treatment includes tap water, KNO₃, CaCl₂, GA₃, NaCl, and KH₂PO₄. Out of these, KNO₃ was proven most impactful for enhancing the yield and yield attributes of the wheat crop. These improvements help in enhancing the productivity of the crop.

Rehman *et al.*, (2024) conducted research on *S. alba* with the application of KNO₃, CaCl₂, NaCl, and moringa leaf extract of all KNO₃ treatments at 0.5% increased number of pods, seed yield, and test weight. This substantial enhancement underscores the effectiveness of KNO₃ in boosting crop productivity. The application of KNO₃ had a significant positive effect on the number of pods, seed yield, and test weight compared to the control.

Prasad *et al.*, (2021) concluded that seed priming with KNO₃ was beneficial increasing the biological yield. Seed priming treatment with KNO₃ (0.5%) recorded the significantly highest value, followed by GA₃ (25ppm) found effective for increasing harvest index when compared with control and

other treatments. This increase indicates a more efficient conversion of biomass into harvestable yield. Overall, the results from treatment with KNO₃ @ 0.5% illustrate a comprehensive enhancement in crop performance, highlighting its significant role in promoting growth, yield, and reproductive efficiency.

Rana *et al.*, (2021) worked on the effects of different KNO₃ concentrations (0.1%, 0.2%, and 0.3%) on linseed. The study found that the harvest index increased.

Rehman *et al.*, (2024) worked on the seed priming effect of KNO₃ (0.5%) on *S. alba*, resulting in a substantial yield. These results demonstrate that KNO₃ significantly enhances both biological yield and harvest index. This dramatic rise illustrates the effectiveness of KNO₃ in maximizing productivity, highlighting its role as an essential agronomic practice for improving crop performance.

Seed priming, particularly with potassium nitrate (KNO₃), shows a significant impact on the germination and early growth of oilseed and linseed crops. This technique improves seed hydration, accelerates metabolic processes, and leads to more uniform and rapid germination. Research indicates that priming with KNO₃ not only enhances germination rates but also boosts seedling vigor and stress resilience (Zhang *et al.*, 2022). For instance, studies by Ghosh and Mukherjee (2023) found that KNO₃-primed seeds exhibited a 30% increase in germination speed and improved growth parameters, including root length and biomass, compared to non-primed seeds. Additionally, the use of KNO₃ can enhance nutrient uptake and contribute to better crop establishment, ultimately leading to higher yields and improved quality in oilseed and linseed production (Kumar and Sharma, 2021 and Ali *et al.*, 2022b). These findings show the efficacy of seed priming as a valuable agronomic practice for optimizing crop performance under varying environmental conditions.

2.3 Biochemical parameters

2.3.1 Chlorophyll content, proline content, and oil content

Kumar *et al.*, (2016) examined the effect of pre-treatment of *S. indicum* seeds with KNO₃ at 15 mM concentration, which resulted in the highest proline content, suggesting its effectiveness as a pre-sowing treatment to improve crop performance.

Kumeera *et al.*, (2018) reported that seed priming of *C. arietinum* with 2% CaCl₂ significantly enhanced total chlorophyll and proline content. Thereby increasing the rate of photosynthesis and developing stress resistance in the plant.

Zrig *et al.*, (2023) examined the impact of seed priming with KNO₃ and L-Ascorbic Acid on linseed (*Linum usitatissimum* L.) sprout development and evaluated its effect on photosynthetic pigments. Results showed that seed priming of linseed with KNO₃ and L-Ascorbic Acid showed a positive impact on the

amount of chlorophyll a and b.

Rehman *et al.*, (2024) found that seed priming of *S. alba* with KNO_3 attained the highest leaf chlorophyll content at different growth stages, which was statistically similar to seeds treated with water. The minimum leaf chlorophyll content at all growth stages was observed in the control.

2.4 Effect of humic acid on oil crops

Humic acids are complex decomposed organic matter having improved soil structure, water holding capacity, and high nutrient availability. It has been shown to positively influence the different morphological and physiological parameters of linseed (*Linum usitatissimum* L) and other oilseed crops. Studies show that the use of humic acid enhances soil fertility by improving nutrient availability and promoting root development, which can lead to increased biomass and seed yield.

Sari *et al.*, (2020) demonstrated that humic acid application significantly improved the seed yield of linseed by enhancing photosynthetic activity and nutrient uptake. Additionally, the beneficial effects of humic acid on oilseed crops, such as sunflower (*Helianthus annuus*) and soybean (*Glycine max*), have been documented, with increases in oil content and overall productivity attributed to its role in stimulating hormonal activity and microbial activity in the rhizosphere (Alia *et al.*, 2018, and Kiani *et al.*, 2019). These findings underscore the effectiveness of humic acid as a valuable amendment for optimizing oilseed crop production. Manna and Siddique (2024) studied the combined effect of humic acid and sulphur, which notably improved various growth and yield parameters.

2.4.1 Effect of humic acid on morphological parameters

Ali *et al.*, (2021) recorded a 20% increase in plant height in linseed treated with humic acid compared to the control set of the treatment. This growth promotion is attributed to enhanced root development and nutrient absorption, facilitating better plant health and vigor. Similarly, Kumar *et al.*, (2022a) concluded an increase of 15% in plant height in sunflower due to humic acid application, indicating a broader applicability of humic acid treatments across oilseed Species.

Imran *et al.*, (2023) worked on *Brassica napus* to study the effect of four different levels of humic acid, including 5, 10, and 15 kg ha⁻¹ in a RCB design with three replications, along with a control. Results revealed that humic acid has a significant and positive impact on plant height in both study years. Plant height increased with increasing humic acid concentration, and treatment with 10 and 15 kg ha⁻¹ humic acid had no significant difference, from which they concluded that humic acid @10 kg ha⁻¹ is capable of increasing the height of mustard plants.

Abdelmasieh *et al.*, (2024) conducted research on soil application of humic acid fertilizer at different levels from 2021 to 2023. Results showed that the use of humic acid increased significantly. In the 2021/2022 season, the length increased. These results highlight the influence of humic acid on the growth of plants, underscoring its potential as an effective soil amendment to optimize crop performance.

Bakry *et al.*, (2015) experimented with the national research center, Egypt. They worked on different doses of sulphur and humic acid on flaxseed on newly reclaimed sandy soil. They reported that humic acid at 20 mg/L increased plant height

2.4.2 Effect of humic acid on dry matter accumulation, LAI, CGR, RGR, and NAR

A study conducted by Khan *et al.*, (2020a) on linseed with the imposition of humic acid at concentrations of 0, 2, and 4 L ha⁻¹. They found that 4 liter ha⁻¹ significantly increased dry matter accumulation, observing a 40% increase in humic acid-treated plants when compared to the control. Similarly, LAI, NAR, CGR, and RGR showed similar results, giving an impressive rise.

Rana *et al.*, (2021) observed the impact of humic acid application at 0, 1.5, and 3.0 liter ha⁻¹ on the mustard crop. Results revealed that 3.0 liter ha⁻¹ of humic acid treatment increased dry matter accumulation.

Jabbar *et al.*, (2023) explored the effectiveness of humic acid at rates of 0, 2.5, and 5 liter ha⁻¹ on sunflower crops. The results demonstrated a 33% increase in dry matter accumulation with 5 liter ha⁻¹ (from 1600 kg ha⁻¹ to 2128 kg ha⁻¹). LAI also improved.

A study by Kumar *et al.*, (2022c) demonstrated that the application of humic acid reduced the days to emergence in mustard crops by 3-5 days, translating to a 15-25% decrease compared to untreated controls. The authors noted that this acceleration in germination is due to improved soil moisture retention and structure, which create optimal conditions for seedling establishment.

Manna and Siddique (2024), in their work with the application of humic acid on *Brassica juncea*, showed that the application of humic acid decreased the days taken for emergence.

2.4.3 Effect of humic acid on yield and yield attributes

Bakry *et al.*, (2015) investigate the influence of three different doses of sulphur fertilizer and foliar humic acid on different morpho-chemical parameters as well as yield quantity and quality of flax grown on sandy soil.

Moreover, Khoshgoftarmanesh *et al.*, (2020) examined the effects of humic acid on various oilseed crops, including soybean and safflower. They observed that the addition of humic acid at varying concentrations resulted in increased branching, with a reported increase in secondary branches by up to 50% compared to untreated controls. This enhancement is believed to be due to the improved

soil structure and nutrient retention capabilities attributed to humic acid.

Research conducted by Patil *et al.*, (2020) found that linseed treated with humic acid yielded 25-40% more seeds compared to untreated controls. This increase was attributed to enhanced nutrient uptake and improved photosynthetic efficiency during critical growth phases.

Imran *et al.*, (2023) worked on the effect of HA on *B. napus* in a randomized block design with different levels of humic acid (5, 10, 15 kg ha⁻¹). The treatment with 15 kg/ha of humic acid yielded the best results, showing an increase in siliqua per plant. Showing a significantly promising effect of humic acid on rapeseed mustard

Abdelmasieh *et al.*, (2024) applied humic acid to soil at different doses in 2021-2022 and 2022-2023. Results disclosed that application 2000 g/fed of humic acid increased capsules number. The highest percent increase was observed in seed yield per plant with the 2000 g HA/fed treatment in the 2021/2022 season, these results underscore the advantageous effects of humic acid on plant reproductive traits, highlighting its potential to enhance crop productivity and quality.

2.4.4 Effect of humic acid on harvest index, biological yield, and oil yield.

Bakry *et al.*, (2015) concluded from their study that humic acid has proved to improve the biological yield per plant of linseed. Similarly, oil content was also found to increase with humic acid application.

Yadav *et al.*, (2022) noted an increase of 1.5% in oil yield for sunflowers treated with humic acid. This improvement is likely due to better seed quality and higher oil accumulation resulting from the physiological benefits of humic acid (HA). For the effect of humic acid application on mustard.

2.4.5 Biochemical parameters

Aydin *et al.*, (2012) investigated the effects of humic acid (HA) foliar sprays on crops experiencing stress. They found that proline content was negatively correlated with humic acid application; as stress-induced proline levels rose, humic acid reduced its accumulation, likely due to decreased stress. Their study also indicated that plants treated with 0.1% humic acid, even under stress, maintained higher total chlorophyll levels compared to those receiving 0.05% humic acid or no treatment.

Lotfi *et al.*, (2018) evaluated the effect of humic acid (0, 500 mg/l) on *Brassica napus* for photosynthetic potential in a RCB design in Iran. Humic acid enhanced the photosynthetic potential by increasing the quantum yield of photosystem II. It had no impact on the non-photochemical de-excitation rate under all conditions.

Khorasaninejad *et al.*, (2018) worked on studying the impact of varying levels of humic acid (0, 250, 500, and 1000 mg/kg) on the chlorophyll content of *Echinacea purpurea* under different soil

moisture regimes (40%, 60%, 80%, and 100% field capacity). The study found that the highest chlorophyll a content was achieved at the 1000 mg/kg level. Conversely, chlorophyll b levels remained unchanged. Humic acid, along with a less water regime, significantly affected chlorophyll a but not chlorophyll b. Overall, the application of humic acid at 1000 mg/kg led to a substantial increase in total chlorophyll content.

Patel *et al.*, (2021) concluded from their study that humic acid treatments led to increased chlorophyll content and photosynthetic efficiency in oilseed crops. This was reflected in higher biomass accumulation and ultimately, greater seed yields

A study conducted by Kumar *et al.*, (2022a) concluded that humic acid treatment resulted in enhanced proline accumulation, which helps in stress tolerance, allowing plants to better withstand adverse conditions, thereby maintaining yield potential.

2.5 Effect of sulphur on morphological growth

The application of sulphur as a soil nutrient significantly increases yield and different yield attributes of oilseed and linseed crops. Sulphur plays a crucial role in protein synthesis, enzyme function, and chlorophyll production, which are vital for healthy plant development. Studies suggested that sulphur deficiency can lead to stunted growth and reduced seed quality, while adequate sulphur application improves seed yield and oil content.

For instance, research by Saha *et al.*, (2021) demonstrated that sulphur application increased oilseed yield and enhanced oil quality. Furthermore, the integration of sulphur into fertilization strategies has been linked to improved nutrient uptake and soil health, promoting better root development and overall crop vigor (Kumar *et al.*, 2022a). These findings highlight the importance of sulphur as a critical nutrient for maximizing the productivity and quality of oilseed and linseed crops in various agro-ecological conditions.

Bakry *et al.*, (2015) researched in linseed field application of different levels of sulphur with foliar application of humic acid in a split-plot experimental design. The result revealed that plant height increased. Showing that sulphur in lower doses is required to significantly improve the growth and harvest quantity compared to the control.

Rakesh and Banik (2016) worked on *Brassica juncea* (L.) to study the effect of varying Sulphur levels ranging from 15 to 30 kg ha⁻¹ from two different sources (bentonite-S and single superphosphate) on the yield parameters during the *Rabi* season of 2013-2014. Plant height showed an increase when treated with 25 kg ha⁻¹ as Bentonite. This enhancement suggests that the application of sulphur positively influences the vertical growth of mustard plants.

Patil *et al.*, (2018) worked on the development and production of linseed by applying phosphorus and sulphur at different doses in a factorial randomized block design. The data revealed that sulphur increased plant height significantly with increasing sulphur level, and concluded that sulphur at 30 kg ha⁻¹

¹ showed increased plant height in linseed.

Kushwaha *et al.*, (2019) evaluated linseed genotypes on four different levels of sulphur at the research farm, Benda-Semaria Road, Rewa (M.P.) in a factorial randomized block design during the winter season of 2017-2019. The application of sulphur showed an enhancement effect on plant height, with the highest measurement recorded at 60 kg ha⁻¹. This represents an increase of 5.7%, indicating that sulphur contributes to enhanced growth of linseed genotypes.

Bainade *et al.*, (2019) in his experiment on linseed for enhancing its growth and production by application of different levels of sulphur to soil in a randomized block design with 8 treatments and 3 replications. Treatments consist of RDF (60:30:00 NPK kg/ha) with different nutrient supplements like sulphur at 15, 20, and 25 kg/ha. The study demonstrates that sulphur application plays a vital role in enhancing the growth.

2.5.1 Effect of sulphur on dry matter accumulation, leaf area, LAI, CGR, RGR, and NAR

Patil *et al.*, (2018) from their study concluded that sulphur at 30 kg ha⁻¹ has a significant result for increasing dry matter accumulation per plant in linseed. It increased it by 17.07% showcasing a positive correlation between sulphur application and dry matter per plant.

Bainade *et al.*, (2019) applied different levels of sulphur (0, 15, 20, 25 kg ha⁻¹) along with RDF to study its effect on linseed growth and yield. The study demonstrates that sulphur application at 25 kg ha⁻¹ enhanced dry matter accumulation significantly. It increased with increasing sulphur level. Dry matter accumulation/ plant increased to 8.68 g at harvest from 3.83 g in the control with no fertilizer application, suggesting that sulphur dose with the basal dose of NPK (60:30:00) proved to be an effective treatment for all.

2.5.2 Effect of sulphur on crop phenology

Akhtar *et al.*, (2020) observed that applying 20 kg ha⁻¹ of sulphur in *Brassica napus* led to a 4-day reduction in days to emergence. They suggested that sulphur promotes root development, allowing plants to better access soil moisture and nutrients, thus accelerating the emergence process.

Sharma *et al.*, (2021) found that application of 30 kg ha⁻¹ of sulphur reduced the days taken for emergence of *Cicer arietinum* by approximately 3 days compared to the control. The authors attributed this effect to improved seed vigor and enhanced nutrient uptake, which facilitated faster germination.

According to research by Ali *et al.*, (2022a), sulphur doses of 40 kg ha⁻¹ advanced the flowering of *Helianthus annuus* by 5 days compared to untreated controls. This early flowering was linked to enhanced photosynthetic activity and nutrient availability, which support the formation of floral

structures.

Furthermore, Singh *et al.*, (2022) reported that in *Brassica oleracea*, sulphur application at 50 kg ha⁻¹ led to an earlier maturity by approximately 8 days compared to the control. The study emphasized that sulphur enhances the overall metabolic processes within the plant, contributing to quicker maturation.

In study conducted by Muneer *et al.*, (2023) it concluded that in *Phaseolus vulgaris*, the application of sulphur @ 50 kg ha⁻¹ resulted in flowering occurring 6 days earlier than in control plants. The authors noted that sulphur application improved hormonal balance, promoting earlier flowering.

2.5.3 Effect of sulphur on yield and yield attributes

Bakry *et al.*, (2015) conducted an experiment on linseed with the different levels of sulphur and humic acid in a split-plot experimental design. The Result showed that sulphur@250 kg/fed increased the number of branches plant⁻¹ whereas sulphur@500 kg/fed significantly increased fruiting branches plant⁻¹ Showing that increasing the sulphur level has a positive impact on the number of fruiting branches of plants, leading to higher yields.

Rakesh and Banik (2016) experimented on Indian mustard, applying different levels of sulphur in RCBD. Results revealed that sulphur has an enhancing effect on the number of branches. Sulphur at 25 kg/ha showed substantial improvement

In a study by Patil *et al.*, (2018), sulphur showed significant improvement in the number of branches of plant⁻¹ by application of 30 kg h⁻¹ of sulphur supplementation. An increasing number of branches.

Similarly, Bainade *et al.*, (2019) demonstrate that sulphur application plays a vital role in enhancing both the physiological development and oil yield of linseed. Sulphur not only increases plant height but also increases the total number of branches per plant.

Kushwaha *et al.*, (2019) evaluated different genotypes of linseed with different levels of sulphur on development and quality in a factorial (RBD). The results showed that application of the sulphur fertilization produced an average of 6.02 branches per plant, an increase from 5.50 branches in the control group. This 9.5% increase demonstrates that sulphur application supports better branching in the plants. Similarly, the same treatment increases the secondary branches per plant by 7.6 % highlighting the role of sulphur in enhancing overall plant structure.

Rakesh and Banik (2016) conducted a field-based experiment in mustard using an RBD design with different levels of sulphur ranging from 15-30 Kg ha⁻¹. The dose of 25 Kg ha⁻¹ was proven as the most effective for the number of siliqua and grains per siliqua as compared to the rest of the treatments, including control;

consequently, the yield of mustard was improved. Therefore, the findings of the work suggested that sulphur application @25 Kg ha⁻¹ optimized production of mustard.

The study conducted by Patil *et al.*, (2018) suggests that increasing sulphur concentration has a significant impact on linseed crop. Their results revealed that when sulphur was applied at 30 kg/ha, it increased the number of capsules.

Solanki *et al.*, (2018) conducted a field experiment on *Brassica juncea* at Udaipur, Rajasthan, during the *rabi* season. The treatments were laid in a factorial RBD in which different sulphur (0, 30, 40, and 50 kg S ha⁻¹) doses were provided to the soil. Results revealed that sulphur concentration is directly proportional to seed yield.

Kushwaha *et al.*, (2019) worked with linseed genotype with different levels of sulphur. The application of sulphur with 60 kg ha⁻¹ has significantly increased the number of capsules per plant. the overall benefits of sulphur in enhancing growth rate and harvest quality.

Bainade *et al.*, (2019) conducted an experiment on linseed with varying regimes of sulphur application for studying its enhancing effect in a randomized block design. Results revealed that RDF + 25 kg S ha⁻¹ increased grain yield.

Khan *et al.*, (2020c) conducted a study on canola (*Brassica napus*) and concluded that applying sulphur @ 40 kg ha⁻¹ significantly increased the harvest index. This increase was attributed to enhanced seed filling and reduced vegetative growth due to sulphur's role in protein synthesis, which promotes seed development.

Similarly, Sharma *et al.*, (2021) evaluated the impact of sulphur application on soybean and reported a marked increase in HI from 32% to 40% with the application of 30 kg/ha of sulphur. The authors suggested that sulphur enhances the physiological processes involved in grain formation, including improved photosynthetic efficiency and nutrient mobilization from vegetative tissues to grains.

Alam *et al.*, (2021) worked on sulphur application at varying rates (0, 20, 40, and 60 kg/ha) on mustard (*Brassica juncea*) and found that biological yield increased with sulphur application. The highest biological yield was recorded. The study emphasized that sulphur enhances root development and overall plant vigor, contributing to increased biomass accumulation.

Maqsood *et al.*, (2022) examined the impact of sulphur on chickpea, and reported that 30 kg/ha of sulphur led to an increase in biological yield, The authors attributed this improvement to better nutrient availability and increased chlorophyll content, which enhanced photosynthetic activity.

2.5.4 Effect of sulphur on Biochemical parameters

Bakry *et al.*, (2015) worked on the field application of sulphur fertilizers at varying levels in a split-plot design resulted in notable increases in chlorophyll content compared to the control group. This trend indicates a positive response of chlorophyll and proline accumulation with increasing sulphur application.

Kushwaha *et al.*, (2019), working with different levels of sulphur application on linseed crop in a randomized block design, found that imposition of 60 kg ha⁻¹ of sulphur supplementation to soil has increased the oil content (%) of the seeds significantly, the positive impact of sulphur on oil production, making it a valuable addition for improving crop profitability.

2.6 Effect of irrigation scheduling on morpho-phenological parameters

Rashwan *et al.*, (2016) conducted a study on flax for both seed and fiber production, findings indicated that flax plants irrigated every 35 days exhibited significant improvements in plant height, showing increase compared to the control treatment.

Patel *et al.*, (2017) worked on the impact of various irrigation schedules and nitrogen doses on the growth and productivity of linseed. The findings indicated that the 0.6 IW/CPE (I₃) treatment was most effective in enhancing plant growth, increasing plant height.

Jat *et al.*, (2018) carried out research on rapeseed-mustard during three consecutive *Rabi* seasons. Treatment was conducted on a split-plot design with 5 irrigation regimes. Irrigation scheduling has a positive correlation with plant height.

Ebied and Badawi (2023) carried out a field experiment on flax varieties studying the effect of irrigation regimes on their yield, quality, and water use efficiency during the two successive seasons of 2019-2021. A split-plot design was used along with four replicates and three irrigation regimes. Results showed that I₃ treatment (three irrigations) proved to be the best, showing plant height increased.

Jat *et al.*, (2020) reported that in linseed (*Linum usitatissimum*), applying irrigation at critical stages resulted in a 25% reduction in days to emergence compared to traditional scheduling practices. This improvement was attributed to better soil moisture conditions that facilitated seed germination.

Similarly, Kumar *et al.*, (2021b) observed that frequent irrigation every 3 days in *Brassica napus* reduced the emergence period by 2-3 days compared to less frequent schedules every 7 days. The enhanced moisture availability allowed for a quicker germination response, which is crucial for establishing a competitive crop.

Furthermore, in soybean, Patil *et al.*, (2020) demonstrated that crops under a scheduled

irrigation regime (irrigated at 50% field capacity) matured 5-8 days earlier than those under irregular irrigation conditions. The consistent water supply was crucial in facilitating timely maturity, allowing for better yield management. Irrigation scheduling also impacts the timing of flowering, a critical phase for yield formation.

In a study by Singh *et al.*, (2022), it was noted that oilseed crops subjected to a well-managed irrigation regime (based on crop water requirements) flowered 4-6 days earlier than those under deficit irrigation conditions. The authors suggested that consistent soil moisture levels promote hormonal balance, facilitating earlier flowering. In linseed, Ranjan *et al.*, (2023) found that crops irrigated at 50% depletion of soil moisture reached 50% flowering approximately 5 days earlier than those irrigated at 70% depletion. This timing advantage can lead to improved yield potential, particularly in environments where climate conditions may adversely affect flowering times.

2.6.1 Effect of irrigation scheduling on leaf area, LAI, CGR, RGR, and NAR

Patel *et al.*, (2017) worked on the yield of linseed, with different irrigation treatments. The water regime at IW/CPE of 0.6 treatment significantly increases dry matter accumulation (35.91%). Sarkar and Sarkar, (2017) in this experiment, vertical plots were established with four distinct irrigation schedules for linseed crops: one irrigation after seeding, 1 irrigation at 35 days after seeding, or DAS, 2 irrigations at 35 and 75 DAS, and 3 irrigations at 0, 35, and 75 DAS. When comparing the rainfed treatment to the irrigation levels of 0.4 and 0.6, dry matter accumulation increased, indicating that irrigation substantially enhances biomass production. These results indicate a clear correlation between irrigation frequency and dry matter accumulation, emphasizing the necessity of adequate water supply at critical growth stages for optimal crop development.

Arun *et al.*, (2020) conducted a field-based study to study the effect of seed priming on cowpea under limited water supply using drip irrigation. The study tested three irrigation intervals, applying water at 0.9, 0.7, and 0.5 Epan replenishment. Treatment with dry matter accumulation (DMA) at 60 days after sowing reaching 11.44 g, a 36.7% increase over the control's 8.39 g. The leaf area index (LAI) also improved significantly. These results highlight that optimal irrigation practices can significantly improve key growth metrics in cowpea.

2.6.2 Yield and yield attributes

A study done by Patel *et al.*, (2017) studied the effect of different irrigation scheduling on the number of branches of linseed crop in a split-plot design. It positively increases primary and secondary branches, demonstrating the critical importance of irrigation scheduling in optimizing crop yield and overall plant health.

Rashwan *et al.*, (2016) worked on flaxseed for both seed and fiber to determine the effect of irrigation levels on different cultivars. Results revealed that irrigation treatment every 35 days showed significant improvements compared to the control.

Patel *et al.*, (2017) in their field experiment examined the impact of various irrigation regimes on linseed fruit development and seed yield. The irrigation regime at 0.6 IW/CPE significantly enhanced key metrics: capsules per plant, seed per capsule, test weight, and seed yield compared to the control.

Sarkar and Sarkar (2017) in their research on linseed on different irrigation levels organized in a split-plot design with three replications. The treatment included three irrigation levels ranging from I_1 to I_2 at an IW/CPE of 0.4 (I_2), and irrigation at an IW/CPE of 0.6 (I_3). Results showed a significant positive impact of the irrigation regime on seed yield. The treatment with IW/CPE of 0.6 (I_3) has a positive impact on seed yield.

Jat *et al.*, (2018) worked on rapeseed-mustard over three *Rabi* seasons using a split plot design with five irrigation treatments: control, 0.4 IW/CPE, 0.6 IW/CPE, 0.7 IW/CPE, and 0.8 IW/CPE. They concluded that applying water at 0.8 IW/CPE has significantly increased the number of siliquae plant⁻¹. These results indicate that 0.8 IW/CPE irrigation treatment maximizes plant growth and productivity across all measured parameters.

Ebied and Badawi, (2023) conducted a field experiment in two successive seasons, employing a split design with 4 replicates for each experiment on linseed irrigation regimes. The irrigation regimes tested included sowing irrigation plus one additional irrigation, sowing irrigation plus two additional irrigations, and sowing irrigation plus three additional irrigations. Treatment I_3 increased the number of capsules per plant, the number of seeds per capsule, and test weight as compared to the control. This indicates that more frequent irrigation positively impacts growth and yield attributes, making I_3 the most effective irrigation strategy for maximizing plant performance.

Kashyap (2020) conducted work on the irrigation scheduling of linseed, The treatments include one irrigation after seeding (I_0), one irrigation at 35 DAS (I_1), two irrigations at 35 and 75 DAS (I_2), and three irrigations at 0, 35, and 75 DAS (I_3), and saw its effect on seed yield ($q\ ha^{-1}$). Results showed that treatment I_3 has a positive impact on the seed yield of the linseed crop.

In study conducted by Rashwan *et al.*, (2016) concluded that treatment irrigated after 35 days (I_2) shows significant improvements compared to control (I_1). The oil yield shows a substantial increase. Therefore, irrigation every 35 days offers an optimal balance between water conservation and crop performance.

Sarkar and Sarkar (2017) conducted a study in which the main plot treatments included three

irrigation levels: rainfed (I_1), irrigation at an IW/CPE of 0.4 (I_2), and irrigation at an IW/CPE of 0.6 (I_3). The results indicated that the oil percentage increased by 2.49% with irrigation at an IW/CPE of 0.4 and by 2.86% with irrigation at an IW/CPE of 0.6 compared to the rainfed condition. Furthermore, the oil yield showed a notable increase.

Jat *et al.*, (2018) concluded that irrigation treatment with 0.8 IW/CPE has a positive impact on oil content and its yield. Irrigation at a ratio of 0.7 IW/CPE resulted in a higher oil content. In contrast, maximum oil yield was observed with the 0.8 IW/CPE treatment, which was also statistically similar to that of the 0.7 IW/CPE treatment.

In a study conducted by Kashyap, (2020) on linseed crops, various irrigation schedules were implemented, including at sowing, at 35 days after sowing, at 75 days after sowing, and a combination of irrigations at 0, 35, and 75 days after sowing. Treatment I_3 demonstrated a significant improvement in biological yield. This represents an increase of approximately 47.8%. These findings highlight the efficacy of the I_3 irrigation schedule in enhancing both seed and biological yields.

Ebied and Badawi (2023) conducted a research experiment on different irrigation regimes with varying levels of irrigation laid on a split-plot design. The I_3 treatment (more frequent irrigation) resulted in the highest percentage increases across seed oil % and overall oil yield. The seed oil content (%) showed improvement. These results highlight that more frequent irrigation enhances both yield and oil production, making I_3 the superior treatment.

Effective irrigation management reduces water stress, enhances plant growth parameters, and improves seed quality, including germination rates and disease resistance (Rai and Choudhary, 2023, and Singh and Gupta, 2020). Furthermore, sustainable irrigation practices not only boost crop performance but also optimize water use, resulting in significant economic benefits for farmers (Bansal and Jain, 2023, and Mehta and Sharma, 2020). Overall, the strategic implementation of irrigation schedules is vital for achieving higher yields and quality in oilseed and linseed production.

2.6.3 Effect of irrigation on Biochemical parameters

Kumar *et al.*, (2021c) evaluated the impact of three irrigation regimes: watering every 3 days, every 5 days, and every 7 days on chlorophyll a and b content in linseed. The study revealed that frequent irrigation led to maximum chlorophyll a content, a 20% increase compared to the deficit irrigation treatment (2.9 mg g^{-1}). The improved moisture availability facilitated better chlorophyll synthesis, enhancing photosynthetic efficiency.

Meena *et al.*, (2021) rectified the effect of varying irrigation frequencies on proline levels in linseed. The treatments included regular irrigation (irrigated at 50% depletion), drought stress (irrigated at 70% depletion), and well-watered conditions. The results revealed that proline content was significantly

higher in drought-stressed plants compared to those receiving regular irrigation.

In a separate study by Ranjan *et al.*, (2022), the effects of irrigation timing on canola were investigated. Treatments included irrigation at 25% field capacity and 50% field capacity. The results indicated that plants irrigated at 50% field capacity had significantly higher chlorophyll content. This finding underscores the necessity of maintaining optimal soil moisture levels for maximizing chlorophyll synthesis.

In the study conducted by Patel *et al.*, (2023), the impact of different irrigation regimes on soybean was analyzed, with treatments including conventional irrigation and regulated deficit irrigation. The findings showed that regulated deficit irrigation led to higher proline levels compared to conventional irrigation ($2.1 \mu\text{mol g}^{-1}$), a notable increase. This suggests that controlled water stress can induce proline synthesis, aiding plant adaptation to environmental stressors.

2.7 Interaction effect of humic acid, sulphur, and irrigation regimes

A study conducted by Alizadeh *et al.*, (2020) on different doses of humic acid (0, 5, 10, and 15 g/kg) in soil was evaluated on linseed under varying irrigation regimes (full irrigation vs. deficit irrigation). The findings show that 10 g kg^{-1} humic acid significantly enhanced plant height, chlorophyll content, and seed yield.

Khan *et al.*, (2020b) found that humic acid @ 5 kg ha^{-1} resulted in a 25% increase in seed yield of oilseeds, from $1,600 \text{ kg/ha}$ in the control group to $2,000 \text{ kg ha}^{-1}$. Additionally, humic acid enhanced chlorophyll content, leading to healthier plants and increased biomass.

Nawab *et al.*, (2021) assessed the effects of irrigation scheduling (alternate wetting and drying) with 10 kg/ha of humic acid and 30 kg/ha of sulphur on mustard. The results showed an increase of 25% in the number of primary branches plant^{-1} from 5 to 6.25, contributing to enhanced biomass accumulation.

Rafique *et al.*, (2021) investigated the combined effects of irrigation and fertilization on oilseed rape. They found that applying 6 kg/ha of humic acid and 50 kg/ha of sulphur with biweekly irrigation improved oil yield. Additionally, the oil quality was enhanced, showing a higher percentage of essential fatty acids.

The combined effects of humic acid and sulphur were examined by Hosseini *et al.*, (2022), where they applied 10 g/kg of humic acid and 30 kg/ha of sulphur to linseed crops under different irrigation regimes. The results showed a synergistic effect, with the combination leading to a 40% increase in seed yield. The study concluded that the application of both humic acid and sulphur improved nutrient uptake and enhanced stress tolerance, particularly under drought conditions.

Shahbaz *et al.*, (2023) noted that the use of humic acid 8 kg ha⁻¹ and sulphur 30 kg ha⁻¹ under regulated irrigation conditions significantly increased oil content in linseed.

Ranjan *et al.*, (2023) assessed the effects of three irrigation regimes: (1) full irrigation, (2) alternate furrow irrigation, and (3) deficit irrigation on the growth of linseed. The study found that full irrigation combined with humic acid (10 g kg⁻¹) and sulphur (30 kg ha⁻¹) yielded the best results, increasing plant height and seed yield.

Manna and Siddique (2024) conducted a study on *Brassica juncea* during 2020-22, using a split plot design with different moisture conditions and individual and combined treatments of humic acid and sulphur, demonstrating remarkable results, increase in the number of secondary branches and rise in siliqua per plant. The combination effect of irrigation and nutrient treatment decreased the days taken for emergence by 50 %. The treatment also has a significant impact on the number of siliqua plant⁻¹, seed yield, biological yield, harvest index, and oil yield, increasing them to an impressive value, showing the usefulness of the combination of humic acid, sulphur, and irrigation regime on growth and yield attributes of *B. juncea*.

2.8 Effect of nutrient application on the economics of linseed

Sarkar and Sarkar (2017) reported that irrigation significantly improved the economic returns of linseed compared to rainfed conditions. Under rainfed cultivation, gross returns were Rs. 21.9×10^3 ha⁻¹, which increased to Rs. 24.1×10^3 ha⁻¹ with moderate irrigation and further to Rs. 25.7×10^3 ha⁻¹ with higher irrigation levels. Net returns also followed a similar trend, increasing from Rs. 7.47×10^3 ha⁻¹ under rainfed conditions to Rs. 9.58×10^3 ha⁻¹ with higher irrigation, along with a benefit–cost ratio of 0.60. The study emphasized that efficient irrigation scheduling enhances the profitability of linseed cultivation.

Jat *et al.* (2018) reported that higher irrigation levels significantly enhanced the economic performance of Indian mustard (variety GDM-4). Irrigation scheduled at an IW/CPE ratio of 0.8 resulted in the highest gross returns, net returns, and benefit–cost ratio. Net returns reached Rs. 72,318 ha⁻¹, showing clear superiority over lower irrigation levels. The study concluded that irrigation at an IW/CPE ratio of 0.8 is economically optimal for Indian mustard cultivation under north Gujarat conditions.

Ahmad *et al.* (2018) reported that the combined application of liquid humic acid with inorganic nutrients significantly improved the economic returns of wheat. The highest net profit (Rs. 90,937 ha⁻¹) was obtained with liquid humic acid applied along with urea and foliar nutrition, followed closely by liquid humic acid applied as a foliar spray. The lowest net profit (Rs. 64,350 ha⁻¹) was recorded under the control treatment. The study concluded that integrating humic acid with nutrient management enhances the profitability of wheat cultivation.

Kushwaha *et al.* (2019) reported that sulphur application significantly improved productivity and economic returns of linseed. The highest net income (Rs 53,267 ha⁻¹) was recorded with adequate sulphur supply. Among the genotypes, JLS-67 performed best, and the application of 60 kg sulphur per hectare was found to enhance yield, quality, and profitability of linseed under Kymore plateau conditions.

Ali *et al.*, (2019) demonstrated that sulphur fertilization improved the biological yield and harvest index of linseed, resulting in an increase in gross income by approximately 30%. The economic analysis revealed a net profit enhancement of Rs. 8,000, raising total profits from Rs. 10,000 to Rs. 18,000 per hectare.

Khan *et al.*, (2020b), concluded that the supply of humic acid enhanced the seed yield of oilseeds by 25%, leading to a net profit of approximately Rs. 12,000 per hectare compared to control treatments, which yielded a net profit of Rs. 9,600. This indicates a return on investment (ROI) of around 25% for farmers using humic acid.

Rao *et al.*, (2022) reported that KNO₃ seed priming led to a yield increase of 22%, with net profits rising by Rs. 9,000, increasing total profits from Rs. 12,000 to Rs. 21,000 per hectare. This emphasizes the cost-effectiveness of this agronomic practice.

Yasin *et al.*, (2022) studied the interaction of 5 kg/ha humic acid and 40 kg/ha sulphur under different irrigation regimes on linseed. They reported an increase in plant height by 20% (from 80 cm in the control to 96 cm in the treated group). The combination also improved days to emergence by 10%, reducing the time from 10 days to 9 days.

Ali *et al.*, (2021) assessed that 5 kg/ha of humic acid and 30 kg/ha of sulphur on linseed crops. They reported a significant yield increase of 35%, with treated plants yielding 2,600 kg/ha compared to 1,900 kg/ha in the control group. The harvest index also improved from 30% to 40%.

Patel *et al.*, (2023) investigated the joint application of humic acid, sulphur, and KNO₃ under various irrigation regimes. Their findings indicated that the combination led to a yield increase of 35%, with a net profit increase of Rs. 15,000, resulting in total profits of Rs. 30,000 per hectare compared to Rs. 15,000 for the untreated control.

Study conducted by Raza *et al.*, (2023). They noted that the combined application of KNO₃ and humic acid resulted in a profit increase of Rs. 15,000/ha, translating to a total profit of Rs. 40,000/ha for treated crops compared to Rs. 25,000/ha for untreated controls. The cost of implementing both treatments was found to be economically viable due to the significant yield increase.

MATERIALS AND METHODS

The experiment entitled “*Effect of seed priming, humic acid and sulphur application on growth, yield and oil quality of linseed under different irrigation intervals*” was conducted over the research farm of Agronomy, School of Agriculture, Lovely Professional University, Phagwara, Punjab, during the *Rabi* seasons of 2022-23 and 2023-24. This chapter explains in detail the materials used, the methodology adopted, and the biochemical process adopted to analyze the impact of treatments during the entire research work.

3.1 Location of field trial

The Agriculture Research Farm of Lovely Professional University, Phagwara (Punjab) is located at a latitude of $31^{\circ}22' 31.81''$ North and at an approximate longitudinal line of $75^{\circ}23' 03.02''$ East, with an average altitudinal level of above 252 meters above mean level of sea. Punjab is located in the sub-tropical region of the middle plain, as per the Agro-Climatic Zone.

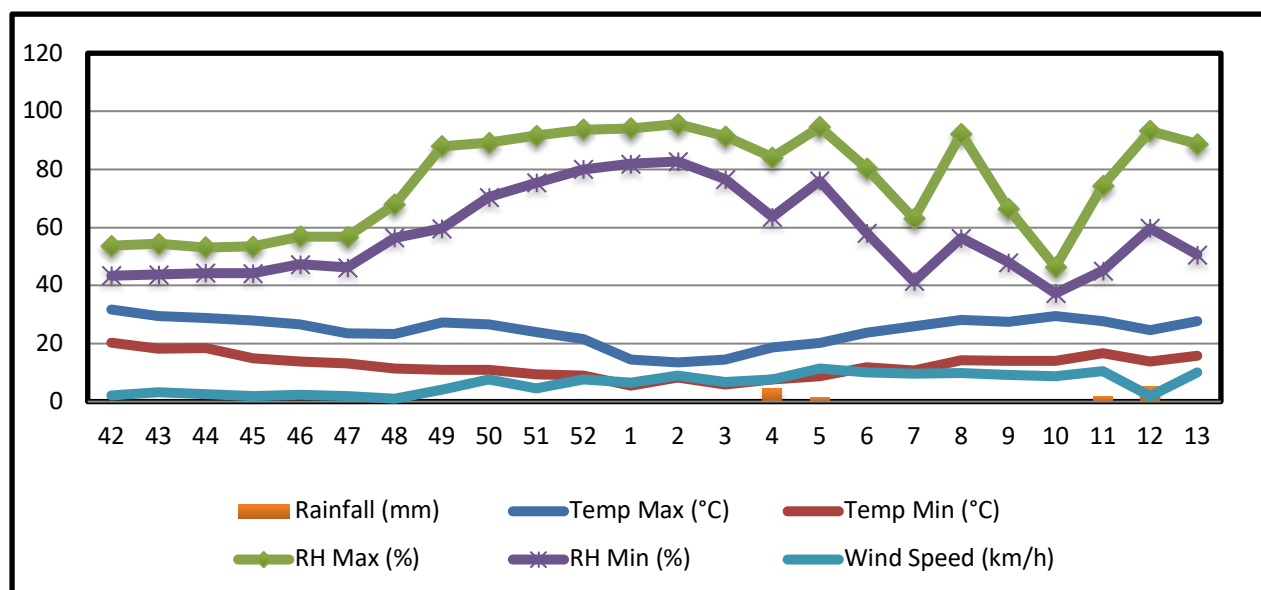


3.2 Climate and weather

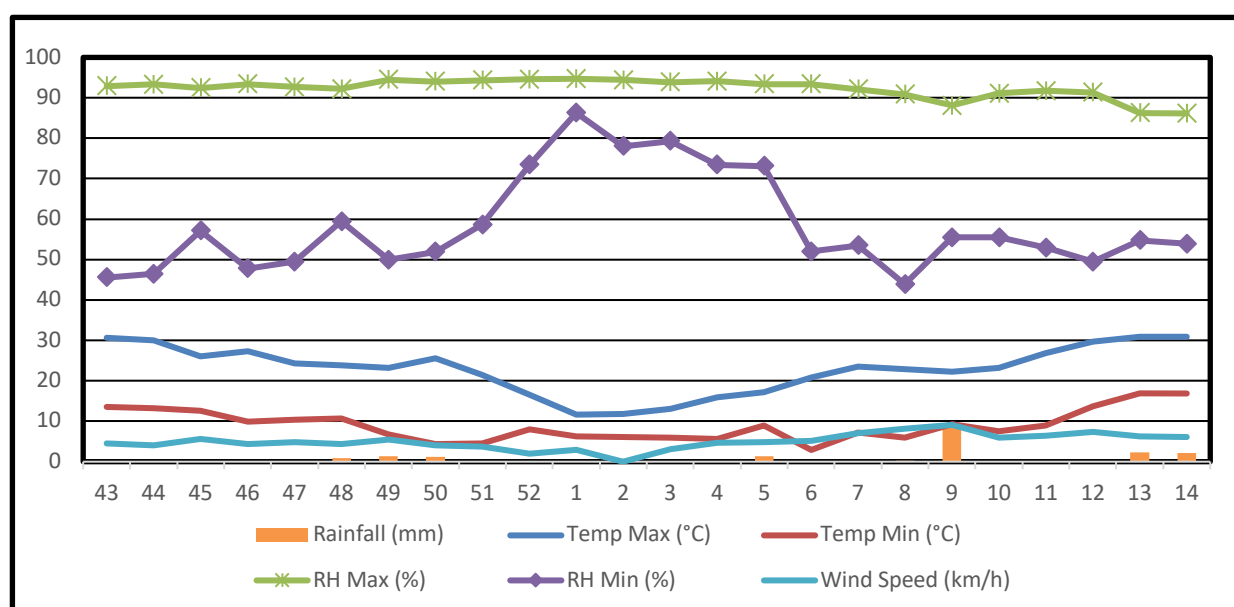
Lovely Professional University, Phagwara, Punjab, experiences a subtropical climate having three distinct seasons: summer, monsoon, and winter. Recording the maximum temperature around 42°C , the summer is intensely hot and dry, beginning in late March and lasting until June, with May being the hottest. The first week of July marks the start of monsoon season, which continues till mid-September, bringing an average annual rainfall of 730 mm approximately, from the south-west monsoon currents primarily. Heavy rainfall is generally concentrated in July and August. The winters are relatively cold and occur during late November, extending until February, with January recording the lowest temperatures usually. During the winter and pre-monsoon summer seasons, the climate remains dry.

The observations of the corresponding meteorology data for the *Rabi* 2022 to 2023 and 2023 to

2024, recorded from the Meteorological Observatory of the LPU, Phagwara, are mentioned in Fig. 3.1.1.a and 3.1.2.b.



3.2.a Weekly Agro-meteorological data during the *Rabi* season (2022-23)



3.2.b Weekly Agro-meteorological data during the *Rabi* season (2023-24)

3.3. Soil characteristics

Before commencing the research work, composite soil specimen was collected from a depth of 30 and 60 cm and stored at 2-4 °C in a zip bag to maintain the integrity of the soil for the physio-chemical analysis pertaining to the representative soil samples. The findings of the soil sample testing provide baseline information regarding the physico- chemical characteristics, like pH of soil, types, EC, organic carbon, and nutrient availability. Results of the soil analysis are summarized in Tables 3.3a and findings

of the soil was neutral (7.2 and 7.5) and ideal for nutrient uptake, while the EC was recorded as low, which suggests that salinity is not a concern with the soil. Furthermore, the organic carbon was noticed in a low range (0.30 and 0.33 dS/m), which indicates the limited microbial activity and organic content that influence the soil fertility. Results are also categorized as the low range of available nitrogen (260.3 and 265.3 Kg ha⁻¹), indicating the need to supply of fertilizer to fulfill the need of healthy crop growth. The results of available phosphorus (17.83 and 18.3 Kg ha⁻¹) indicate a medium range of phosphorus, which is adequate to support the medium growth of the plant, while the availability of potassium (181.6 and 183.9 kg ha⁻¹) indicates a sufficient range required for the growth. However, the analysis of sulphur content in the soil indicates a lower availability of sulphur, which we need to supply externally to maintain the yield and oil content of the respective crop.

Table 3.3.a: Mechanical composition of the soil

Component	Percentage of weight	Method use
Sand	62.58	International Pipette technique Piper (1966)
Silt	19.21	
Clay	13.10	
Textural type	Clay loam	Triangle method
Bulk density (g/cm ³)	1.41	Black 1965
Particle density (g/cm ³)	2.51	

Table 3.3.b: Chemical analysis of experimental soil

S.No.	Soil component	2022-2023	2023-2024	Mean	Method used
1	pH (1:2)	7.2	7.5	7.4	Glass Electrode pH meter (Jackson, 1973)
2	Electrical conductivity (dS/m)	0.3	0.33	3.2	Solubridge method (Richard, 1954)
3	Organic Carbon (%)	0.45	0.48	0.47	Walkley and Black's method (1934)
4	Available Nitrogen (kg ha ⁻¹)	260.3	265.3	262.8	Alkaline permanganate method (Subbiah and Asija, 1954)
5.	Available Phosphorus (kg ha ⁻¹)	17.83	18.3	18.07	Olsen's method (Olsen <i>et al.</i> , 1954)
6	Available Potassium (kg ha ⁻¹)	181.6	183.9	182.8	Flame Photometer (Jackson, 1973)
7	Available Sulphur (ppm)	10.41	10.84	10.63	Williams and Steinberg (1959)

3.4 : Previous cropping history of the yield:

Table 3.4 gives a short summary of the experimentation field's cropping trajectory across the two-year study.

Table 3.4.a: Cropping history of the experimental field

Sl. No	Year	<i>Kharif</i> season	<i>Rabi</i> season
1	2020-21	Maize	Barley
2	2021-2022	Sesame	Maize
3	2022-2023	Present experiment	Nil
4	2023-2024	Present experiment	Nil

3.5 : Experimental details:

During the *Rabi* seasons of 2022–2023 and 2023–2024, the research study was carried out at the Institute of Agriculture's Agricultural Research Establishment in Phagwara, Punjab.

with the same treatment and same site. The layout proposal of the testing is shown in Fig. 3.4, and the figures of the experiment are as follows:

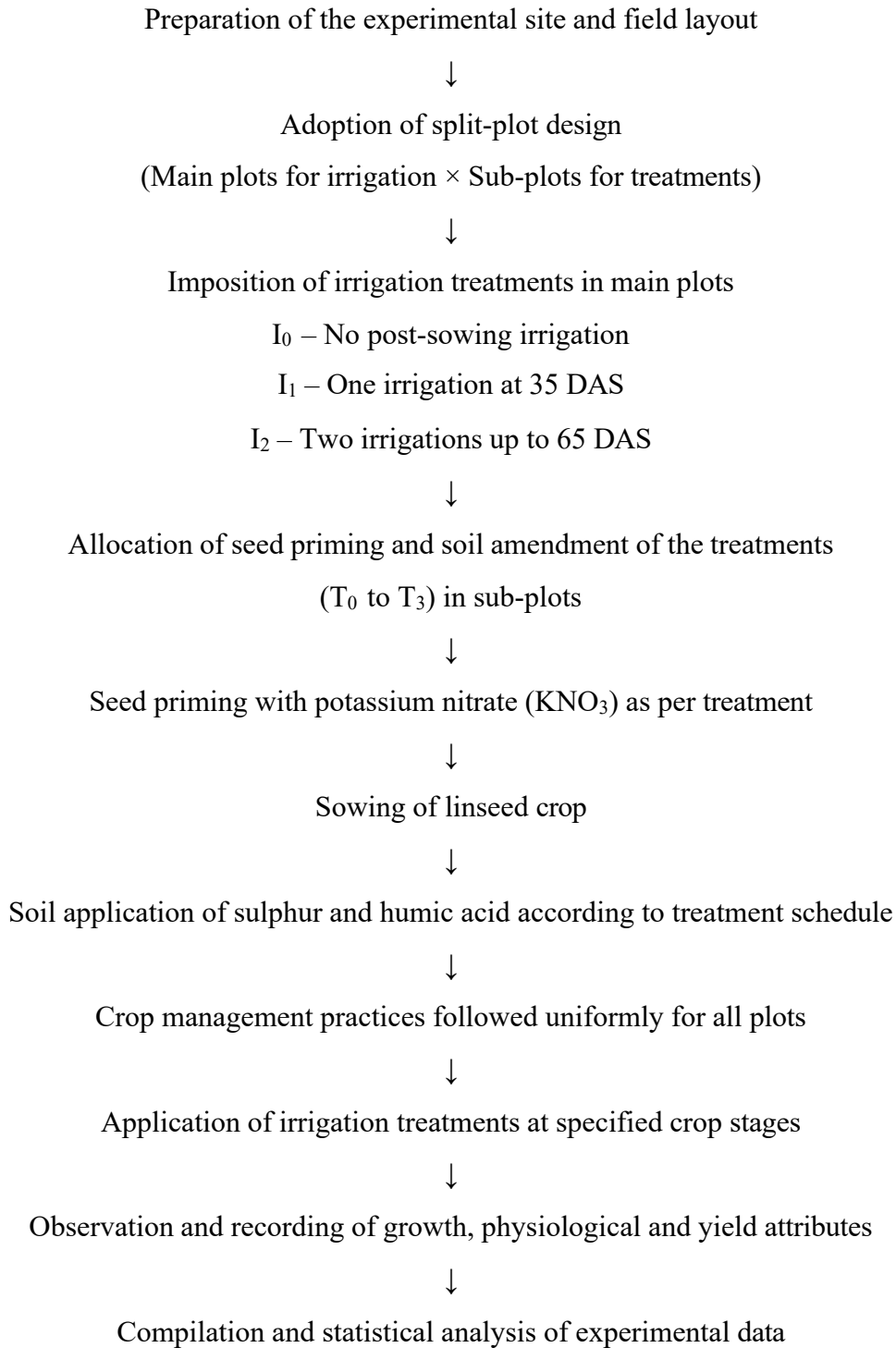
Table 3.5.a Experimental details

Location of the Research Farm	Lovely Professional University
Crop	Linseed (<i>Linum usitatissimum</i> L)
Crop variety	LC 2063
Year of experimentation	2022-2023 and 2023-2024
Number of treatments	21
Number of replications	3
Sum total number of plots	63
Gross plot area	5 m X 5 m = 25 m ²
Experimental design	Split Plot Design (SPD)
Main plot	Irrigation levels
Sub plot	Nutrient application
Net plot area	25 m ²
Total cultivated area	1575 m ²
Spacing	30 X 10 cm

3. 5.b Treatment details

Main Plot	
I ₀	No post-sowing irrigation
I ₁	One post-sowing irrigation (at 35DAS)
I ₂	Two post-sowing irrigation (at 65DAS)
Sub-Plot	
T ₀	Control
T ₁	(KNO ₃) (15mM) (Seed Priming)
T ₂	Sulphur @60 kg ha ⁻¹ (soil application)
T ₃	Humic acid @12kg ha ⁻¹ (soil application)
T ₄	KNO ₃ (15mM) + Sulphur (60 kg ha ⁻¹) (Seed priming) (Soil application)
T ₅	KNO ₃ (15mM) + Humic acid (Seed priming) (Soil application)
T ₆	Sulphur (60 kg ha ⁻¹) + Humic acid (Seed priming) (Soil application)

3. 5.c Workflow diagram



3.6 Specific features of crop Linseed variety and treatments:

3.6.a. Linseed variety (LC 2063)

- It is a recommended variety of linseed for the irrigated area, particularly for the Punjab region.
- It took around 158 to 160 days to mature, while it bears blue flowers and produces capsules with dark brown seeds.
- Its efficiency in producing oil is high, at around 38%, making it more demanding.
- It is a disease-resistant variety, particularly for the powdery mildew.
- It has a great potential for grain yield, which produces 4-5 qt acre⁻¹ under optimum climatic conditions. Overall, it shows a high potential for disease resistance, grain, and oil yield as well, making them more popular among the farmers under favorable climatic conditions.

3.6.b. KNO₃

The seed priming was conducted with potassium nitrate as a primer, and it was fixed at a specific concentration of 15 mM for a specified period of 5 hours. This specific choice of 15 mM resulted from the fact that this level of concentration is known to lie between 10 mM and 20 mM and improve germination and vigor of a seedling through the level of N and the commencement of metabolism. The selection of a 5-hour period for priming was made to permit the hydration of the seeds without the protrusion of radicles or the loss of reserves. Low-dose priming with KNO₃ has been observed to enhance the performance of the seeds of various crops, both oil and field, as reported by Harris *et al.* (1999) and Ashraf and Foolad (2005), and by Farooq *et al.* (2006).

3.6.c. Sulphur application

Application of sulphur to the soil was done at a dose rate of 60 kg/ha through a soil application method during sowing time. This dose has been adopted due to the higher requirement of sulphur in oilseed crops, the role of these crops in the synthesis of proteins, the generation of chlorophyll, and the biosynthesis of oils containing the sulphur atom. HT has observed that application of sulphur in the dose range between 40 and 60 kg/ha helps in the development of growth components in oilseed crops to an optimum level under sulphur-deficient conditions (Tisdale *et al.*, 1999; Havlin *et al.*, 2014).

3.6.d. Humic acid application

Humic acid was applied at the rate of 12 kg ha⁻¹ at the time of sowing to the soil. It is a well-known fact that the application of humic acid to the soil improves the physico-chemical properties of the soil, increases the availability of nutrients to the plants, and promotes the development of the roots of the plants. It is

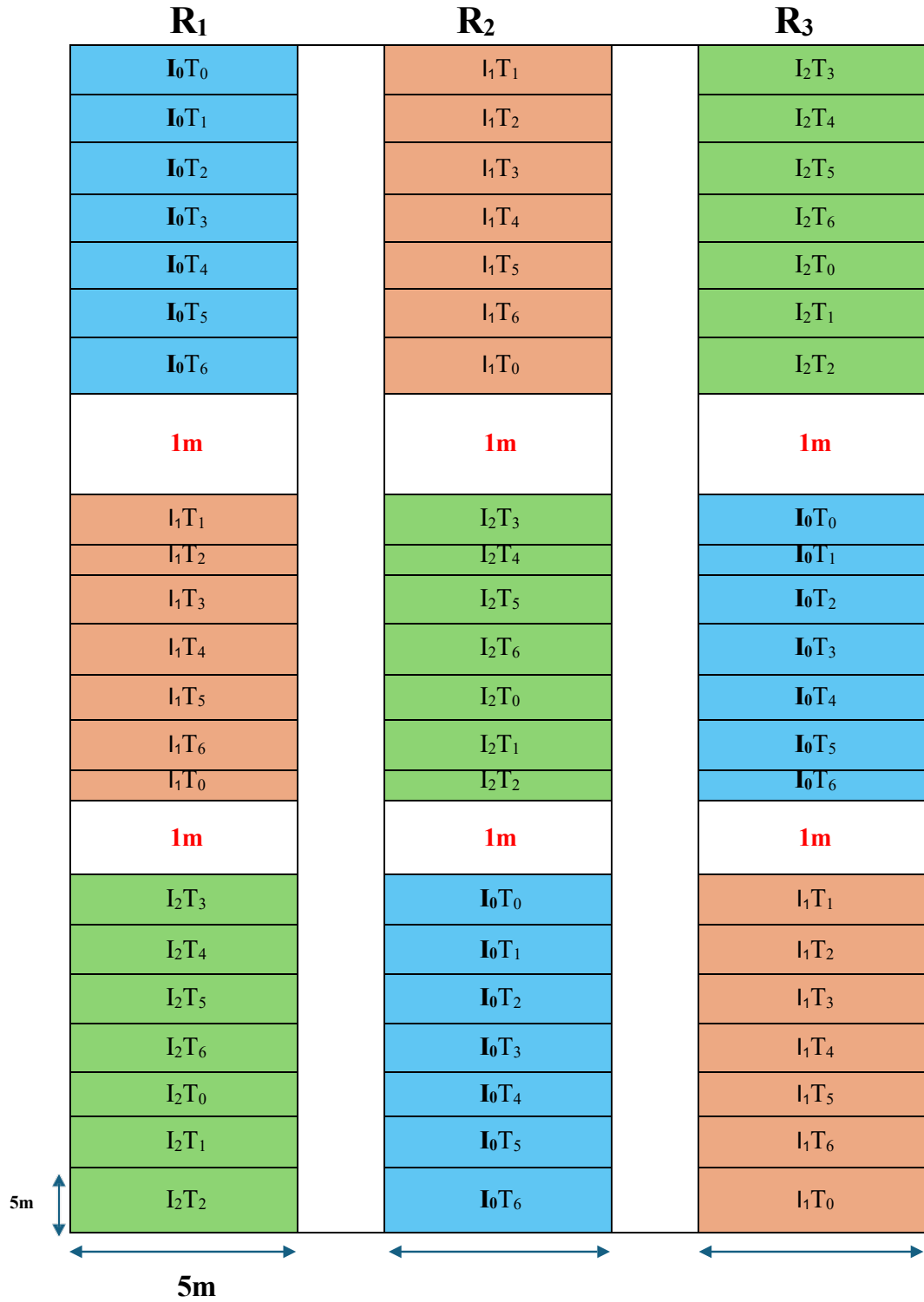
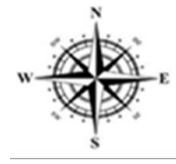
reported from the previous research works that the application of humic acid at the rate of 10-15 kg ha⁻¹ improves the growth of the crops without the occurrence of any nutrient imbalance (Chen and Aviad, 1990; Nardi *et al.*, 2002).

3.6.1 Field preparation and layout of the experiment

The preparation of experimental area underwent comprehensive steps, which included one deep ploughing through a disc plough followed by leveling through a plank. The experimental layout was fixed and constructed before the use of treatments. Each main plot was grouped into seven subplots, and each subplot was considered 5x5m² while, the bund of 30 cm was maintained between the two subplots. The use of treatments, particularly humic acid and sulphur through gypsum, was done @ of 0.247 and 60 Kg ha⁻¹ according to the experimental plan over the field, while the irrigation treatment was applied at critical stages from the tube well 9 of LPU, which was operated through a hybrid mode of solar as well as electric to the linseed plant. The details of the treatment allocation over the layout for the linseed plant are illustrated in Figure 3.4.

3.6.2 Seed priming treatment

As per the research proposal, seed priming was one of the treatments applied to the seed before sowing in the field. Potassium nitrate (KNO₃) was the chemical used @ 15 mM for seed priming, wherein the linseed seeds were invigorated in the respective solution for the desired period at ambient room temperature and dried-back it up to the original weight under a blower by avoiding exposure to direct sunlight.



3.5.d Layout of field experiment

Table 3.6.a: Details of pre- and post-sowing operations

Field preparation			
		2022-2023	2023-2024
1.	a. Ploughing via disc plough	22 October	24 October
	b. Secondary tillage and planking via rotavator	23 October	24 October
	Seed bed preparation and sowing	25 October	27 October
	d. Fertilizer application	25 October	27 October
	e. Pre-emergence herbicide application	26 October	28 October
	f. Thinning	26 November	24 November
	g. Pesticide application	10 December	13 December
2.	Irrigation		
	a. First irrigation	29 November	1 December
	b. Second irrigation	29 December	31 December
3.	Weeding		
	a. First	3 December	5 December
	b. Second	23 December	25 December
4.	Treatment application		
	a. First application	25 October	27 October
5.	Observation taken		
	a. First	24 November	26 November
	b. Second	24 December	26 December
	c. Third	24 January	26 January
5.	Harvesting	31 March	2 April
6.	Threshing and winnowing	7 April	9 April

3.6.3 Fertilization and sowing

In order to fulfill crop nutritional requirements throughout the primary growth period, 25 nitrogen and 16 kg of phosphorus per acre were spread using urea and SSP in accordance with the prescribed fertilizer dosage. The full dose of phosphorus and half of the nitrogen were utilized at the moment of sowing, whereas the balance of the dosage of nitrogen served as top dressing after 30 to 35 DAS. Despite this, humic and sulphur were supplied by soil application through humic acid and gypsum @12 and 60 kg ha⁻¹ to ensure balanced nutrition according to the experimental layout.

3.6.4 Sowing details

Linseed (*Linum usitatissimum* L) var. LC 2063 seed procured from the Punjab Agriculture University (PAU), Ludhiana, Punjab, having genetic purity of 98% and germination of 90%. Seeds are sown in a line sowing method with spacing 30cm X 10cm, at 4- 5cm depth utilizing a seed rate of 25 kg ha⁻¹.

3.6.5 Agronomic Operations

As per the agronomic operations are concerned, to maintain the uniform spacing, gap filling was carried out after 10th days after sowing, while to retain the vigorous crop establishment, thinning was completed at 15th days post the sowing was done. To keep the field weed-free, a single time use of pendimethalin as a pre-emergence herbicide was used, which was followed by hand weeding. The crop was harvested from the ground, followed by the crop being tied up into a bundle and carried over the threshing floor for sun drying, followed by threshing, which was carried out at 18% moisture content to recover the optimal grain from the linseed plant.

3.7 Details of observation recorded

We randomly picked five representative plants from each net plot and labelled them. The labelled plants had their biometric observations written down every so often. We picked those plants separately to check their yield per plant and other yield qualities.

3.7.1 Plant length (cm)

To determine the plant's growth in centimeters at various growth phases, five randomly labeled plants were chosen from each plot. Three separate measurements were taken from the bottom of the plant to the topmost point of the shoot using a meter scale in order to determine the height of the plant. The plant height was represented by the average mean value.

3.7.2 Fresh weight and dry matter accumulation (g plant⁻¹)

The five randomly tagged plants from every plot were removed through the field, subsequently their initial weight was recorded, followed by sun-drying after being cut down from the base. Then they were dehydrated in the oven at $\pm 65^{\circ}\text{C}$ for total of 48 hours to get some consistent weight. The dry mass of plant specimens was recorded using a digital weighing scale. To indicate both the dry and fresh weight in g plant⁻¹ at various growth stages, the mean figure was calculated.

3.7.3 Leaf area (cm² plant⁻¹)

After removing the five arbitrarily marked plants from every plot from the field, the leaf area meter (Model Number-211) was used to measure the plants leaf area at three different growth stages which are 30, 60, and 90 DAS. To measure the leaf area of the linseed plant, the total leaves of a plant were placed on the digital plate of the leaf area meter at a time, which provided the total leaf area expressed as cm² plant⁻¹.

3.7.4 Leaf area index (LAI)

Leaf area index (LAI) is the ratio of leaf area to ground area and was calculated according to (Watson, 1947). To calculate the LAI, the leaf area of different growth stages was divided by the ground area of the linseed plant to determine the photosynthetic efficiency at different growth stages, while the following formula was used to calculate the leaf area index

$$\text{Leaf area index} = \text{Total leaf area (cm}^2\text{)} / \text{Total ground area (cm}^2\text{)}$$

3.7.5 Crop growth rate (g m⁻² day⁻¹)

Crop growth rate (CGR) was measured by using the method described by Hunt (2012) at the intervals of 30-60, 60-90 DAS. The measurement of CGR indicates dry matter produced in a unit area each day, which was computed by utilizing the following method.

$$\text{Crop Growth Rate} = \frac{W_2 - W_1}{T_2 - T_1} \times \frac{1}{A} \text{ (g m}^{-2} \text{ day}^{-1}\text{)}$$

Whereas,

W_1 and W_2 are dry weight at T_1 and T_2 T_1 and T_2 are time intervals

A is the representative sample area

3.7.6 Relative growth rate (g g⁻¹ day⁻¹)

Relative growth rate (RGR) was measured by using the method described by Hoffmann and Poorter (2002) at the intervals of 30-60, 60-90 DAS. The dry matter created by one gram of currently present dry matter each day is shown by the RGR measurement. The alteration in the natural logarithm of dry matter accumulation over a given interval was computed using this subsequent formula.

$$\text{Relative Growth Rate} = \frac{\ln W_2 - \ln W_1}{T_2 - T_1} \text{ (g g}^{-1} \text{ day}^{-1}\text{)}$$

Whereas,

W_1 and W_2 are dry weights at T_1 and T_2 T_1 and T_2 are time intervals

3.7.7 Net assimilation rate (g g⁻² day⁻¹)

Net assimilation rate (NAR) was measured by using the method described by Radford (1967) at the intervals of 30-60, 60-90, and 90-145 DAS. The measurement of NAR is an indicator of an increment in dry mass of the plant per unit leaf area per unit time. It was computed by using this

method.

$$\text{Net assimilation rate} = \frac{W_2 - W_1}{T_2 - T_1} \times \frac{\ln A_2 - \ln A_1}{A_2 - A_1} \quad (\text{g g}^{-1} \text{ day}^{-1})$$

Whereas,

W_1 and W_2 represent the dry weights at T_1 and T_2 A_1 and A_2 represent the leaf area at T_1 and T_2

3.8 Crop phenology

3.8.1 Days taken for emergence.

Days taken for the emergence is the number of days it takes for seeds to sprout and emerge after sowing. It was recorded at regular intervals as it reached complete emergence. It depends on many factors, like temperature and moisture present in the soil.

3.8.2 Days for branching

Days to branching were noticed in the linseed plant by counting the visible number of branches on the main stem from each plant, while the observations were made on the pre-tagged plant to ensure more reliable results and the number of visible branches were recorded accordingly. The average value of the data was used to represent the day for the branching.

3.8.3 Days undertaken for 50% flowering

The number of days that passed from the linseed plant's seeding to 50% blooming in each plot was used to calculate the amount of time needed for 50% flowering. Each plot's already-tagged plants were observed, and the data representing 50% flowering was represented by the average.

3.8.4 Days taken for maturity:

The days required for the maturity were determined by counting the days from the sowing of the linseed plant to physiological maturity from the pre-tagged plant in each plot. It was decided that when at least 80-90% of the capsules turned brown and their leaves turned yellow, while average value was used to represent the data of days required for maturity.

3.9 Yield parameters

3.9.1 Number of primary and secondary branches⁻¹

At harvest the five randomly labeled plants total number of branches were counted and average number of branches per plant was calculated and displayed.

3.9.2 Number of capsules plant⁻¹

The number of capsules per plant was calculated by taking the average number of capsules from the five marked plants used for growth monitoring. The entire number of capsules was taken into account and then subdivided by the number of plants to determine how many capsules each plant would have.

3.9.3 Weight of seed per capsule (g)

The number of seed yield per capsule in pre-tagged plants was counted manually and their average value represents the treatment-wise details of seed yield per capsule of linseed.

3.9.4 Test weight (g)

Test weight was measured by manually counting 1000 seeds from a representative pre-tagged sample of each treatment and weighing them using a digital weighing balance. The average weight of 1000 seeds was used to express the test weight of linseed in grams.

3.9.5 Harvest index (%)

The economic yield (seed yield) divided by the biological yield (total of seed and stover production) was the linseed harvest index. The resulting value was expressed as a percentage, following the method outlined by Donald and Hamblin (1976)

$$\text{Harvest index (\%)} = \text{Economic Yield} / \text{Biological Yield} \times 100$$

3.9.6 Biological yield (q ha⁻¹)

The biological yield was computed and presented as above-ground biomass, including straw and seed harvested from every net plot in kilograms per plot. Later, the value is converted into kg ha⁻¹, while the value given below was utilized to compute the value of biological yield kg ha⁻¹.

$$\text{Biological yield (kg ha}^{-1}\text{)} = \text{Seed yield (kg ha}^{-1}\text{)} + \text{Stover yield (kg ha}^{-1}\text{)}$$

3.9.7 Seed yield (q ha^{-1})

The net plot harvest of material was used to determine the seed yield and stover yield. The sundried material was used to separate the grain and stover in linseed treatment-wise net and recorded their weight separately in kg plot^{-1} and made it into Kg ha^{-1} .

3.9.8 Oil content and oil yield (q ha^{-1})

Quantification of oil content (%) was done as per Danlami *et al.* (2015) using the Soxhlet extraction method.

Procedure of oil extraction:

- a- The samples of linseed seeds were dried in an oven at a standard temperature of 65°C for 3 to 4 hours to remove moisture content present in the samples.
- b- A 500 g of finely ground sample was placed in an extraction thimble and inserted into the chamber.
- c- A round-bottom flask (pre-weighed) was connected to the Soxhlet apparatus, followed by 200 ml of hexane solvent.
- d- The sample was heated, and oil extraction was carried out by solvent evaporation, condensation, and dripping into the thimble for 6 to 8 hrs until complete extraction.
- e- The round-bottom flask was carefully removed from the apparatus and allowed to cool.
- f- The oil content was computed after recording the weight of the flask using the following formula:

Weight of extracted oil (g)

$$\text{Oil content (\%)} = \frac{\text{Weight of extracted oil (g)}}{\text{Weight of sample (g)}} \times 100$$

The oil yield was calculated in kg ha^{-1} by using the following formula.

$$\text{Oil yield (kg ha}^{-1}\text{)} = \text{Oil content (\%)} \times \text{seed yield (kg ha}^{-1}\text{)}$$

3.10 Physiological observations

3.10.1 Relative water content (%)

From each experimental plot, fresh leaves of linseed weighing 500 mg were randomly sampled and

gently cleaned to remove surface impurities. The initial fresh weight (FW) of the samples was recorded immediately after collection. The leaf samples were then immersed in distilled water and kept at ambient laboratory conditions for a period of six hours to allow full hydration. After incubation, excess surface moisture was carefully removed using blotting paper, and the turgid weight (TW) was noted. Subsequently, the samples were dried treatment-wise in a hot air oven maintained at 70°C for 48 hours or until a stable dry weight was obtained, which was recorded as dry weight (DW). The relative water content (%) was calculated using the following equation given by Wetherly (1962).

$$\text{RWC (\%)} = \frac{\text{Fresh weight (mg)} - \text{Dry weight (mg)}}{\text{Turgid weight (mg)} - \text{Dry weight (mg)}} \times 100$$

3.10.2 Membrane stability index (%) and membrane injury index (%)

Procedure

At the designated crop growth stage, healthy and fully developed leaves were sampled from the experimental field. For evaluating cellular membrane integrity, 500 mg of fresh leaf material was accurately weighed and placed in test tubes containing 10 mL of double-distilled water. The samples were processed in two independent sets. In the first set, test tubes were maintained in a temperature-controlled water bath at 40 °C for 30 minutes, after which the electrical conductivity of the leachate was recorded as C₁. The second set was then subjected to boiling at 100 °C for 10 minutes to ensure complete release of electrolytes from the tissues, and the conductivity was measured as C₂. Electrical conductivity readings were obtained using a digital conductivity meter (ME977-C, Max Electronics, India).

To calculate the MSI and MII, the following formula was used, described by Premchandra *et al.*, (1990).

$$\text{Membrane stability index (\%)} = [1 - C_1/C_2] \times 100 \quad \text{Membrane injury index (\%)} = [C_1/C_2] \times 100$$

3.11 Biochemical parameters

3.11.1 Chlorophyll a, b, and total (mg g⁻¹)

Procedure

- a- Fully fresh leaf samples of linseed (100mg) were collected from the field treatment- wise
- b- Leaf samples were cleaned and chopped into fine pieces after removing the midrib.
- c- The leaf samples were homogenized using 20ml of 80% acetone in a pestle and mortar.
- d- Samples were centrifuged using the centrifuging instruments at 5000 rpm for 10 minutes to segregate the aliquot from the residue.
- e- Supernatant was transferred into 100ml of volumetric flask and made up their volume upto 100ml using 80% acetone.
- f- Optical density of supernatant was recorded at 645 and 663, using spectrophotometer.

The following formula given by Arnon (1949) was used to calculate the chlorophyll (a), (b), and total chlorophyll in mg g⁻¹.

Chlorophyll 'a' (mg/g fresh weight) = $12.7(A_{663}) - 2.69(A_{645}) \times V1000 \times W$

Chlorophyll 'b' (mg/g fresh weight) = $22.9(A_{645}) - 4.68(A_{663}) \times V1000 \times W$

otal chlorophyll (mg/g fresh weight) = $20.2(A_{645}) + 8.02(A_{663}) \times V1000 \times W$

Whereas,

V represents the final volume of the extract W represents the fresh weight of the leaves A represents the absorbance at the specific wavelength.

3.11.2 Proline content (µg g⁻¹ FW)

The estimation of proline content from the leaves of linseed at different growth stages was carried out by using the methods of Bates *et al.*, (1973).

Reagents

- a- Acidic ninhydrin reagent (Dissolve 1.25 g of ninhydrin in 30 ml of glacial and 20 ml of 6M phosphoric acid)
- b- 3% Aqueous sulphosalicylic acid

- c- Glacial Acetic Acid
- d- Toluene

Standard proline

solution Procedure:

- a- A mortar and pestle were employed to blend 100 mg of leaf material in 10 ml of 3% sulphosalicylic acid.
- b- After centrifuging it for ten minutes at 6000 rpm, the resulting product was gathered
- c- Two milliliters of the extract and two milliliters of glacial acetic acid and ninhydrin reagent were placed in a test tube.
- d- The reaction mixture was heated up for 30 minutes at 100°C in a vessel of water until brick- like hue formed.
- e- Added 5 mL toluene to the reaction mixture and then transferred to a separating funnel.
- f- Recorded optical density at 520 nm.
- g- The measure of proline was calculated by utilizing the standard curve of proline

3.12. Soil moisture

The moisture content of the soil profile up to 15 cm depth was determined using the gravimetric method, followed by the volumetric method, and calculation of soil water moisture (mm). The soil up to 15 cm was collected using a soil auger. In the gravimetric method, soil moisture content was calculated by measuring the weight difference between the fresh soil sample and the oven-dried soil sample using the formula as per Black *et al.* (1965).

i. By the gravimetric method

$$\text{Soil Moisture Content (\%)} = \frac{\text{FW} - \text{DW}}{\text{DW}} \times 100$$

Wherein,

FW represents the fresh weight of soil

DW represents the oven-dry weight of soil (105 °C for 24 hours)

ii. By the volumetric method (Hillel 1998)

$$\text{VMC\%} = \text{GMC\%} \times \text{Bulk density}$$

iii. **Soil Moisture (mm)**

Finally, the total soil water moisture (mm) at 15 cm depth was determined using the formula as per Jury and Horton (2004).

Soil Moisture (mm) = VMC (%) / 100 × Soil layer depth (mm),

where the soil layer depth is 30 cm (300 mm).

3.13. Economic appraisal of treatment

The economic analysis of various treatments was conducted based on the mean yield values. The cost of cultivating linseed was determined by considering the expenses associated with the inputs utilized. This included calculating the power and labor requirements for different operations like ploughing, intercultural activities, plant protection measures, harvesting, and threshing, all computed per hectare using the prevailing rates at the research farm, Lovely Professional University, Punjab. The costs of seeds, fertilizers, and pesticides were considered based on market prices at the respective year's minimum support price (MSP).

3.13.1 Gross returns

Considering the current market values, the total output of linseed, which includes both seeds and straw, was transformed into gross returns in rupees per hectare.

The following formula is used to determine gross returns

$$\text{Gross return} = \text{Price of Stover} \times \text{stover yield} + \text{Price of Seed} \times \text{seed yield}$$

3.13.2 Net returns

The net profit per hectare was calculated by deducting the whole expenditure on cultivation out of the gross return. The overall return was computed using the following formula.

$$\text{Net returns} = \text{Gross returns} - \text{Total cost of cultivation}$$

3.13.3 Benefit: cost ratio (B: C ratio)

The following formula was used to calculate the B: C ratio, which was then expressed as rupees per rupee invested.

B: C ratio = Net returns / total cost of production

3.14 Statistical Analysis

A split-plot design was used to assess the significance of treatments across different parameters following the methodology outlined by Cochran and Cox (1967). The experimental data collected during the research study were subjected to statistical analysis through analysis of variance (ANOVA) at a significance level of $p \leq 0.05$, as described by Gomez and Gomez (1984), using the STAR (Statistical Tools for Agriculture Research).

PHOTO GALLERY

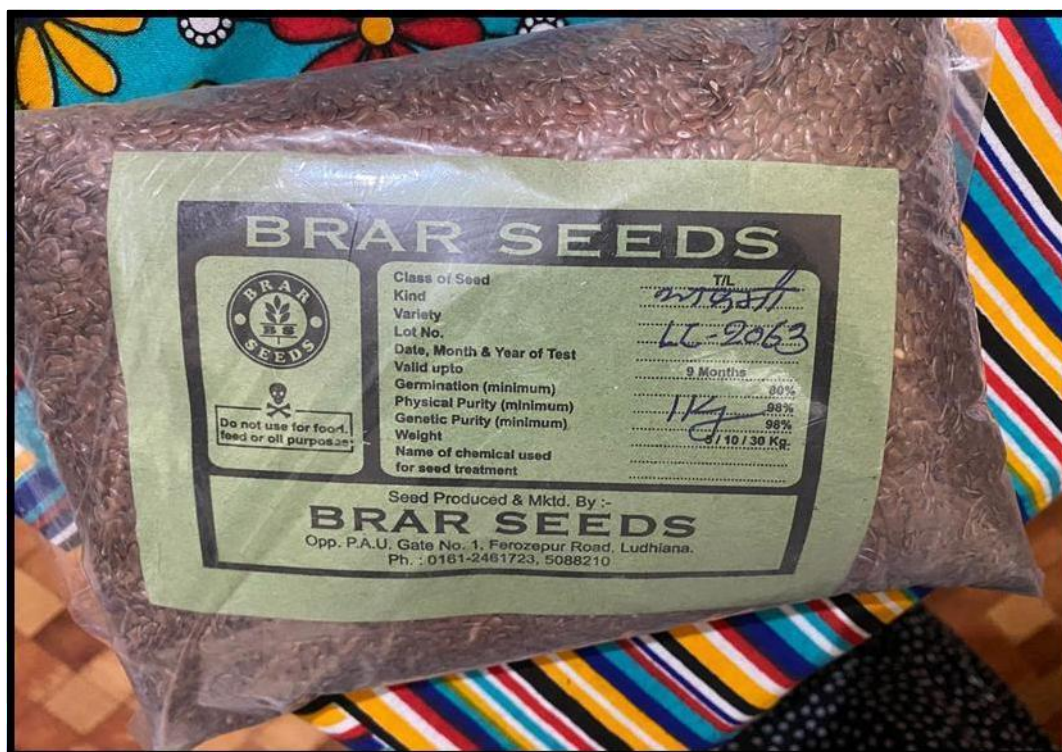


Image 1: Seeds of linseed procured from PAU



Image 2: Seed priming with KNO₃ @15mM concentration



Image 3: Water soluble humic acid 98% pure



Image 4: Field preparation before the sowing



Image 5: Seed sowing (Linseed) at the research farm of LPU



Image 6: Life-saving irrigation before sowing



Image 7: First hand weeding after the emergence



Image 8: Second-hand weeding at the flowering stage



Image 9: Irrigation over the field according to the schedule



Image 10: measurement of plant height at initial stage of growth



Image 11: Soil analysis for the pH and EC



Image 12: Linseed plant at 50% flowering



Image 13: Measuring leaf area (Leaf area meter)



Image 14: Sample preparation for the analysis of MSI and MII



Image 15: Sample preparation for the analysis of proline content from the leaf of linseed



Image 16: Sample processing for the analysis of proline content



Image 17: Recording the optical density using a spectrophotometer



Image 18: Number of seeds in a capsule of linseed



Image 19: Harvesting of linseed

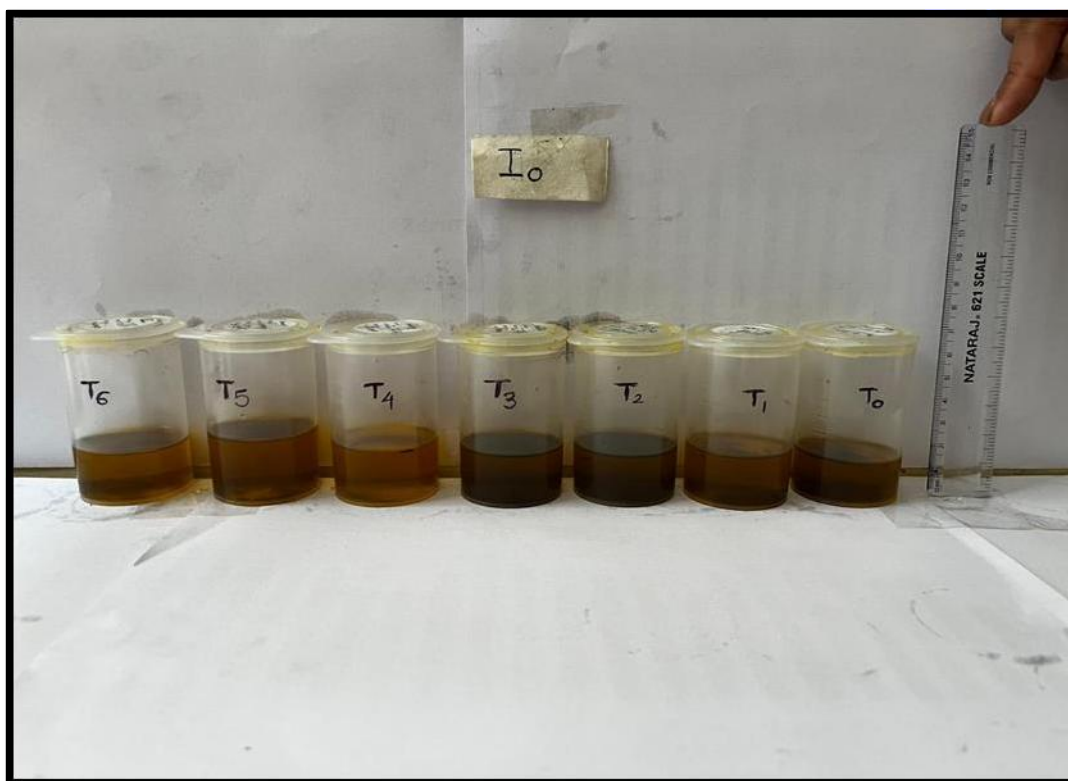


Image 20: Oil estimated irrespective of main and subplot treatment

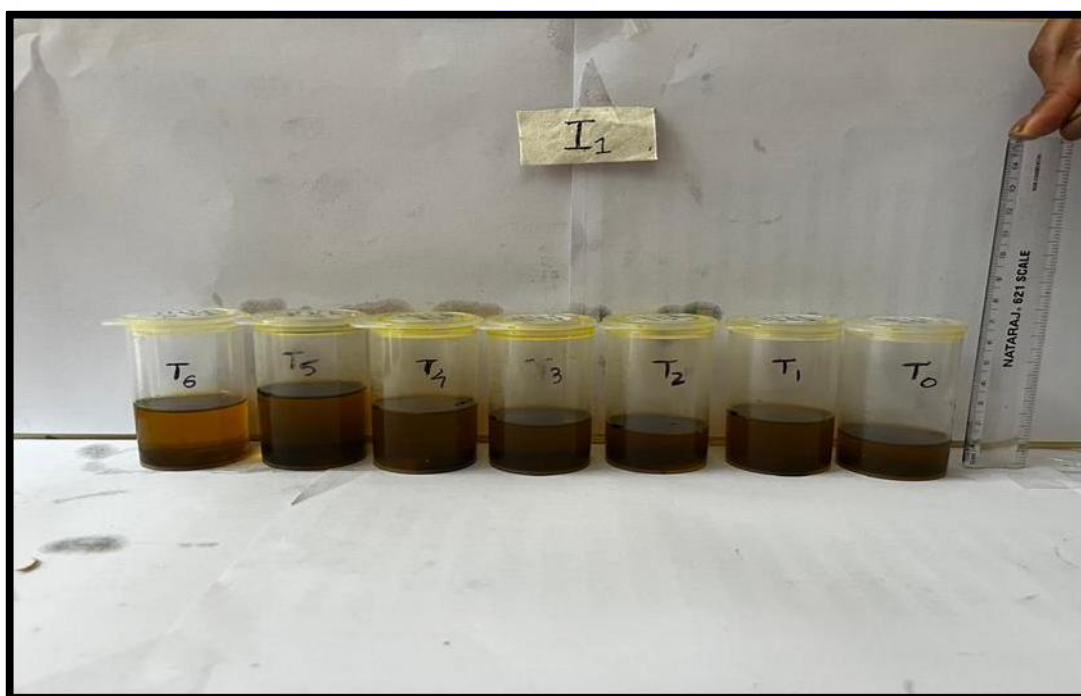


Image 21: Oil estimated irrespective of the main and subplot treatment

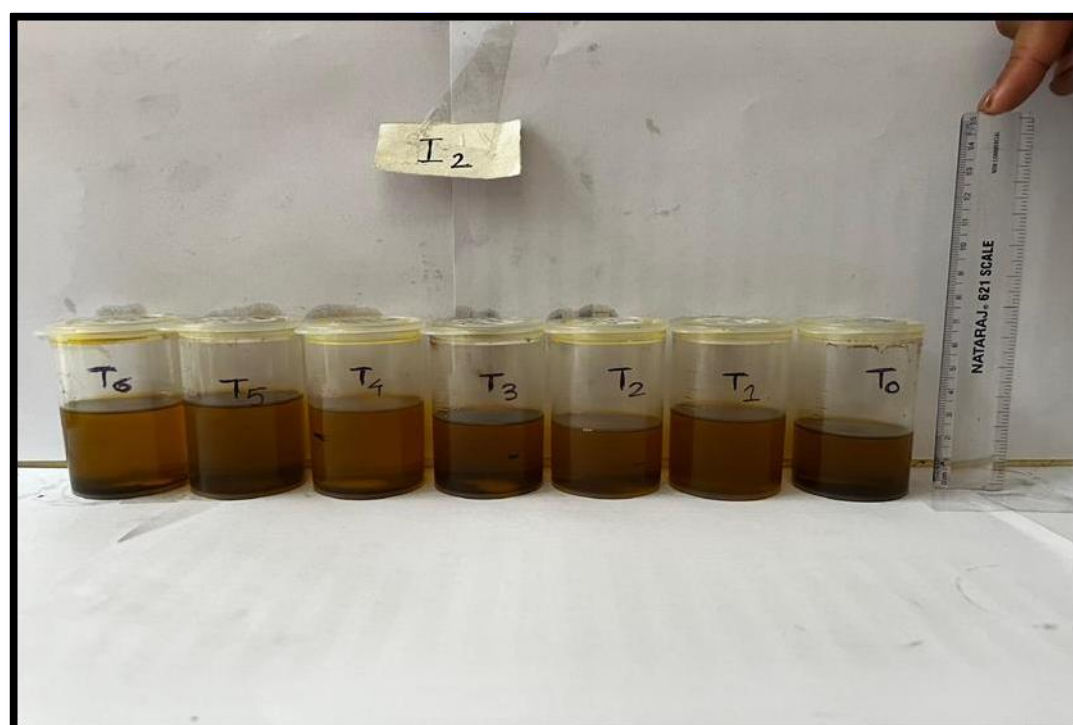


Image 22: Oil estimated irrespective of the main and subplot treatment

RESULT AND DISCUSSION

4.1 Growth parameter

4.1.1 Effect of seed priming, humic acid, and sulphur application on plant height of linseed under different irrigation intervals.

Plant height of linseed was significantly influenced by irrigation levels and nutrient application at different growth stages during both the experimental years (2022–23 and 2023–24) (Table 4.1.2a and 4.1.2b).

Effects of irrigation level on plant height

The effect of frequency of irrigation on plant height increased with frequency of irrigation up to 30 days after sowing. Irrigation interval I_2 produced the highest plant height (16.54 cm), which was comparable to that produced by irrigation interval I_1 (16.50 cm), but both were significantly greater than the height (16.49 cm) of plants grown under irrigation interval I_0 , because this height was more than the critical difference (CD) of 1.02 cm ($P=0.05$). These patterns were also noted through 60 days after sowing, 90 days after sowing, and at harvest. At harvest, plant height was greatest for I_2 (89.99 cm), followed by I_1 (89.28 cm), and both I_1 and I_2 were greater than I_0 (86.32 cm), for which the CD ($P=0.05$) was 0.63 cm at harvest.

The impact of irrigation on plant height was not clear in the early stages of crop growth (e.g., 30 DAS). The fact that there were no significant differences in average height at this early time suggests that all irrigation treatments provided equal advantages during the initial establishment of the crops. After 60 DAS, however, the effect of irrigation on plant height was apparent. Irrigation treatment I_2 produced the tallest plants (82.66 cm) at harvest, significantly greater than treatment I_0 , which had an average of 76.92 cm. The difference in average height between treatments I_2 and I_0 exceeded the critical difference (2.48 cm) ($P=0.05$), but the average height of treatment I_1 was not significantly different from treatment I_2 .

Effect of nutrient application

The impact of nutrient treatments was significant on the height of plants at each stage of development over both years. The tallest plants at the time of harvest in 2022-23 were produced with T_5 , which consisted of KNO_3 and humic acid, at 95.24 cm. This value was significantly greater than all other treatments and was found to exceed the CD of 1.45 cm at $P=0.05$, followed by T_4 (KNO_3 + sulphur), which measured 92.76 cm, and T_6 (sulphur + humic acid), which measured 90.50 cm, both of which were significantly taller than the plants grown using single nutrients. The minimum height recorded was in the control treatment (T_0) at 80.64 cm.

In the 2023–24 growing season, T_5 continued this trend by having the tallest plants (84.55 cm) at harvest, which were significantly greater than T_0 (73.96 cm) or the other treatments in this study. The minimum

difference was greater than the CD ($P=0.05$) of 3.73 cm. Additionally, the combined nutrient treatments consistently produced greater plant growth than either individual application of these same nutrients at all stages of development.

Interaction effect ($I \times T$)

While the interaction between irrigation levels and nutrient application was found to be insignificant for most growth periods for both years, an interaction of statistical significance (CD $P=0.05$) was noted on day 60 after sowing (DAS) during the 2023-24 growing season, with a mean difference of 2.76 cm. It is important to note that, in this instance, the tallest plants resulted from the $I_2 \times T_5$ combination of treatments at 40.85 cm. Based upon their height, the tallest plants for $I_2 \times T_5$ were significantly taller than most other treatment combinations and were followed closely by $I_2 \times T_4$ and $I_2 \times T_6$ (40.55 cm and 39.84 cm, respectively), thereby showing the benefit of using integrated nutrient applications under adequate moisture conditions.

At 30 DAS, plant height was similar among irrigation types in both years because there was no irrigation before 30 DAS, and there were favorable weather conditions during early development of the crop; October – November has moderate temperatures, high relative humidity, and little rain (hence a low crop water requirement and low evaporative demand). Under these conditions, residual soil moisture would be adequate for early vegetative development, which would lead to similar plant height among means of irrigation (Saxena and Rath, 2020). At this stage, some differences in plant height were found among treatments; however, the interaction of treatment and irrigation did not show significant differences because there was an equal supply of moisture. From 60 DAS onwards, irrigation and nutrient effects on plant height became more evident. With the onset of active vegetative growth, crop water demand increased, and the application of irrigation improved soil moisture availability under higher irrigation levels. Adequate moisture under I_2 and I_1 promoted cell elongation and vegetative growth, resulting in taller plants compared to I_0 . These differences were further reflected at 90 DAS and at harvest, when rising temperature and lack of rainfall increased moisture stress under lower irrigation levels. Combined nutrient application, particularly KNO_3 with humic acid, consistently produced taller plants by improving nutrient uptake, photosynthetic activity, and overall plant vigor. The significant interaction observed at 60 DAS indicates that nutrient efficiency was higher under adequate soil moisture conditions. These findings are in agreement with earlier studies emphasizing the importance of proper irrigation and integrated nutrient management for improved crop growth (Yadav and Meena, 2019; Kumar *et al.*, 2021b; Sharma *et al.*, 2018).

Table 4.1.1.a: Effect of seed priming, humic acid, and sulphur application on plant height of linseed under different irrigation intervals (2022-23 and 2023-24)

Plant height (cm)								
Treatment	30 DAS		60 DAS		90 DAS		At harvest	
	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24
Main plot: Irrigation level (I)								
I ₀	16.49	14.29	38.07	34.92	71.68	65.65	86.32	76.92
I ₁	16.50	14.49	39.70	37.67	74.49	69.97	89.28	81.24
I ₂	16.54	14.53	40.31	38.46	75.15	71.40	89.99	82.66
SEm±	1.02	0.21	0.39	0.39	0.15	0.63	0.16	0.63
CD (P=0.05)	NS	NS	1.52	1.52	0.60	2.48	0.63	2.48
Subplot: Nutrient application (T)								
T ₀	11.86	10.89	34.74	35.51	66.70	62.70	80.64	73.96
T ₁	16.26	13.89	38.31	35.91	73.97	67.83	89.03	79.09
T ₂	15.72	13.90	38.56	35.49	70.29	65.26	85.01	76.53
T ₃	16.03	14.97	39.79	37.18	71.91	69.92	86.53	81.18
T ₄	18.02	15.63	41.06	38.25	77.92	72.49	92.76	83.76
T ₅	18.87	16.36	42.68	39.11	79.96	73.29	95.24	84.55
T ₆	18.06	15.41	40.38	37.65	75.67	71.57	90.50	82.84
SEm±	0.29	0.41	0.49	0.56	0.50	1.30	0.51	1.30
CD (P=0.05)	0.85	1.18	1.39	1.59	1.44	3.73	1.45	3.73
Interaction I × T								
SEm±	0.54	0.69	0.84	0.96	0.87	2.25	0.88	2.25
CD (P=0.05)	NS	NS	NS	2.76	NS	NS	NS	NS
Interaction T × I								
SEm±	0.72	0.56	1.02	1.02	0.41	1.67	0.43	1.67
CD (P=0.05)	NS	NS	NS	2.74	NS	NS	NS	NS

Note:

- 1- I₀: No post sowing irrigation, I₁: Post sowing irrigation one, I₂: Post sowing irrigation two,
- 2- T₀: Control, T₁: Potassium Nitrate, T₂: Sulphur, T₃: Humic acid, T₄: KNO₃ + S, T₅: KNO₃ + HA, T₆: Sulphur + HA
- 3- SEm± represents the standard error of the mean, and C.D. represents the Critical difference.

Figure 4.1.1 (a): Effect of seed priming, humic acid, and sulphur application on plant height of linseed under different irrigation intervals 2022-23

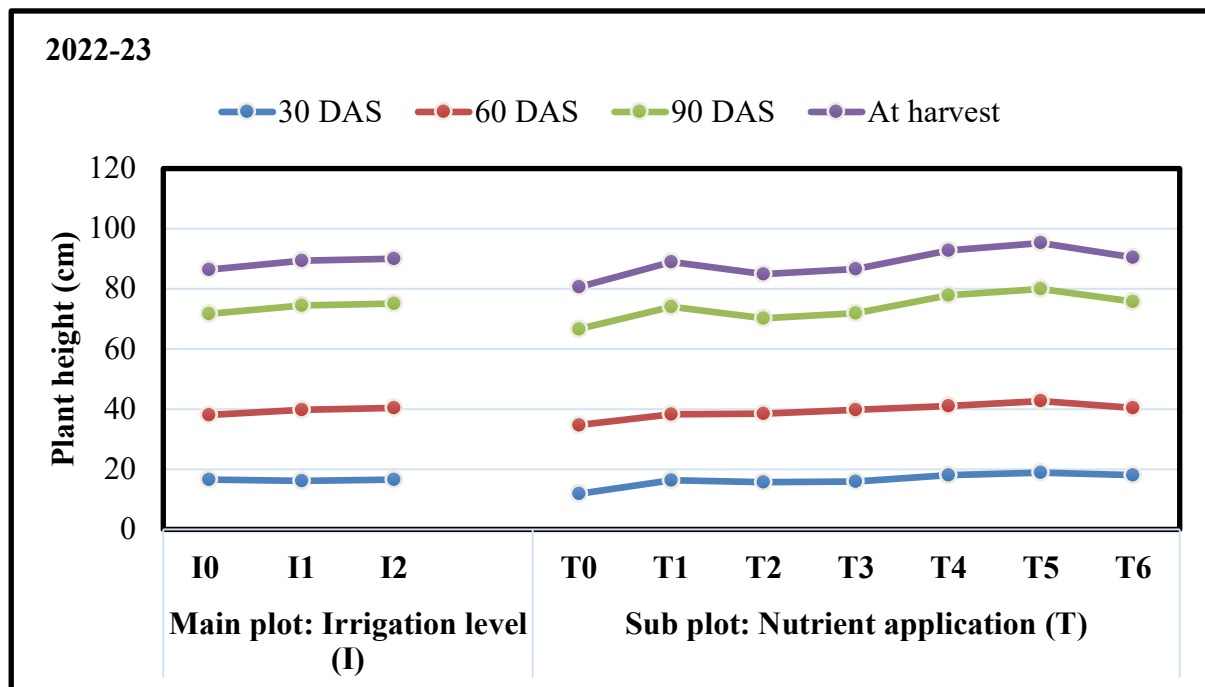


Figure 4.1.1 (b): Effect of seed priming, humic acid, and sulphur application on plant height of linseed under different irrigation intervals 2023-24.

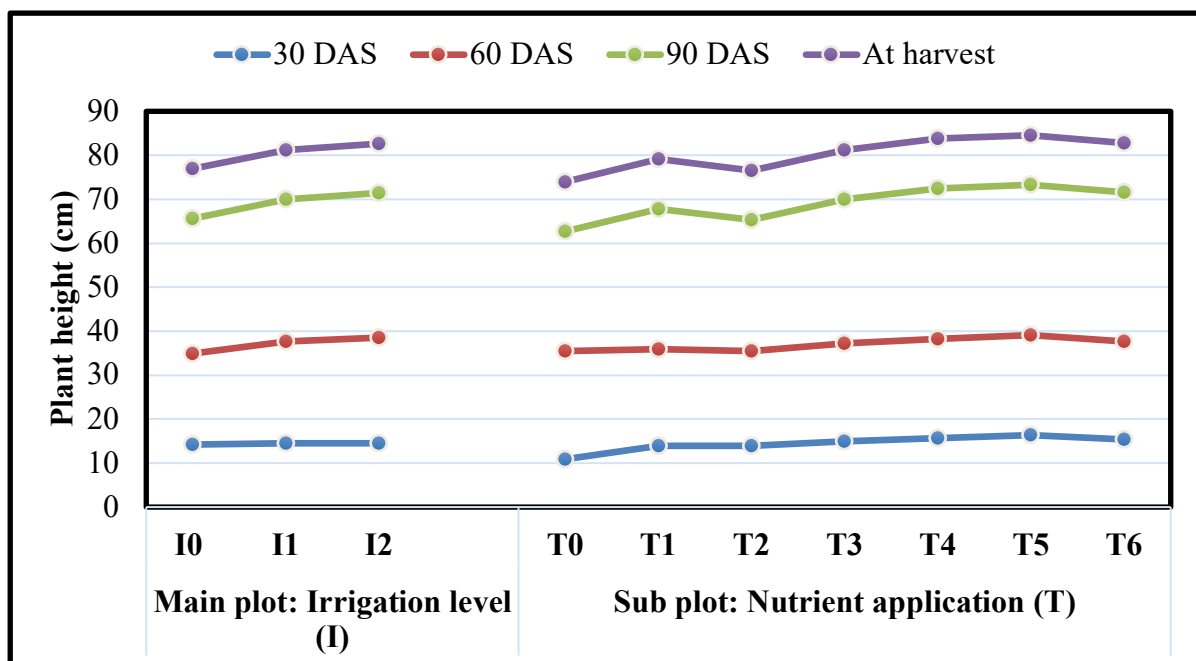


Table 4.1.1 (b): Interaction effect of seed priming, humic acid, and sulphur application on plant height at 60 DAS of linseed under different irrigation intervals (2023-24)

60 DAS				
	2023-24			
	I₀	I₁	I₂	Mean
T ₀	31.28	40.15	35.10	35.51
T ₁	35.34	35.62	36.79	35.91
T ₂	34.43	35.42	36.63	35.49
T ₃	35.59	36.47	39.48	37.18
T ₄	35.62	38.58	40.55	38.25
T ₅	36.55	39.94	40.85	39.11
T ₆	35.62	37.48	39.84	37.65
Mean	34.92	37.67	38.46	
SEm±	0.96			
CD (P=0.05)	2.76			

Note:

- 1- I₀: No post sowing irrigation, I₁: Post sowing irrigation one, I₂: Post sowing irrigation two,
- 2- T₀: Control, T₁: Potassium Nitrate, T₂: Sulphur, T₃: Humic acid, T₄: KNO₃ + S, T₅: KNO₃ + HA, T₆: Sulphur + HA

4.1.2 Effect of seed priming, humic acid, and sulphur application on fresh weight of linseed under different irrigation intervals.

Fresh weight of linseed was significantly influenced by irrigation levels and nutrient application at various growth stages during both years of experimentation (2022–23 and 2023–24), as presented in Table 4.1.2.a.

Effect of irrigation levels on fresh weight

During the initial growth stage (30 DAS), irrigation levels did not exert a significant effect on fresh weight in either year, as the differences among treatments were non-significant. This indicates uniform early biomass accumulation under all irrigation regimes.

At 60 DAS in 2022-23, there were significant effects of irrigation on fresh weight and the highest fresh weight was found in treatment I₂ (7.14 g plant⁻¹), which did not differ statistically from treatment I₁ (6.92 g plant⁻¹) and both treatments were significantly higher than I₀ (5.94 g plant⁻¹), since the difference between I₂ and I₀ was greater than the Critical Difference (CD) at the 5% level, which was 0.56 g plant⁻¹. In contrast to 2022-23, there were no significant differences between irrigation types regarding fresh weight at 60 DAS in 2023-24.

The irrigation types had substantial influences on fresh weight at 90 DAS in both years. For 2022-23, the highest fresh weight was recorded as treatment I₂ (23.80 g plant⁻¹) and was significantly greater than I₀ (19.60 g plant⁻¹), and the difference exceeded the CD of 2.55 g plant⁻¹ at 5%. Similarly, in 2023-24, the highest fresh weight was treatment I₂ (24.20 g plant⁻¹) and was significantly greater than I₀ (19.27 g plant⁻¹) and exceeded the CD of 0.77 g plant⁻¹ at 5%. In addition, I₁ had no significant difference from I₂.

During harvest, fresh weight exhibited a comparable trend. In 2022–23, I₂ exhibited the highest fresh weight at 31.89 g plant⁻¹, followed by I₁ at 30.09 g plant⁻¹, both significantly surpassing I₀, which recorded 27.64 g plant⁻¹, as the difference exceeded the critical difference (CD) of 2.54 g plant⁻¹ at P = 0.05. In 2023–24, I₂ (30.60 g plant⁻¹) exhibited a significantly greater fresh weight compared to I₀ (25.72 g plant⁻¹), with a critical difference (P = 0.05) of 0.67 g plant⁻¹.

Effect of nutrient application on fresh weight

Fresh weight was significantly affected by the application of nutrients throughout both years of the experiment at each of the growing stages measured. The highest levels of fresh weight (2.32 g plant⁻¹ in 2022-23 and 2.28 g plant⁻¹ in 2023-24) occurred 30 days after seeding (30 DAS) for T₅ (KNO₃ + Humic acid) and were significantly higher than those of other treatments, which had standard errors greater than or equal to the least significant difference (CD P=0.05) of 0.26 g plant⁻¹ (2022-23) and 0.15 g plant⁻¹ (2023-24). The lowest level of fresh weight recorded was in the control treatment (treatment 0).

At 60 DAS, T₅ continued to show the highest fresh weight (9.08 g plant⁻¹ in 2022-23 and 8.23 g plant⁻¹ in 2023-24), which was significantly higher than that of the other treatments as the difference was greater than

the respective CD ($P=0.05$) for each of the two years (0.68 for 2022-23 and 1.08 for 2023-24). T₄ (KNO₃ + Sulphur) and T₆ (Sulphur + Humic Acid) were next in terms of fresh weight and suggested the benefit of using a combination of nutrients rather than just one nutrient alone.

Similar trends were noted for the two harvests at 90 DAS and harvest. Results from 2022-23 showed that T₅ produced the fresh weight per plant at harvest (33.67 g), which was substantially greater than the other treatments and exceeded the critical difference (CD) of 1.18 g/plant at a significance level of 0.05. In 2023-24, T₅ also produced more fresh weight than any other treatment group (31.39 g) and greater than the control (24.22 g). The CD was 1.32 g per plant at a significance level of 0.05. With all growth intervals measured, nutrient combinations outperformed the application of individual nutrients for increased plant production.

Interaction effect ($I \times T$)

The evidence does not indicate there was no interaction of irrigation levels and application of nutrients during any of the year's growth stages as shown by the lack of significance for the CD values at all growth stages. Therefore, it seems evident that the fresh weight accumulation in linseed plants was predominantly the result of the main effects of both nutritional application and irrigation acting independently.

In both years, there was no significant difference in the fresh weight of linseed from different irrigation treatments at 30 days after seeding (DAS) because irrigation had not been applied up to this point, and weather conditions were favourable with moderate temperatures, sufficient relative humidity, and little rainfall, showing a low crop water requirement and uniformity in soil moisture available to crops. Irrigation had a significant effect on fresh weight between 60 DAS and harvest due to an increase in the demand for water from the crops during the period of active vegetative growth as well as the provision of sufficient moisture by the higher irrigation levels (I₂ and I₁) to promote cell expansion, photosynthesis and biomass accumulation over the non-irrigated treatment (I₀). The effects of these treatments were shown again at both 90 DAS and harvest because of increasing temperatures and vapor pressure deficits (evaporative demand) due to the lack of rainfall since planting. The treatments produced the greatest fresh weight of linseed consistently through the improved absorption of nutrients, osmotic regulation within the plants, and improved plant growth as a widespread positive effect of nutrient applications regardless of the irrigation level (no significant interaction between the treatment and irrigation treatments). Similar results have been shown in oilseed crops by other researchers using an integrated nutrient and irrigation management strategy (Yadav and Meena, 2019; Kumar *et al.*, 2021b; Sharma *et al.*, 2018).

Table 4.1.2.a: Effect of seed priming, humic acid, and sulphur application on fresh weight of linseed under different irrigation intervals (2022-23 and 2023-24)

Fresh weight (g plant⁻¹)								
Treatment	30 DAS		60 DAS		90 DAS		At harvest	
	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24
Main plot: Irrigation level (I)								
I₀	1.11	1.07	5.94	5.71	19.60	19.27	27.64	25.72
I₁	1.19	1.09	6.92	6.11	22.05	21.18	30.09	27.62
I₂	1.15	1.14	7.14	6.38	23.80	24.20	31.89	30.60
SEm±	0.04	0.05	0.14	0.14	0.65	0.20	0.65	0.17
CD (P=0.05)	NS	NS	0.56	NS	2.55	0.77	2.54	0.67
Sub plot: Nutrient application (T)								
T₀	0.71	0.73	4.39	3.86	18.43	17.78	26.47	24.22
T₁	0.87	0.87	6.27	5.59	20.44	20.72	28.48	27.16
T₂	0.81	0.84	5.97	5.12	19.15	19.03	27.19	25.47
T₃	0.92	0.89	6.57	6.04	22.01	22.39	30.16	28.72
T₄	1.64	1.82	7.34	7.14	24.01	23.35	32.05	29.80
T₅	2.32	2.28	9.08	8.23	25.63	24.95	33.67	31.39
T₆	1.28	0.99	7.04	6.49	23.06	22.65	31.10	29.10
SEm±	0.09	0.05	0.24	0.37	0.42	0.43	0.41	0.46
CD (P=0.05)	0.26	0.15	0.68	1.08	1.21	1.23	1.18	1.32
Interaction I × T								
SEm±	0.16	0.09	0.41	0.65	0.73	0.74	0.71	0.80
CD (P=0.05)	NS	NS	NS	NS	NS	NS	NS	NS
Interaction T × I								
SEm±	0.10	0.12	0.37	0.37	1.71	0.51	1.71	0.44
CD (P=0.05)	NS	NS	NS	NS	NS	NS	NS	NS

Note:

- 1- **I₀**: No post sowing irrigation, **I₁**: Post sowing irrigation one, **I₂**: Post sowing irrigation two,
- 2- **T₀**: Control, **T₁**: Potassium Nitrate, **T₂**: Sulphur, **T₃**: Humic acid, **T₄**: KNO₃ + S, **T₅**: KNO₃ + HA, **T₆**: Sulphur + HA

Figure 4.1.2 (a): Effect of seed priming, humic acid, and sulphur application on fresh weight of linseed at different irrigation intervals (2022-23)

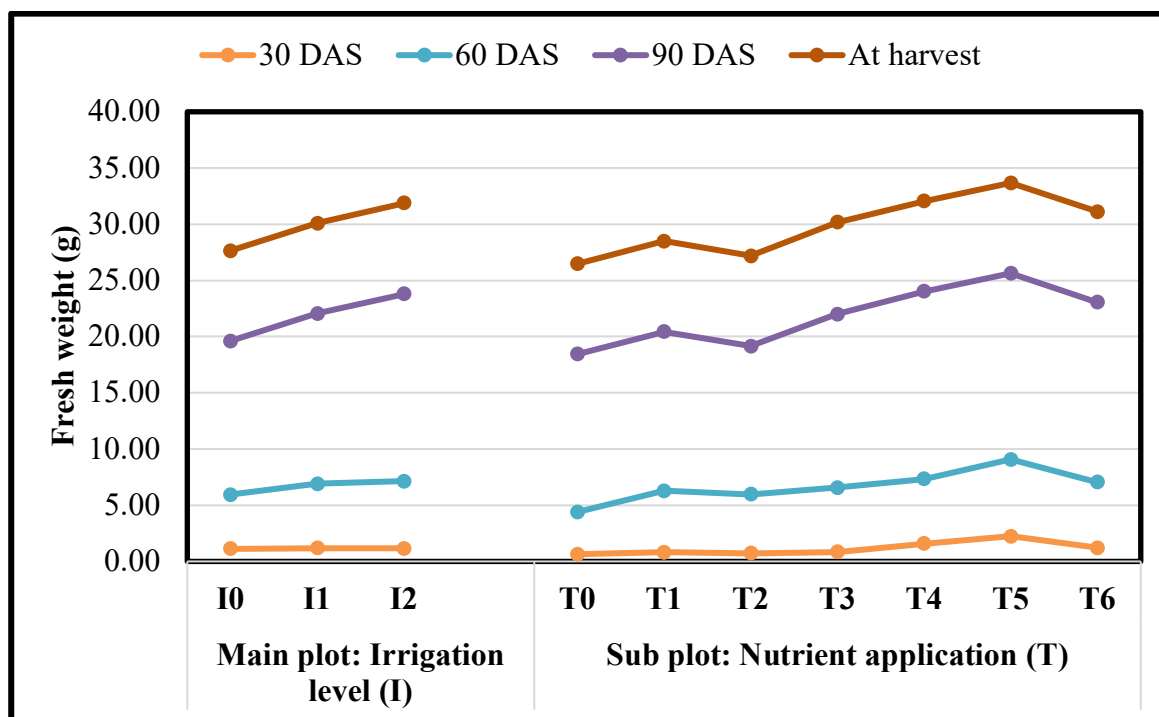
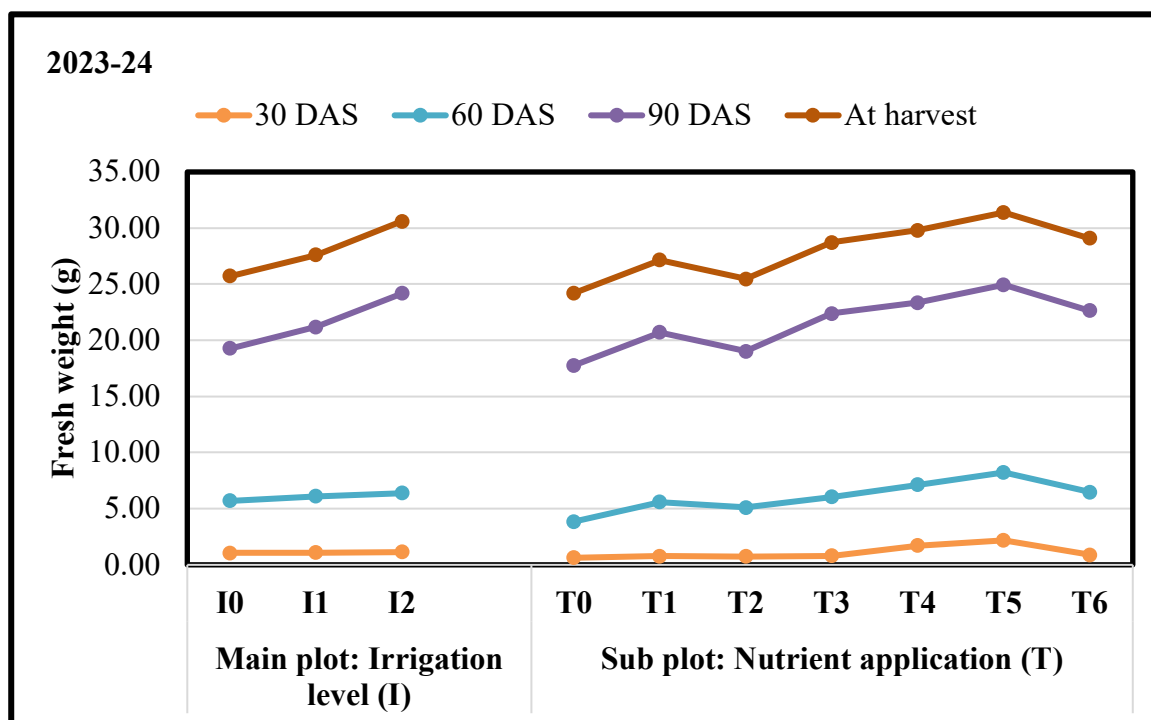


Figure 4.1.2 (b): Effect of seed priming, humic acid, and sulphur application on fresh weight of linseed at different irrigation intervals (2023-24)



4.1.3 Effect of seed priming, humic acid, and sulphur application on dry matter accumulation of linseed under different irrigation intervals.

Data presented in Tables 4.1.3 (a) and 4.1.3 (b) revealed that dry matter accumulation of linseed was significantly influenced by irrigation levels and nutrient application at successive growth stages during both years of experimentation (2022–23 and 2023–24).

Effect of irrigation levels

Over the two years, dry matter accumulation for each irrigation level was not statistically different from one another at 30 days after seeding (DAS). However, starting at 60 DAS, differences among treatment means for dry matter accumulation were statistically significant. Dry matter accumulation increased significantly with increasing frequency of irrigation over time; dry matter accumulation for I_2 (two post-sowing irrigations) was the highest amount of dry matter of all irrigation treatments at 60 DAS (1.04 g/plant in 2022–23 and 0.92 g/plant in 2023–24) and significantly greater than for I_0 . The amount of dry matter accumulation for I_1 was statistically similar to that of I_2 for both years.

The highest cumulative dry weight was observed for I_2 (6.25 and 6.40 g plant⁻¹ for 2022–23 and 2023–24, respectively), and the differences between I_2 and I_0 were statistically significant as they were larger than the critical difference (0.55 and 0.29, respectively) at 90 DAS. There was also a significant advantage in dry weight for I_2 at harvest (8.39 and 8.35 g plant⁻¹) compared to I_0 ; however, I_1 was statistically similar to I_2 in both years.

Effect of nutrient application

Nutrient applications at every stage of development in both years affected the accumulation of dry matter significantly. After 30 days after planting (DAS) and 60 DAS, T_5 had the highest dry matter accumulation (KNO_3 + humic acid), and values were statistically significant compared to all other treatments based on the critical difference values. T_4 (KNO_3 + sulphur) and T_6 (sulphur + humic acid) also produced a significantly higher amount of dry matter than the no treatment control (T_0) at both the 30 and 60 DAS dates.

By 90 days after seeding (DAS), T_5 had the highest amount of total dry matter/plant (6.68 g/plant for 2022–23 and 6.71 g/plant for 2023–24) compared to all other treatments (T_4 was second), and they were statistically significant compared to single nutrient treatments. The highest amount of total dry matter per plant also occurred at harvest, with T_4 producing 8.82 g/plant in 2022–23 and 8.67 g/plant in 2023–24, which are both significantly greater than all other treatments and the control.

Interaction effects

At 60DAS, no significant interaction of irrigation level and treatment was observed; however, significant interaction of both treatment and irrigation levels were observed at the 90-day sampling date and harvest. At these respective times, treatment differences were statistically significant as they exceeded the critical

difference values (0.78, 0.86).

The use of the combined application of $I_2 \times T_5$ resulted in the highest accumulation of dry matter at both the 90-day and harvest times during both the 2022–23 and 2023–24 growing seasons when compared to all other treatments. The combined application produced dry matter values of 8.62 and 8.58 g plant⁻¹ and 10.76 and 10.53 g plant⁻¹ at the 90-day and harvest periods, respectively. No matter which crop year, the $I_0 \times T_0$ treatment combination had the lowest accumulation of dry matter; thus, indicating that moisture stress combined with a total lack of nutrient supplements negatively affected the crop. Dry matter accumulation is an important indicator of both the photosynthetic efficiency of the plant and overall plant growth. Dry matter accumulation of linseed did not differ significantly among irrigation treatments at 30 DAS during both years due to the absence of irrigation up to this stage and favourable weather conditions with moderate temperature, adequate relative humidity, and negligible rainfall, which resulted in low crop water requirement and uniform soil moisture availability. From 60 DAS onwards, irrigation significantly affected dry matter accumulation as crop water demand increased during the active vegetative growth. Irrigation levels (I_2 and I_1) maintained better soil moisture, which enhanced the photosynthesis and biomass accumulation compared to I_0 . The differences became more evident at 90 DAS and at harvest due to rising temperature and increased evaporative demand under rain-free conditions, causing moisture stress in lower irrigation treatments. Nutrient treatments, particularly the combined application of KNO_3 and humic acid, consistently resulted in higher dry matter accumulation by improving nutrient uptake and physiological activity. The significant interaction at 90 DAS and at harvest indicates that integrated nutrient application was more effective under adequate moisture conditions. These findings agree with earlier reports on the positive role of irrigation and integrated nutrient management in improving biomass production (Yadav and Meena, 2019; Kumar *et al.*, 2021b; Sharma *et al.*, 2018).

Table 4.1.3 (a): Effect of seed priming, humic acid, and sulphur application on dry matter accumulation of linseed at different irrigation intervals (2022-23 and 2023-24).

Dry matter accumulation (g plant⁻¹)								
Treatment	30 DAS		60 DAS		90 DAS		At harvest	
	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24
Main plot: Irrigation level (I)								
I₀	0.59	0.55	0.84	0.75	3.38	3.19	5.52	5.15
I₁	0.60	0.57	0.97	0.90	5.55	5.35	7.69	7.31
I₂	0.62	0.57	1.04	0.92	6.25	6.40	8.39	8.35
SEm±	0.01	0.02	0.02	0.02	0.14	0.07	0.14	0.07
CD (P=0.05)	NS	NS	0.08	0.07	0.55	0.29	0.55	0.29
Subplot: Nutrient application (T)								
T₀	0.41	0.39	0.62	0.58	3.32	3.20	5.46	5.16
T₁	0.57	0.53	0.82	0.80	4.70	4.63	6.84	6.58
T₂	0.54	0.45	0.75	0.64	4.55	4.42	6.69	6.38
T₃	0.57	0.55	0.93	0.85	4.88	4.75	7.02	6.70
T₄	0.69	0.66	1.13	1.02	6.05	5.83	8.19	7.79
T₅	0.84	0.74	1.32	1.16	6.68	6.71	8.82	8.67
T₆	0.63	0.60	1.10	0.95	5.23	5.32	7.37	7.28
SEm±	0.01	0.02	0.05	0.07	0.16	0.17	0.16	0.17
CD (P=0.05)	0.04	0.06	0.14	0.19	0.45	0.50	0.45	0.50
Interaction I × T								
SEm±	0.02	0.04	0.09	0.12	0.27	0.30	0.27	0.30
CD (P=0.05)	NS	NS	NS	NS	0.78	0.86	0.78	0.86
Interaction T × I								
SEm±	0.02	0.05	0.05	0.04	0.36	0.19	0.36	0.19
CD (P=0.05)	NS	NS	NS	NS	0.85	0.88	0.85	0.88

Note:

- 1- **I₀**: No post sowing irrigation, **I₁**: Post sowing irrigation one, **I₂**: Post sowing irrigation two,
- 2- **T₀**: Control, **T₁**: Potassium Nitrate, **T₂**: Sulphur, **T₃**: Humic acid, **T₄**: KNO₃ + S,
T₅: KNO₃ + HA, **T₆**: Sulphur + HA

Fig 4.1.3(a): Effect of seed priming, humic acid, and sulphur application on dry matter accumulation of linseed at different irrigation intervals (2022-23)

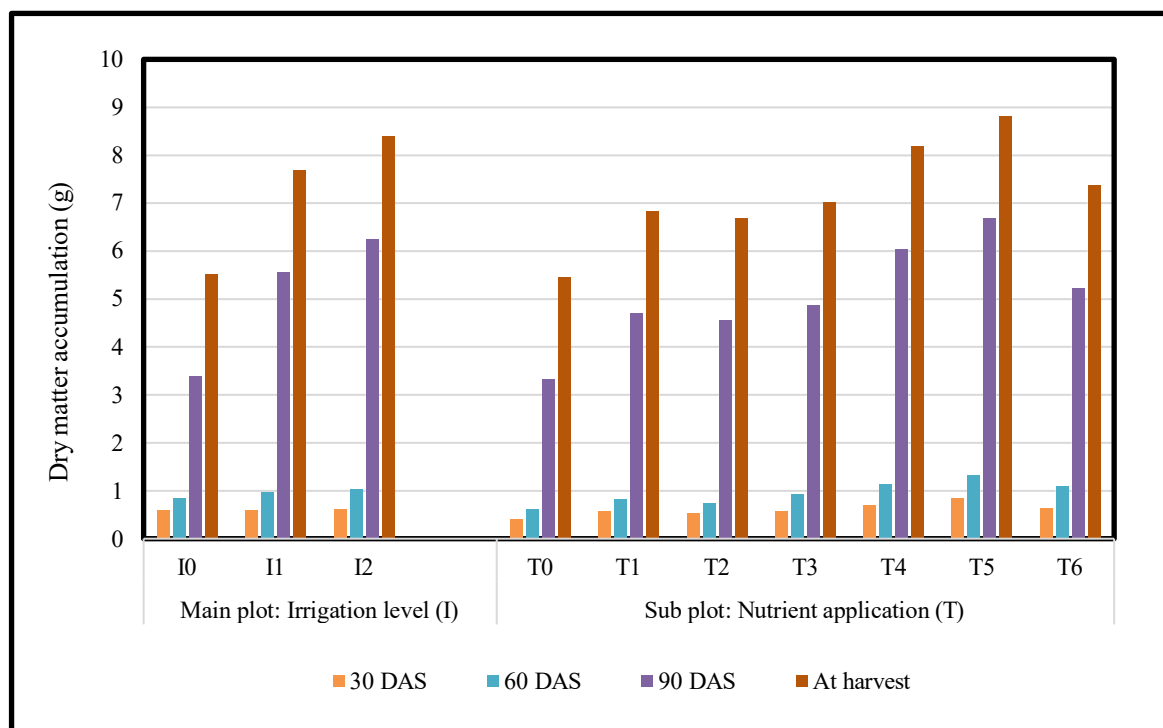


Fig 4.1.3.(b): Effect of seed priming, humic acid, and sulphur application on dry matter accumulation of linseed different irrigation intervals (2023-24).

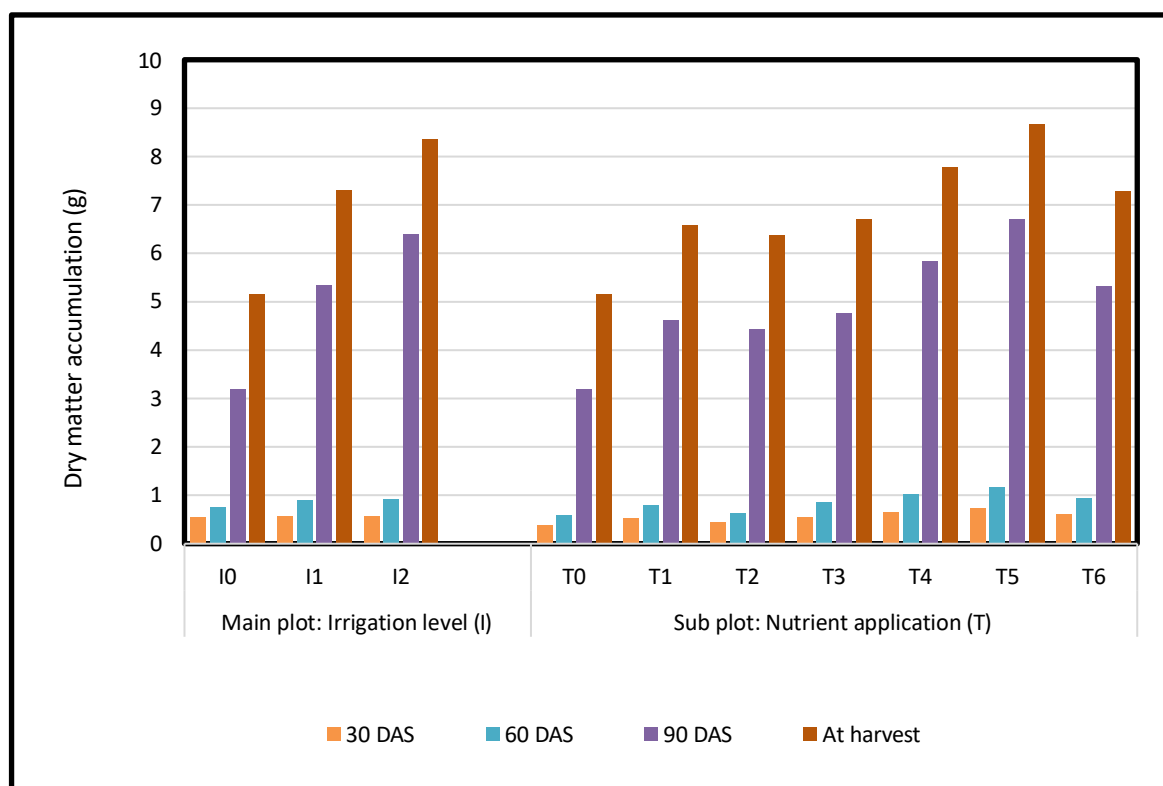


Table 4.1.3 (b): Interacting effect of seed priming, humic acid, and sulphur application on dry matter accumulation at 90 DAS and harvest of linseed, different irrigation intervals (2022-23 and 2023-24).

Dry matter accumulation 90 DAS								
	2022-23				2023-24			
	I ₀	I ₁	I ₂	Mean	I ₀	I ₁	I ₂	Mean
T ₀	2.79	3.28	3.89	3.32	2.59	2.85	4.15	3.20
T ₁	3.19	5.34	5.56	4.70	3.08	4.76	6.04	4.63
T ₂	3.04	5.13	5.47	4.55	2.84	4.63	5.81	4.42
T ₃	3.38	5.53	5.73	4.88	3.18	4.92	6.14	4.75
T ₄	3.79	6.55	7.80	6.05	3.63	6.53	7.32	5.83
T ₅	4.05	7.38	8.62	6.68	3.79	7.76	8.58	6.71
T ₆	3.40	5.65	6.65	5.23	3.22	6.00	6.75	5.32
Mean	3.38	5.55	6.25		3.19	5.35	6.40	
SEm±	0.27				0.30			
LSD (P=0.05)	0.78				0.86			
At harvest								
	2022-23				2023-24			
	I ₀	I ₁	I ₂	Mean	I ₀	I ₁	I ₂	Mean
T ₀	4.93	5.42	6.03	5.46	4.55	4.81	6.11	5.16
T ₁	5.33	7.48	7.70	6.84	5.03	6.72	8.00	6.58
T ₂	5.18	7.27	7.61	6.69	4.80	6.58	7.76	6.38
T ₃	5.52	7.67	7.87	7.02	5.14	6.88	8.10	6.70
T ₄	5.93	8.69	9.94	8.19	5.59	8.49	9.28	7.79
T ₅	6.19	9.52	10.76	8.82	5.75	9.72	10.53	8.67
T ₆	5.54	7.79	8.79	7.37	5.18	7.96	8.70	7.28
Mean	5.52	7.69	8.39		5.15	7.31	8.35	
SEm±	0.27				0.30			
LSD (P=0.05)	0.78				0.86			

Note:

- 1- I₀: No post sowing irrigation, I₁: Post sowing irrigation one, I₂: Post sowing irrigation two,
- 2- T₀: Control, T₁: Potassium Nitrate, T₂: Sulphur, T₃: Humic acid, T₄: KNO₃ + S, T₅: KNO₃ + HA, T₆: Sulphur + HA.

4.1.4 : Effect of seed priming, humic acid, and sulphur application on leaf area of linseed under different irrigation intervals.

The data presented in Table 4.1.4 (a) indicate that leaf area of linseed was markedly influenced by irrigation levels and nutrient application at later growth stages during both years of experimentation (2022–23 and 2023–24).

Effect of irrigation levels

The leaf area at 30 and 60 days after sowing there was no significant effect of irrigation level on leaf area for either year, as the differences in leaf area among the four irrigation treatments were not statistically significant. However, the irrigation level had a significant effect on leaf area at 90 days after sowing. The irrigation treatment which provided two post-planting irrigations produced leaves with the largest leaf area measured (218.53 and 220.38 cm² plant⁻¹ for 2022-23 and 2023-24, respectively), which were significantly larger than the irrigation treatment without an irrigation at this time; moreover, the pairwise difference between this treatment and treatment I₀ exceeded the critical difference values of 14.48 and 20.51 cm² for 2022-23 and 2023-24 respectively. There was no significant difference in leaf area between irrigation treatments I₁ and I₂ for either year.

The same trend was observed at harvest, with two post-planting irrigations producing leaves with the largest leaf area measured (297.50 and 298.78 cm² plant⁻¹ for 2022-23 and 2023-24, respectively) as well as treatment I₁ (290.89 and 290.13, respectively); both treatments were significantly larger than the irrigation treatment with no post-planting irrigation. It appears that increased frequency of irrigation positively influences leaf area development during the latter stages of plant growth and yields greater leaf area development at harvest.

Effect of nutrient application

Throughout the growth stages of both years, the application of nutrients had a large effect on leaf area. The highest leaf area at 30 DAS was in T₅ (KNO₃ + humic acid) at 84.36 cm²/plant (year 1) and 72.73 cm²/plant (year 2) and was significantly greater than T₀ and all other treatments with more than 10 cm²/plant difference than CD.

At 60 DAS, T₅ continued to produce the greatest leaf area of 112.43 cm²/plant (year 1) and 108.53 cm²/plant (year 2), while T₄ (KNO₃ + sulphur) produced the second greatest leaf area. Both T₅ and T₄ were greater than single nutrient treatments and T₀ for both years. At 90 DAS, leaf area continued to increase under combined nutrient treatments and T₅ had the greatest leaf area of 241.89 cm²/plant (year 1) and 232.49 cm²/plant (year 2), and both of those values were significantly greater than all other treatment values. At harvest, T₅ produced the greatest leaf area of 320.86 cm²/plant (year 1) and 310.89 cm²/plant (year 2) and was greater than T₄ which produced greater than T₀ for both years.

Interaction effects

The interaction effects of irrigation levels and nutrient application ($I \times T$ and $T \times I$) were found to be non-significant at all growth stages during both years of study, indicating that the individual effects of irrigation and nutrient application on leaf area were independent of each other.

Leaf area of linseed did not differ significantly among irrigation treatments at 30 and 60 DAS during both years, which can be attributed to the absence of irrigation up to early growth stages and favorable weather conditions with moderate temperature, adequate relative humidity, and negligible rainfall, resulting in low crop water demand and uniform soil moisture availability. After 90 DAS, the effect of irrigation on leaf area growth became more pronounced as the crop's water requirement increased during the active growth phase. The higher levels of irrigation (I_2 and I_1) maintained better soil moisture, which helped in leaf growth, delayed leaf senescence, and resulted in higher leaf area than I_0 . These values were also sustained at harvest, driven by higher temperatures and increased evaporation demand in the absence of rain, which hampered leaf growth at lower irrigation levels. The treatments of nutrients, particularly the combined application of KNO_3 and humic acid, resulted in higher leaf area by improving nutrient uptake, chlorophyll content, and photosynthetic efficiency. The non-significant interaction between irrigation and nutrient treatments shows that the effect of nutrients on leaf area was consistent across the irrigation levels. The above results are in agreement with the previous findings, which emphasized the importance of proper irrigation and integrated nutrient management for improving leaf growth and canopy development (Yadav and Meena, 2019; Kumar *et al.*, 2021b; Sharma *et al.*, 2018).

Table 4.1.4.a: Effect of seed priming, humic acid, and sulphur application on leaf area of linseed at different irrigation intervals 2022-23 and 2023-24.

Leaf area (cm ² plant ⁻¹)								
Treatment	30 DAS		60 DAS		90 DAS		At harvest	
	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24
Main plot: Irrigation level (I)								
I ₀	67.40	57.32	95.64	90.75	169.64	185.41	248.61	263.81
I ₁	68.91	59.58	99.38	97.48	211.92	211.73	290.89	290.13
I ₂	68.70	59.76	100.86	99.71	218.53	220.38	297.50	298.78
SEm±	1.96	1.44	1.07	1.89	3.69	5.22	3.69	3.60
CD (P=0.05)	NS	NS	NS	NS	14.48	20.51	14.48	14.14
Sub plot: Nutrient application (T)								
T ₀	53.99	45.40	85.87	84.23	170.80	180.52	249.77	258.92
T ₁	63.88	54.05	95.09	92.74	183.59	200.00	262.56	278.40
T ₂	60.24	51.83	93.61	91.23	175.38	193.09	254.34	271.49
T ₃	67.42	58.54	98.16	94.90	196.24	204.37	275.21	282.77
T ₄	78.40	67.79	105.43	101.86	221.94	221.46	300.91	299.86
T ₅	84.36	72.73	112.43	108.53	241.89	232.49	320.86	310.89
T ₆	70.	61.87	99.80	98.38	210.39	208.95	289.36	287.35
SEm±	3.45	2.98	2.59	3.41	5.70	7.26	5.70	6.64
CD (P=0.05)	9.92	8.54	7.42	9.78	16.36	20.83	16.36	19.04
Interaction I × T								
SEm±	5.87	5.16	4.48	5.91	9.88	12.58	9.88	11.50
CD (P=0.05)	NS	NS	NS	NS	NS	NS	NS	NS
Interaction T × I								
SEm±	5.18	3.80	2.83	4.99	9.75	10.70	9.75	10.71
CD (P=0.05)	NS	NS	NS	NS	NS	NS	NS	NS

Note:

- 2- I₀: No post sowing irrigation, I₁: Post sowing irrigation one, I₂: Post sowing irrigation two,
3- T₀: Control, T₁: Potassium Nitrate, T₂: Sulphur, T₃: Humic acid, T₄: KNO₃ + S, T₅: KNO₃ + HA, T₆: Sulphur + HA.

Fig 4.1.4(a): Effect of seed priming, humic acid, and sulphur application on leaf area of linseed different irrigation intervals (2022-23)

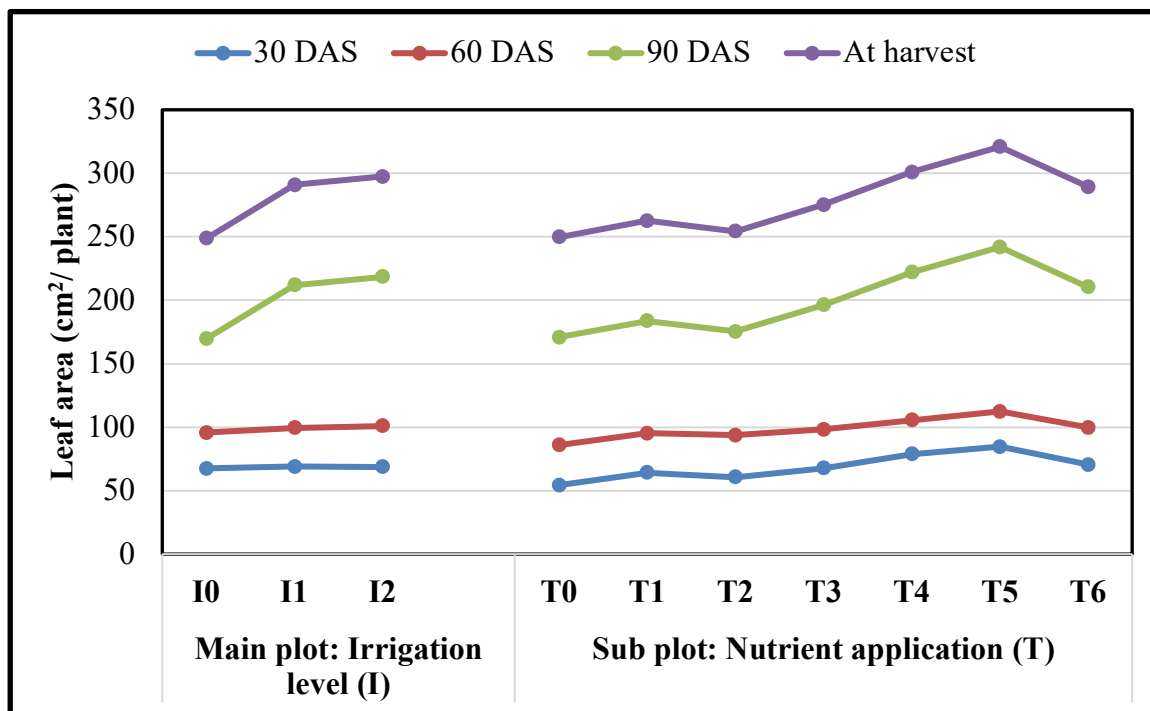
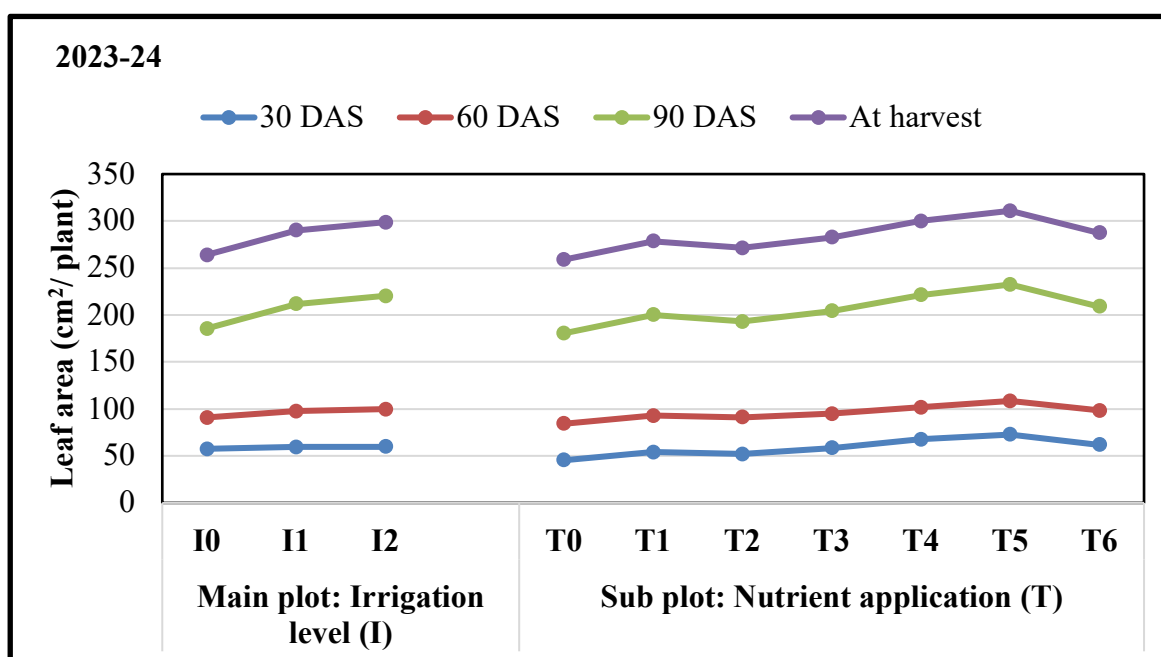


Fig 4.1.4.(b): Effect of seed priming, humic acid, and sulphur application on leaf area of linseed different irrigation intervals (2023-24)



4.2 Phenological parameters:

4.2.1 : Effect of seed priming, humic acid, and sulphur application on leaf area index of linseed under different irrigation intervals.

The data presented in Table 4.2.1 (a) reveal that leaf area index (LAI) of linseed was influenced mainly by nutrient application, while irrigation levels and interaction effects did not show a significant influence during both years of study (2022–23 and 2023–24).

Effect of Irrigation Levels

The leaf area index (LAI) did not show any significant impact based on irrigation levels in any of the crop growth stages for either year, as there were no statistically significant differences between the treatments. For instance, at 30 days after seeding (DAS), LAI was between 0.13 and 0.14 for both 2022-23 and 2023-24 while it was between 0.12 and 0.13 at 60 days after seeding (DAS) for both years; this same trend can be seen for 90 DAS and harvest, showing that under the experimental conditions, varying lengths of time between irrigations had no significant effect on the growth of LAI.

Effect of nutrient application

There were significant differences in leaf area index (LAI) among treatments due to nutrient application at each growth stage for both years of experimentation. The highest LAI value at 30 days after sowing (DAS) came from T₅ (KNO₃ + humic acid) (0.17 and 0.14 for 2022–23 and 2023–24, respectively), significantly different from T₀ (the control) as the differences were greater than the critical difference (CD) values of 0.02 and 0.03. Treatments T₄ (KNO₃ + sulphur) and T₆ (sulphur + humic acid) had similar LAI as T₅ but were both significantly different from T₀. Progressive increases in LAI were noted at 60 DAS, with maximum LAI recorded under T₅ (0.56 and 0.48) being significantly greater than all other treatments for both years. The combined nutrient application treatments (T₄, T₅, and T₆) consistently provided larger LAI than the single nutrient treatments and T₀. The maximum LAI at 90 DAS was recorded under T₅ (0.76 and 0.74), followed by T₄ (0.70 and 0.69), both treatments being significantly different compared to T₀ based on the respective CD values of 0.05 and 0.07. At harvest, T₅ had the largest LAI (1.20 and 1.14) and was significantly different from all other treatments in both years, while control (T₀) had by far the lowest LAI.

Interaction Effect

At every growth stage in both years, there were no significant differences in LAI associated with I, T or the interactions of I and T ($i \times t$) or T and I ($t \times i$). Therefore, the effect on LAI of T was not dependent on the level of I at that time and/or vice versa.

During both years, the non-significant variation in leaf area index (LAI) as affected by

irrigation levels throughout all growth stages could have resulted from prevailing meteorological conditions and when irrigation was applied. At 30 DAS, there was little variation in LAI as a result of relatively moderate temperature and humidity during early growth; residual soil moisture at planting was uniform, and all treatments applied irrigation at the same time after planting, which inhibited any differentiation among treatments due to irrigation. At 60 and 90 days after sowing (DAS), although there was moisture in the irrigated plots recorded at 35 DAS, the favorable temperature conditions for both developing the canopy and having no significant atmospheric stress resulted in equivalent development of the canopy between irrigation levels. Thus, there were no significant effects between different irrigation levels at harvest. However, the slightly lower leaf area index (LAI) at harvest for the 2023-24 growing season compared to 2022-23 may be due to the greater temperatures and evaporative demands that would have resulted in increased leaf senescence during late stages of growth. On the other hand, and across all of the growing periods, nutrient treatments had significant effects on LAI development. The mixture of KNO_3 + humic acid (T_5) produced the highest tree and leaf area index (LAI) at all time frames due to the increased nutrient uptake from this application combination, improved chlorophyll synthesis, and the stability of the physiological characteristics of the leaves under the varying conditions of climate. Thus, for the weather conditions under which these experiments were conducted, tree and LAI development in linseed was more likely to be attributed to physiological processes induced by nutrient applications than to irrigation applications (Saxena and Rathi, 2020; Yadav and Meena, 2019; Kumar *et al.*, 2021b).

Table 4.2.1.a: Effect of seed priming, humic acid, and sulphur application on leaf area index of linseed different irrigation intervals 2022-23 and 2023-24.

Leaf area index								
Treatment	30 DAS		60 DAS		90 DAS		At harvest	
	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24
Main plot: Irrigation level (I)								
I ₀	0.13	0.12	0.44	0.38	0.65	0.63	1.09	1.03
I ₁	0.14	0.12	0.47	0.40	0.66	0.65	1.10	1.05
I ₂	0.14	0.13	0.46	0.40	0.67	0.66	1.11	1.06
SEm±	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.02
CD (P=0.05)	NS	NS	NS	NS	NS	NS	NS	NS
Sub plot: Nutrient application (T)								
T ₀	0.10	0.09	0.36	0.30	0.57	0.56	1.01	0.96
T ₁	0.13	0.11	0.43	0.36	0.64	0.63	1.08	1.03
T ₂	0.10	0.10	0.40	0.35	0.62	0.61	1.06	1.01
T ₃	0.14	0.12	0.45	0.39	0.66	0.65	1.09	1.05
T ₄	0.16	0.14	0.52	0.45	0.70	0.69	1.14	1.09
T ₅	0.17	0.14	0.56	0.48	0.76	0.74	1.20	1.14
T ₆	0.16	0.13	0.47	0.41	0.67	0.67	1.11	1.07
SEm±	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02
CD (P=0.05)	0.02	0.03	0.07	0.06	0.05	0.07	0.05	0.07
Interaction I × T								
SEm±	0.01	0.02	0.04	0.03	0.03	0.04	0.03	0.04
CD (P=0.05)	NS	NS	NS	NS	NS	NS	NS	NS
Interaction T × I								
SEm±	0.01	0.02	0.03	0.02	0.03	0.04	0.02	0.04
CD (P=0.05)	NS	NS	NS	NS	NS	NS	NS	NS

Note:

- 1- I₀: No post sowing irrigation, I₁: Post sowing irrigation one, I₂: Post sowing irrigation two,
- 2- T₀: Control, T₁: Potassium Nitrate, T₂: Sulphur, T₃: Humic acid, T₄: KNO₃ + S, T₅: KNO₃ + HA, T₆: Sulphur + HA.

Fig 4.2.1 (a): Effect of seed priming, humic acid, and sulphur application on leaf area index of linseed different irrigation intervals (2022-23)

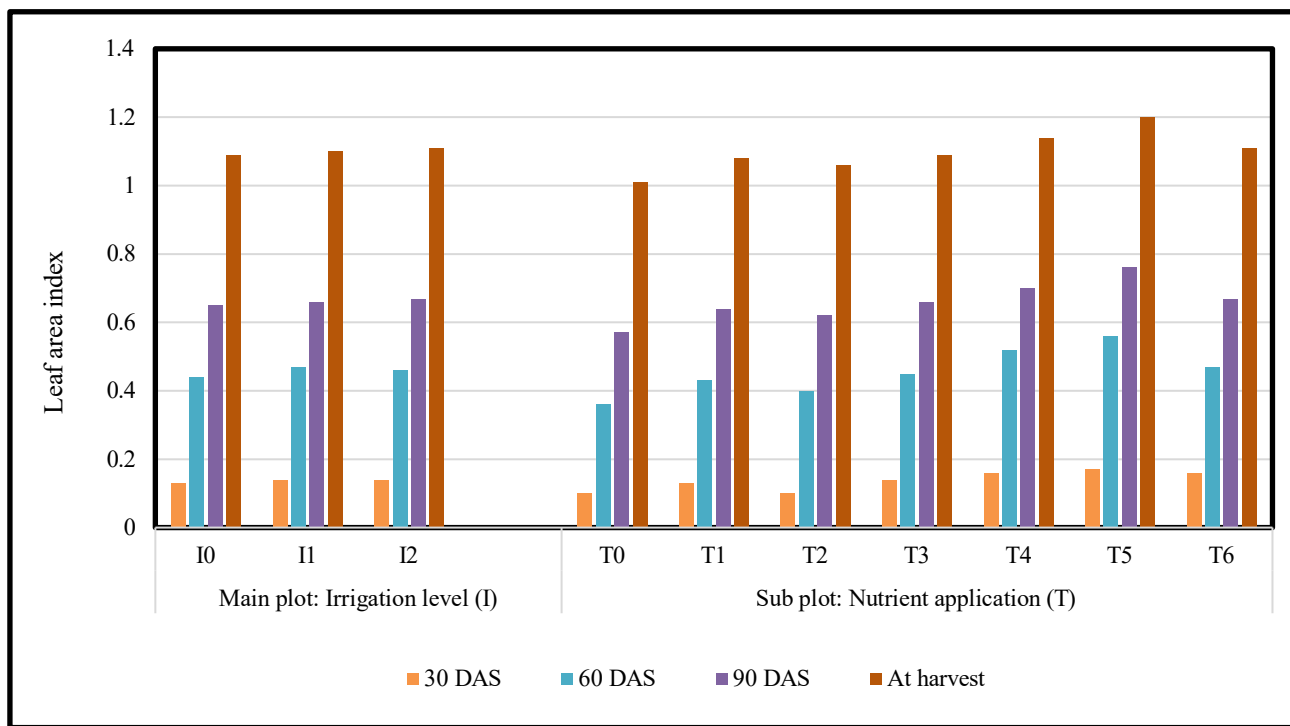
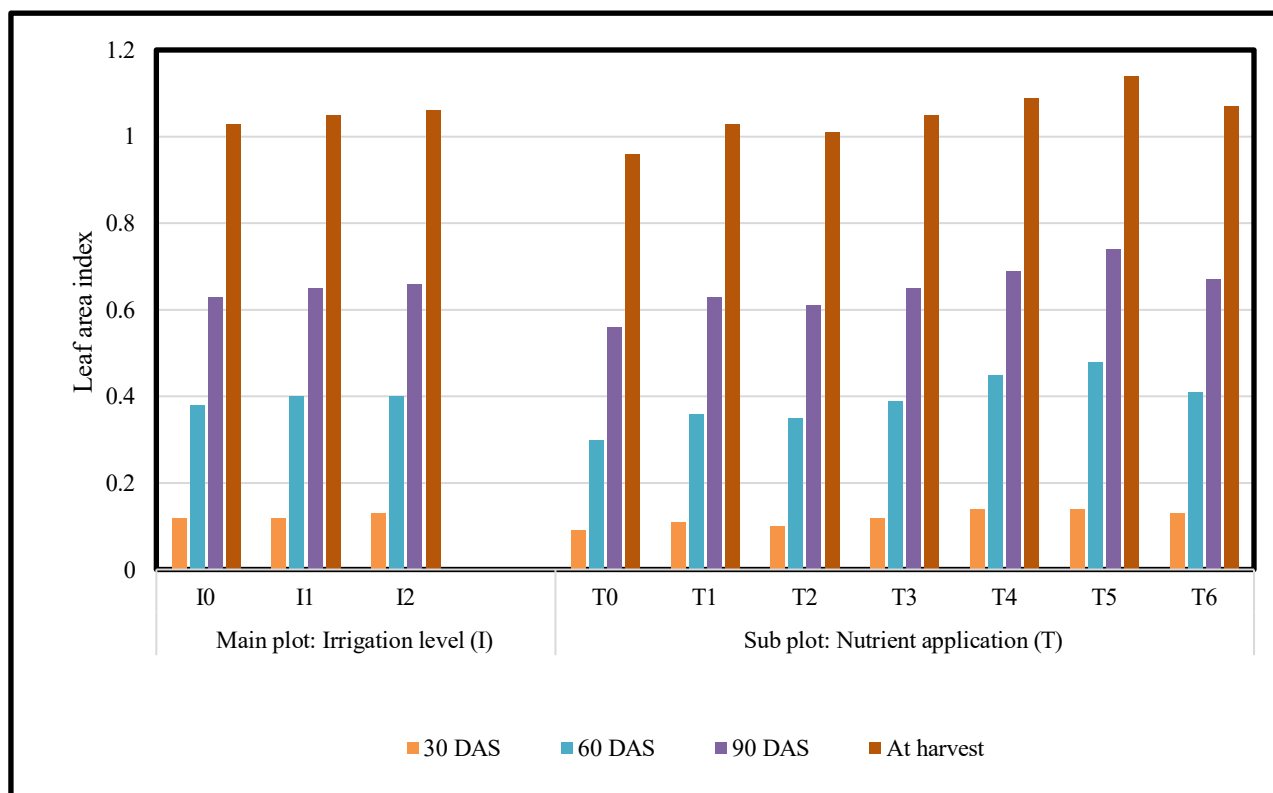


Fig 4.2.1(b): Effect of seed priming, humic acid, and sulphur application on leaf area index of linseed different irrigation intervals (2023-24)



4.2.2 Effect of seed priming, humic acid, and sulphur application on the crop growth rate of linseed under different irrigation intervals.

Crop growth rate (CGR) of linseed was significantly influenced by irrigation levels and nutrient application during both growth periods (30–60 DAS and 60–90 DAS) in both experimental years (2022–23 and 2023–24), as presented in Table 4.2.2(a) and 4.2.2(b).

Effect of irrigation levels on crop growth rate

During the early growth period, CGR was significantly influenced by the levels of irrigation in both years. In 2022-23, the highest CGR was recorded under I_2 ($0.020 \text{ g m}^{-2} \text{ day}^{-1}$), which was statistically at par with that recorded under I_1 ($0.019 \text{ g m}^{-2} \text{ day}^{-1}$) but significantly superior to that under I_0 ($0.015 \text{ g m}^{-2} \text{ day}^{-1}$), since the difference was greater than CD ($P = 0.05$) of $0.002 \text{ g m}^{-2} \text{ day}^{-1}$. During 2023-24, I_2 ($0.024 \text{ g m}^{-2} \text{ day}^{-1}$) recorded significantly higher CGR than I_0 ($0.016 \text{ g m}^{-2} \text{ day}^{-1}$), since the difference was greater than the respective CD ($P = 0.05$) of $0.003 \text{ g m}^{-2} \text{ day}^{-1}$.

Irrigation at different rates had a greater effect on crop growth in the later growth period (60-90 DAS) than in earlier growth periods. The highest CGR was recorded for I_2 in 2022–23 ($0.119 \text{ g m}^{-2} \text{ day}^{-1}$), with a significantly higher result compared to I_1 ($0.099 \text{ g m}^{-2} \text{ day}^{-1}$) and I_0 ($0.056 \text{ g m}^{-2} \text{ day}^{-1}$), and therefore, the differences among treatments exceeded the CD ($P = 0.05$) of $0.005 \text{ g m}^{-2} \text{ day}^{-1}$. In 2023–24, I_2 also produced significantly higher CGR than both I_0 ($0.057 \text{ g m}^{-2} \text{ day}^{-1}$) and I_1 ($0.102 \text{ g m}^{-2} \text{ day}^{-1}$) with a value of $0.124 \text{ g m}^{-2} \text{ day}^{-1}$.

Effect of nutrient applications on crop growth rate

Nutrient treatments during growth periods of 30 days after seeding (DAS) to 60 DAS resulted in significant increases in crop growth rates (CGR) for the combined nutrient treatment T_5 , compared to single nutrient applications (T_0 to T_3). T_5 (combination of KNO_3 and humic acid) produced the highest CGR for both 2022-2023 ($0.023 \text{ g m}^{-2} \text{ day}^{-1}$) and 2023-2024 ($0.028 \text{ g m}^{-2} \text{ day}^{-1}$), significantly higher than all other nutrient treatments, and exceeded the critical difference (CD; $P=0.05$) of $0.002 \text{ g m}^{-2} \text{ day}^{-1}$ for both years. The control treatment (T_0) produced the lowest CGR.

For the period of 60-90 DAS, again T_5 produced the maximum CGR ($0.123 \text{ g m}^{-2} \text{ day}^{-1}$ for 2022-2023 and $0.127 \text{ g m}^{-2} \text{ day}^{-1}$ for 2023-2024) with both values significantly higher than the CGR of each nutrient treatment (T_0 to T_3) and exceeded their respective CD ($0.009 \text{ g m}^{-2} \text{ day}^{-1}$, $P = 0.05$). The combination of nutrients (T_4 , T_5 , and T_6) producing higher CGRs than any single nutrient treatment indicates that these combined treatments have a synergistic effect.

Interaction effect ($I \times T$)

Irrigation levels did not significantly interact with nutrient application at 30–60 days after sowing (DAS) in both years. However, during the period of 60–90 DAS there was statistical significance of the interactions

between the two treatments in both experimental years since the differences among the treatment combinations exceeded the critical difference ($P = 0.05$) of $0.015 \text{ g m}^{-2} \text{ day}^{-1}$ (2022–23) and $0.016 \text{ g m}^{-2} \text{ day}^{-1}$ (2023–24) (Table 4.2.2b).

For the period of 2022–23, the highest crop growth rate (CGR) recorded was for the $I_2 \times T_5$ interaction ($0.161 \text{ g m}^{-2} \text{ day}^{-1}$), which was significantly higher than for most of the other treatment combinations. Following this interaction were the $I_2 \times T_4$ ($0.142 \text{ g m}^{-2} \text{ day}^{-1}$) and $I_2 \times T_6$ ($0.124 \text{ g m}^{-2} \text{ day}^{-1}$) combinations. The same trend was seen during 2023–24, with the $I_2 \times T_5$ treatment combination having the highest CGR ($0.167 \text{ g m}^{-2} \text{ day}^{-1}$).

Both irrigation and nutrient management played a significant role in shaping the crop growth rate of Linseed across two growth stages (*i.e.*, 30–60 days after sowing, DAS, and 60–90 DAS). The amount of precipitation received throughout the year was responsible for the yearly fluctuation in crop growth rate. The period 30–60 DAS measured the lowest CGRs during both seasons as a result of a limited amount of canopy coverage and photosynthetic activity, thus limiting the amount of nutrient production. The crop growth rate for I_1 and I_2 at 30–60 DAS may have started to rise due to the occurrence of the irrigation applied at sowing plus 35 DAS, which provided additional soil moisture and nutrients for the plant to produce more assimilates (*i.e.*, increase the total amount of plant's biomass). Within the measurement of 60–90 DAS, a significant increase in crop growth rate was found for all treatments, but particularly for I_2 . This increase was due to the increased demand for crop water, increased leaf area indexed, and increased crop's photosynthetic capacity. The relatively higher CGR in 2022–23 compared to 2023–24 may be associated with comparatively favourable thermal regimes and lower evaporative stress during mid-season. Integrated nutrient treatments, especially KNO_3 + humic acid (T_5), consistently recorded higher CGR due to improved nutrient uptake, enhanced chlorophyll activity, and better translocation of photosynthates. The significant $I \times T$ interaction during 60–90 DAS indicates that nutrient-induced physiological responses were optimally expressed under adequate soil moisture conditions, emphasizing the combined role of irrigation, nutrition, and weather in regulating crop growth dynamics (Saxena and Rathi, 2020; Sharma *et al.*, 2018; Kumar *et al.*, 2021b).

Table 4.2.2 (a): Effect of seed priming, humic acid, and sulphur application crop growth rate of linseed different irrigation intervals 2022-23 and 2023-24.

Crop growth rate ($\text{g m}^{-2} \text{ day}^{-1}$)				
Treatment	30-60 DAS		60-90 DAS	
	2022-23	2023-24	2022-23	2023-24
Main plot: Irrigation level (I)				
I ₀	0.015	0.016	0.056	0.057
I ₁	0.019	0.022	0.099	0.102
I ₂	0.020	0.024	0.119	0.124
SEm$\pm$	0.001	0.001	0.001	0.001
CD (P=0.05)	0.002	0.003	0.005	0.005
Subplot: Nutrient application (T)				
T ₀	0.012	0.013	0.059	0.061
T ₁	0.015	0.017	0.086	0.089
T ₂	0.014	0.016	0.084	0.087
T ₃	0.019	0.022	0.086	0.089
T ₄	0.021	0.024	0.109	0.112
T ₅	0.023	0.028	0.123	0.127
T ₆	0.021	0.025	0.094	0.097
SEm$\pm$	0.001	0.001	0.003	0.003
CD (P=0.05)	0.002	0.002	0.009	0.009
Interaction I $\times$ T				
SEm$\pm$	0.001	0.001	0.005	0.005
CD (P=0.05)	NS	NS	0.015	0.016
Interaction T $\times$ I				
SEm$\pm$	0.002	0.002	0.003	0.003
CD (P=0.05)	NS	NS	0.018	0.018

Note:

- 1- I₀: No post sowing irrigation, I₁: Post sowing irrigation one, I₂: Post sowing irrigation two,
- 2- T₀: Control, T₁: Potassium Nitrate, T₂: Sulphur, T₃: Humic acid, T₄: KNO₃ + S, T₅: KNO₃ + HA, T₆: Sulphur + HA.

Fig 4.2.2(a): Effect of seed priming, humic acid and sulphur application crop growth rate of linseed different irrigation intervals (2022-23)

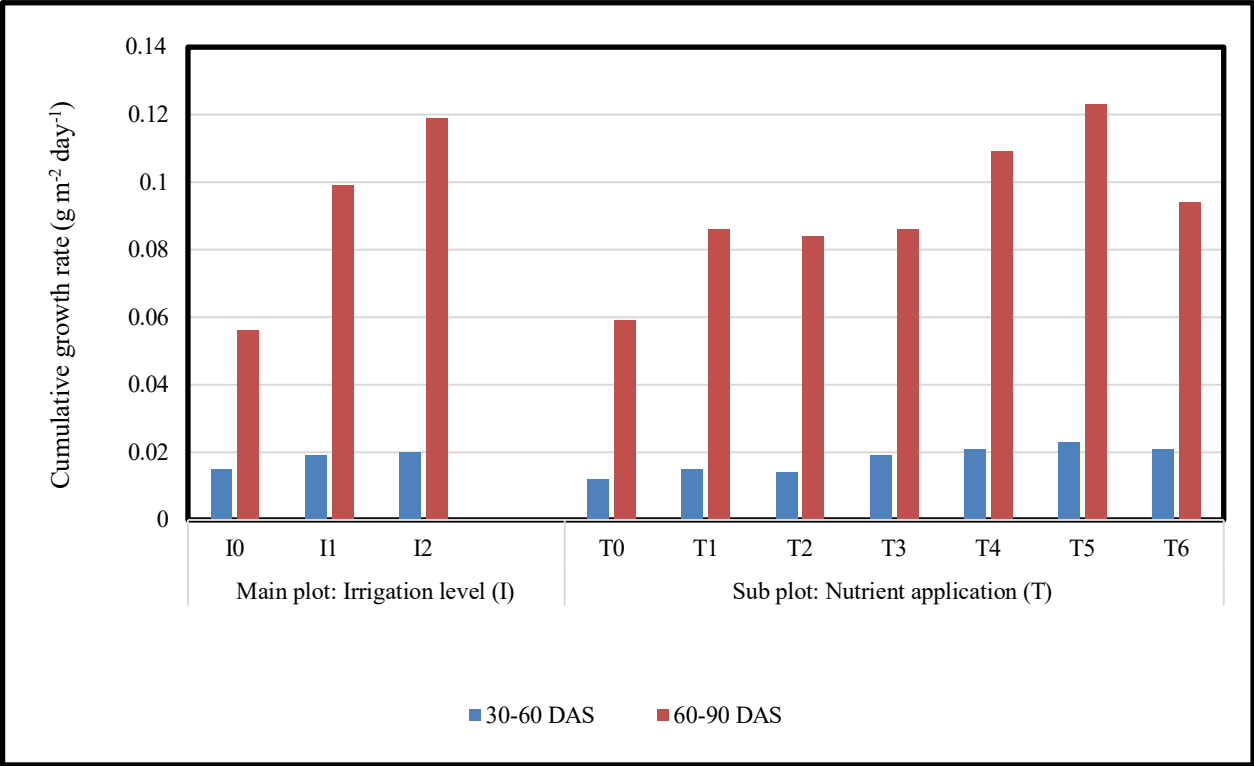


Fig 4.2.2(b): Effect of seed priming, humic acid, and sulphur application crop growth rate of linseed different irrigation intervals (2023-24)

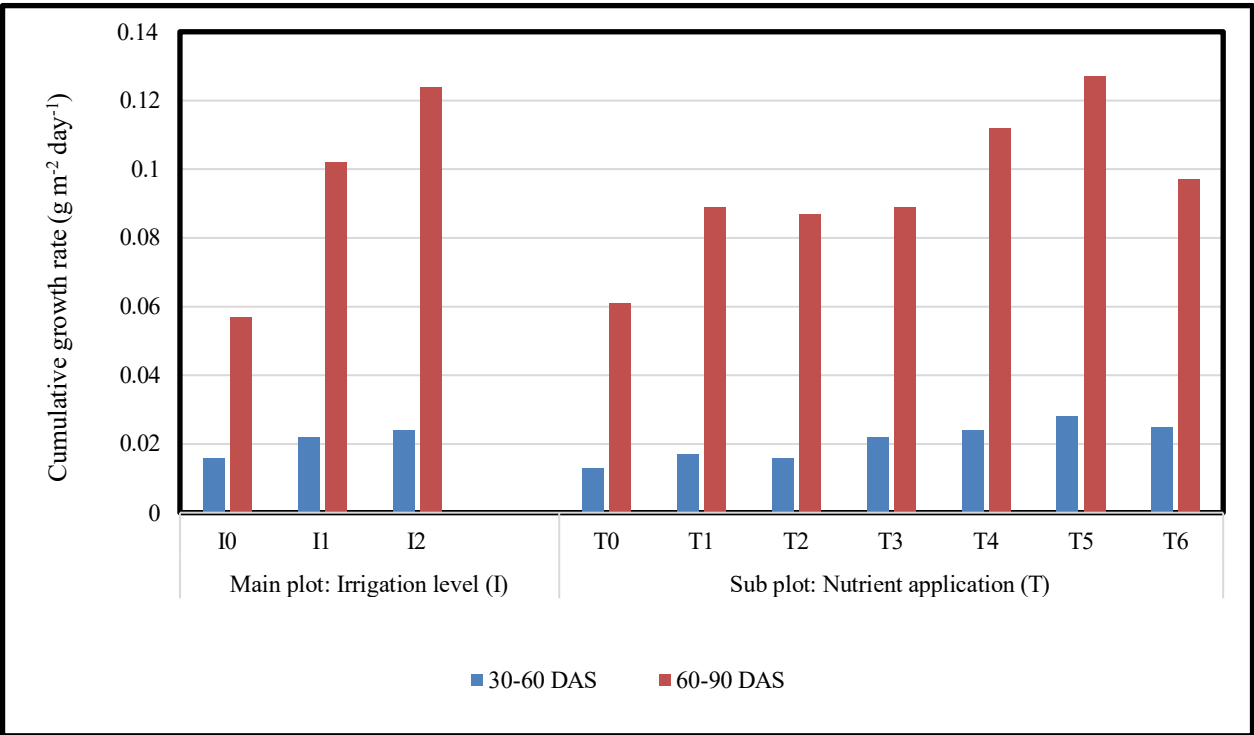


Table 4.2.2(b): Interactive effect of seed priming, humic acid, and sulphur application on crop growth rate during 60-90 DAS of linseed different irrigation intervals 2022-23 and 2023-24.

60-90 DAS								
	2022-23				2023-24			
	I ₀	I ₁	I ₂	Mean	I ₀	I ₁	I ₂	Mean
T ₀	0.048	0.054	0.076	0.059	0.049	0.055	0.079	0.061
T ₁	0.054	0.093	0.112	0.086	0.055	0.096	0.116	0.089
T ₂	0.052	0.091	0.110	0.084	0.054	0.093	0.114	0.087
T ₃	0.055	0.093	0.110	0.086	0.057	0.096	0.114	0.089
T ₄	0.064	0.121	0.142	0.109	0.065	0.124	0.147	0.112
T ₅	0.066	0.141	0.161	0.123	0.067	0.145	0.167	0.127
T ₆	0.054	0.104	0.124	0.094	0.055	0.107	0.129	0.097
Mean	0.056	0.099	0.119		0.057	0.102	0.124	
SEm±	0.005				0.005			
CD (P=0.05)	0.015				0.016			

4.2.3 : Effect of seed priming, humic acid, and sulphur application on the relative growth rate of linseed under different irrigation intervals.

The relative growth rate (RGR) of linseed was influenced by irrigation levels, nutrient application, and their interaction during different growth stages (30–60 DAS and 60–90 DAS) over the two years of experimentation (2022–23 and 2023–24), as presented in Table 4.2.3(a).

Effect of irrigation levels

Irrigation levels significantly impacted the rate of growth in 2022-2023 and 2023-2024 for the 30 to 60 Days After Sowing growth period. For example, I_2 produced the highest rate of growth at 0.079 grams per gram per day in 2022-2023, followed by I_1 with a rate of growth of 0.078 grams per gram per day and then I_0 with a rate of growth of 0.069 grams per gram per day. The difference between I_2 and I_0 was significantly different with a CD ($P=0.05$) value of 0.006 grams per gram per day.

In addition, I_2 produced the highest rate of growth of 0.081 grams per gram per day during the 2023-2024 growth period, I_1 with an RGR of 0.077, and I_0 with an RGR of 0.067. The difference between I_2 and I_0 is again statistically significant, with CD being less than 0.006 grams per day and therefore supports the conclusion above.

From 60 to 90 Days After Sowing, irrigation levels produced non-meaningful differences in RGR for both years based on the non-significant CD, though the numerical difference was in favor of I_2 , followed by I_1 and with I_0 the lowest.

Effect of nutrient application

During both years of the experiment, there was no significant difference in RGR between the different nutrient application treatments at either growth stage.

The RGR values were between 0.069 and 0.080 $\text{g g}^{-1} \text{day}^{-1}$ in 2022–23 and between 0.068 and 0.079 $\text{g g}^{-1} \text{day}^{-1}$ in 2023–24. Even though T_1 (seed priming) had higher RGR values on paper, these values were not statistically different from those of the other treatments because the differences were within the CD ($P = 0.05$) limits.

In 2022–23, RGR ranged from 0.044 to 0.049 $\text{g g}^{-1} \text{day}^{-1}$, and in 2023–24, it ranged from 0.045 to 0.051 $\text{g g}^{-1} \text{day}^{-1}$. The control treatment (T_0) exhibited slightly elevated values; however, these discrepancies were statistically insignificant, and all nutrient treatments maintained statistical equivalence.

Interaction effect ($I \times T$)

The interaction between irrigation levels and nutrient application ($I \times T$) was not significant in either growth stage or year of study, showing that the combined effect of irrigation and nutrient treatments did

not lead to statistically significant changes in RGR.

With respect to RGR in linseed from 30 DAS through to 60 DAS, it appears that there is a slight increase as the amount of irrigation increased, although no significant differences were observed between treatments at 60 DAS and 90 DAS. This could be due to the fact that the inherent nature of RGR means that as plants age, the number of structural parts tends to increase and therefore RGR would be expected to decrease. During the early part of the growth cycle (30-60 DAS), the optimum temperature and humidity during the two growing seasons caused a large increase in biomass production based on dry weight, thus resulting in a slight increase in RGR for the I₁ and I₂ irrigation treatments. However, when comparing the I₁ treatment to the I₂ treatment for 60-90 DAS there were no significant differences observed between irrigation treatments as a result of similar thermal conditions and the increase in partitioning to reproductive parts that occurred for both irrigation treatments. At both early and late growth stages relative growth rates (RGR) were not significantly different between treatments nor for interaction between nutrients and irrigation. The results indicate that initial intrinsic growth potential is the primary determinant of relative biomass growth rather than from external inputs. It appears that at later growth stages RGR is more dependent on the crops' phenological development and current environmental conditions compared to how much was irrigated or fertilized (Hunt, 1990; Radford, 1967; Sharma *et al.*, 2019).

Table 4.2.3.a: Effect of seed priming, humic acid, and sulphur application on relative growth rate of linseed different irrigation intervals 2022-23 and 2023-24.

Relative growth rate ($\text{g g}^{-1}\text{day}^{-1}$)				
Treatment	30-60 DAS		60-90 DAS	
	2022-23	2023-24	2022-23	2023-24
Main plot: Irrigation level (I)				
I ₀	0.069	0.067	0.043	0.046
I ₁	0.078	0.077	0.045	0.047
I ₂	0.079	0.081	0.048	0.050
SEm$\pm$	0.002	0.002	0.001	0.001
CD (P=0.05)	0.006	0.006	NS	NS
Sub plot: Nutrient application (T)				
T ₀	0.069	0.068	0.049	0.051
T ₁	0.080	0.079	0.047	0.048
T ₂	0.079	0.078	0.048	0.050
T ₃	0.078	0.078	0.046	0.048
T ₄	0.076	0.075	0.044	0.046
T ₅	0.071	0.070	0.044	0.046
T ₆	0.078	0.077	0.044	0.045
SEm$\pm$	0.003	0.003	0.003	0.003
CD (P=0.05)	NS	NS	NS	NS
Interaction I $\times$ T				
SEm$\pm$	0.006	0.006	0.005	0.005
CD (P=0.05)	NS	NS	NS	NS
Interaction T $\times$ I				
SEm$\pm$	0.004	0.004	0.004	0.003
CD (P=0.05)	NS	NS	NS	NS

Note:

- 1- I₀: No post sowing irrigation, I₁: Post sowing irrigation one, I₂: Post sowing irrigation two,
- 2- T₀: Control, T₁: Potassium Nitrate, T₂: Sulphur, T₃: Humic acid, T₄: KNO₃ + S, T₅: KNO₃ + HA, T₆: Sulphur + HA.

Fig 4.2.3 (a): Effect of seed priming, humic acid, and sulphur application on relative growth rate of linseed at different irrigation intervals 2022-23 and 2023-24.

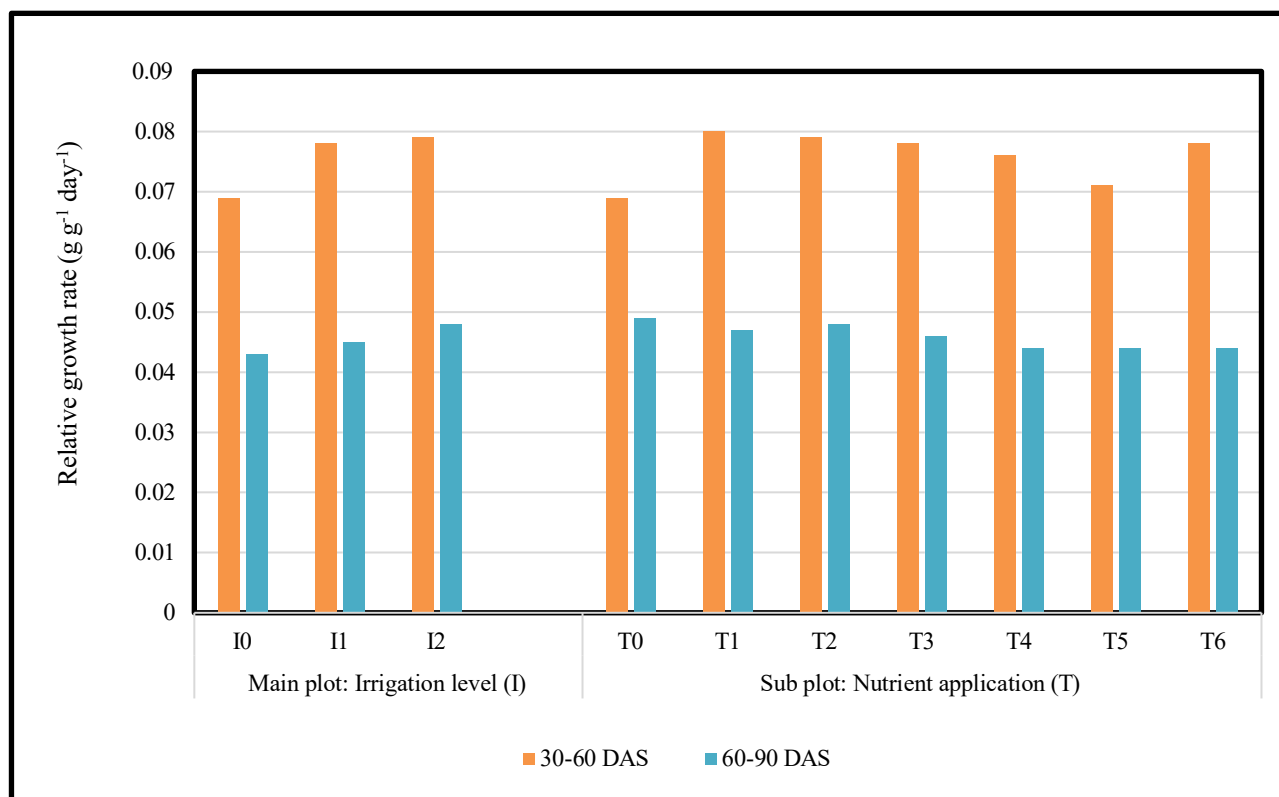
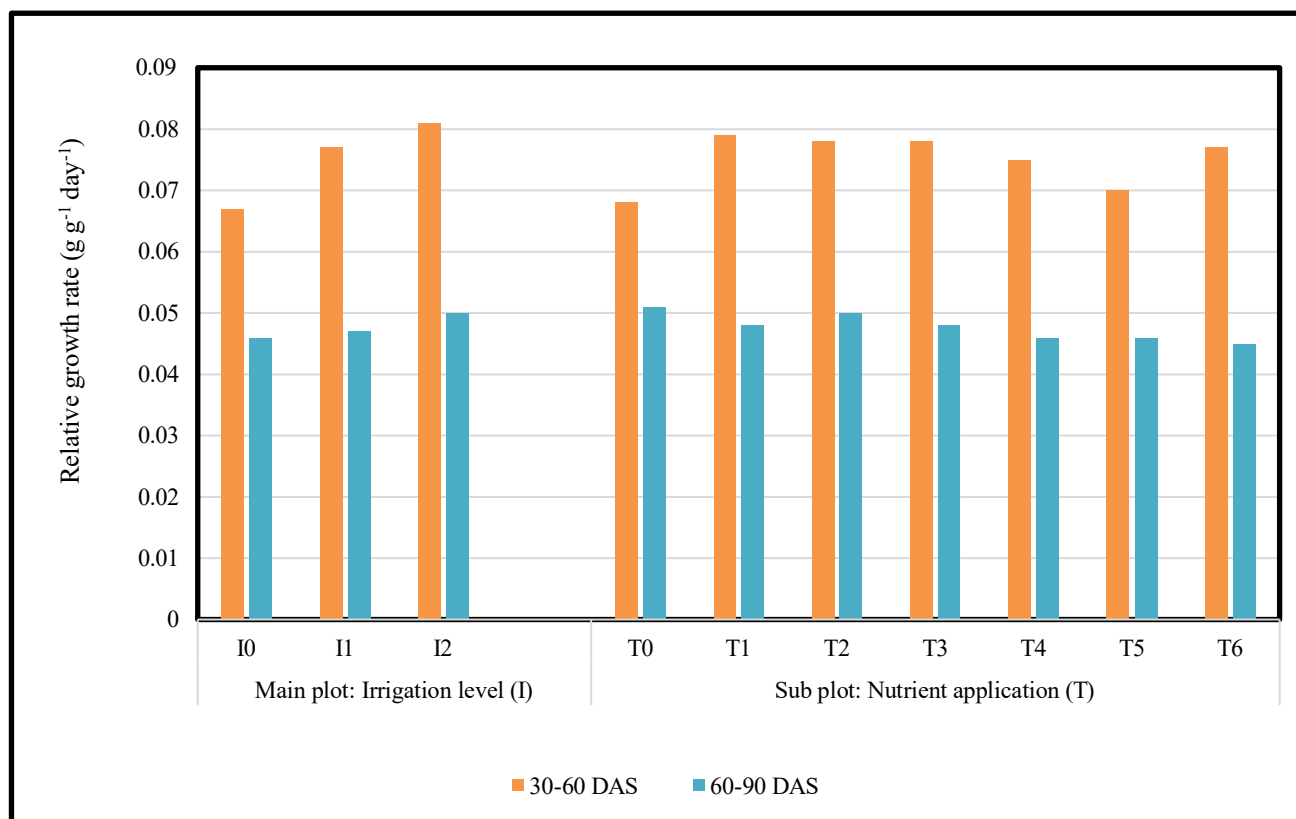


Fig 4.2.3(b): Effect of seed priming, humic acid, and sulphur application on relative growth rate of linseed different irrigation intervals (2023-24)



4.2.4 : Effect of seed priming, humic acid, and sulphur application on net assimilation rate of linseed under different irrigation intervals.

The net assimilation rate (NAR) of linseed was significantly influenced by irrigation levels and nutrient application during the early growth stage (30–60 DAS), whereas during the later growth stage (60–90 DAS), the effects were found to be non-significant in both years of experimentation (2022–23 and 2023–24), as presented in Table 4.2.4(a).

Effect of irrigation levels

Irrigation levels had a statistically significant effect on NAR in both years between 30 and 60 DAS. The highest NAR in 2022–23 was under I_2 ($0.144 \text{ g g}^{-1} \text{ day}^{-1}$), which was much higher than I_0 ($0.101 \text{ g g}^{-1} \text{ day}^{-1}$) and statistically the same as I_1 ($0.131 \text{ g g}^{-1} \text{ day}^{-1}$) because the differences were within the CD ($P = 0.05$) value of $0.024 \text{ g g}^{-1} \text{ day}^{-1}$.

A similar pattern was observed in 2023–24, when I_2 ($0.147 \text{ g g}^{-1} \text{ day}^{-1}$) had a much higher NAR than I_0 ($0.100 \text{ g g}^{-1} \text{ day}^{-1}$) and was still the same as I_1 ($0.133 \text{ g g}^{-1} \text{ day}^{-1}$).

During 60–90 DAS, the levels of irrigation did not cause a big change in NAR in either year, as shown by the CD values not being significant. Under I_2 , the NAR was higher than under I_1 , and under I_0 , it was the lowest.

Effect of nutrient application

During 30 to 60 days after sowing (DAS) in both years, nutrient application treatments had a statistically significant effect on NAR. The highest NAR in 2022–23 was found under T_5 ($0.180 \text{ g g}^{-1} \text{ day}^{-1}$), which was much higher than any other nutrient treatment. The differences were greater than the CD ($P = 0.05$) value of $0.025 \text{ g g}^{-1} \text{ day}^{-1}$. The control group (T_0 : $0.069 \text{ g g}^{-1} \text{ day}^{-1}$) had the lowest NAR.

The treatments T_4 ($0.155 \text{ g g}^{-1} \text{ day}^{-1}$) and T_6 ($0.145 \text{ g g}^{-1} \text{ day}^{-1}$) were statistically similar, but they were much better than T_1 , T_2 , and T_3 .

A similar pattern occurred in 2023–24, with T_5 ($0.181 \text{ g g}^{-1} \text{ day}^{-1}$) showing a much higher NAR than T_4 and T_6 , and the control treatment staying much lower.

The nutrient application treatments did not differ significantly during 60–90 DAS in either year, as shown by the non-significant CD values. Nonetheless, T_5 exhibited a numerically superior NAR in comparison to other treatments.

Effect of interaction ($I \times T$)

The interaction effect between irrigation levels and nutrient application ($I \times T$) was determined to be non-significant during both growth stages and across both years, suggesting that the response of NAR to nutrient treatments was not influenced by irrigation regimes.

At 30 days after sowing (DAS), the net assimilation rate (NAR) for linseed increased significantly across each irrigation level relative to the other treatments throughout the entire growing season. The treatment with I₂ had the highest NAR values during both growing seasons. These results support the conclusion that increased soil moisture improves photosynthetic efficiency because of the benefits associated with turgidity of leaves and the mobility of nutrients for the plant to utilise. The combination of KNO₃ with humic acid (T₅) also yielded the highest NAR values from both growing seasons. The synergy of the combined treatments on NAR indicates that these types of treatments improve nutrient uptake, promote chlorophyll synthesis, and increase the metabolic activity of the plant. There were no significant differences in crop growth 60-90 days after sowing due to the application of nitrogen and irrigation treatments. This may be attributed to leaf ageing, saturation and increased use of assimilates for reproductive growth which would reduce net photosynthetic efficiency on a unit area basis. There were no significant interaction effects between these treatments so NAR during this later stage of growth level appears to be influenced largely by crop phenological stages and prevailing environmental conditions rather than the application of nitrogen and/or irrigation (Radford 1967; Hunt 1990; Taiz *et al* 2015).

Table 4.2.4.a: Effect of seed priming, humic acid, and sulphur application on net assimilation rate of linseed at different irrigation intervals (2022-23 and 2023-24).

Net assimilation rate ($\text{g m}^{-2} \text{ day}^{-1}$)				
Treatment	30-60 DAS		60-90 DAS	
	2022-23	2023-24	2022-23	2023-24
Main plot: Irrigation level (I)				
I ₀	0.101	0.100	0.373	0.381
I ₁	0.131	0.133	0.429	0.444
I ₂	0.144	0.147	0.460	0.480
SEm±	0.006	0.006	0.021	0.022
CD (P=0.05)	0.024	0.025	NS	NS
Sub plot: Nutrient application (T)				
T ₀	0.069	0.069	0.373	0.386
T ₁	0.111	0.112	0.412	0.426
T ₂	0.092	0.093	0.410	0.424
T ₃	0.127	0.129	0.416	0.430
T ₄	0.155	0.156	0.410	0.424
T ₅	0.180	0.181	0.500	0.518
T ₆	0.145	0.146	0.423	0.438
SEm±	0.009	0.009	0.026	0.027
CD (P=0.05)	0.025	0.025	NS	NS
Interaction I × T				
SEm±	0.015	0.015	0.045	0.046
CD (P=0.05)	NS	NS	NS	NS
Interaction T × I				
SEm±	0.016	0.017	0.057	0.059
CD (P=0.05)	NS	NS	NS	NS

Note:

- 1- I₀: No post sowing irrigation, I₁: Post sowing irrigation one, I₂: Post sowing irrigation two
- 2- T₀: Control, T₁: Potassium Nitrate, T₂: Sulphur, T₃: Humic acid, T₄: KNO₃ + S, T₅: KNO₃ + HA, T₆: Sulphur + HA.

Fig 4.2.4(a): Effect of seed priming, humic acid, and sulphur application on net assimilation rate of linseed different irrigation intervals (2022-23)

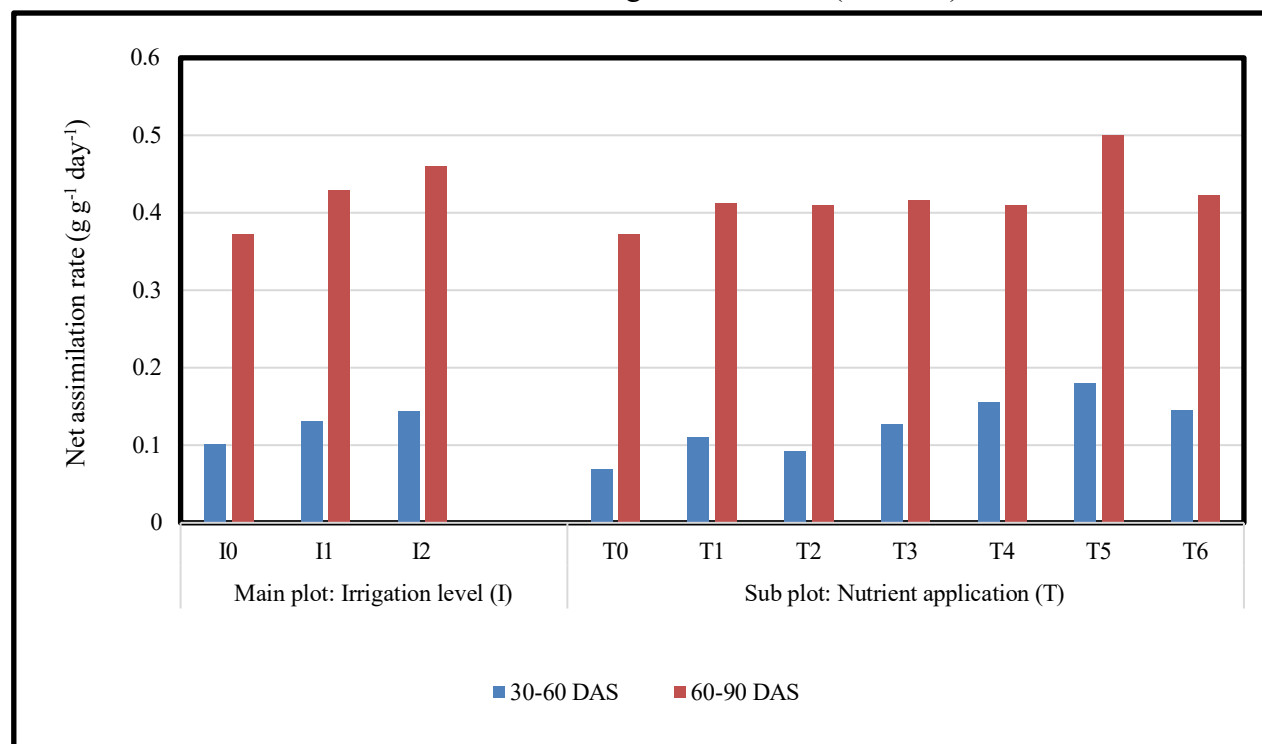
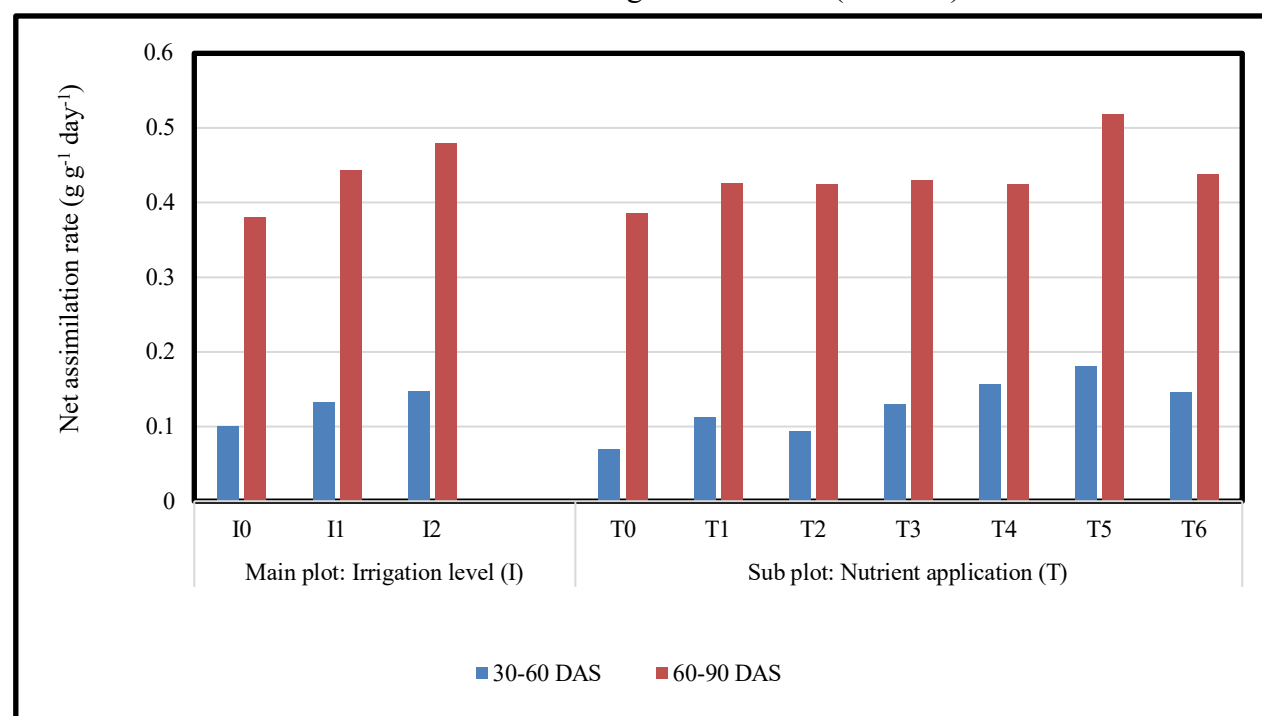


Fig 4.2.4(b): Effect of seed priming, humic acid, and sulphur application on net assimilation rate of linseed different irrigation intervals (2023-24)



4.2.5 Effect of seed priming, humic acid and sulphur application on crop phenology of linseed under different irrigation intervals.

Irrigation levels exerted a significant influence on most phenological stages of linseed, except days taken for emergence, during both the years of experimentation (2022–23 and 2023–24) (Table 4.2.5a and 4.2.5b)

Days taken for emergence

The number of days taken for emergence was not significantly affected by irrigation levels during both years, as the differences among treatments were smaller than the CD ($P = 0.05$). However, numerically, I_0 recorded the earliest emergence, while I_2 showed slightly delayed emergence, indicating that soil moisture variation had little influence on seedling emergence.

Days taken for branching

The number of days used for branching decreased when irrigation levels were increased over both growing seasons. In 2022-23, I_2 had more hours of development before branching started (75.05 days) than I_1 (64.57) or I_0 (57.62) that were statistically significant since the differences between the means exceeded the critical difference of 2.42 days. In the 2023-24 year, the delay in development before branching began with I_2 (70.97) versus I_1 (64.27) and I_0 (57.20) was also statistically significant. This suggests that more irrigation delayed branching, probably because the plants grew more vegetatively for a longer time in good moisture conditions.

Days taken for 50% flowering

The number of days until 50% flowering occurred increased significantly as the level of irrigation increased in both years. The maximum number of days to flowering recorded for I_2 in 2022-23 was 112.15 days, which was significantly longer than I_1 (104.63 days) and I_0 (95.17 days), with a CD ($P=0.05$) of 3.33 days. The same trend was found for 2023-24, with I_2 (108.42 days) being significantly longer than I_1 (101.08 days) and I_0 (94.78 days).

Days taken for maturity

The results from both years showed that higher levels of irrigation significantly delayed crop maturity. The biggest delay in crop maturity happened in 2022–23 with an irrigation level of I_2 . It took 144.90 days for the crops to mature, which was much longer than the levels I_1 (136.01 days) and I_0 (123.52 days). This was because the differences in maturity rates were greater than the critical difference of 1.29 days. For the 2023–24 growing season, crops grown with irrigation level I_2 took a lot longer to mature than crops grown with irrigation levels I_1 and I_0 .

Effect of nutrient application

Results of both years indicate that application of nutrients had a large impact on all phenological parameters measured. T_5 had significantly earlier emergence and significantly later branching, flowering,

and maturity as compared with control (T_0). Differences between T_5 and T_0 exceeded CD ($P = 0.05$) value for the respective years for the various phenological parameters. The combination of nutrient treatments typically had much greater impact than the individual nutrient treatments tested; however, T_0 consistently exhibited early flowering and maturity indicating less vegetative growth.

Interaction effect ($I \times T$)

Statistical analysis revealed that the interaction between irrigation levels and treatment application rates significantly influenced the days taken for emergence during both years and branching during 2023–24 (Table 4.2.5b; CD at $P=0.05$). The maximum delay in branching was observed under the $I_2 \times T_5$ treatment combination. This suggests that plant growth under comparatively higher soil moisture conditions might have been prolonged due to enhanced nutrient availability resulting from the application of 20% higher nutrients than the recommended NPK dose. However, no significant interaction effect between irrigation and treatments was observed for flowering and maturity, indicating that irrigation and nutrient treatments acted independently under the prevailing environmental conditions.

Days taken for emergence remained non-significant across irrigation levels during both years, suggesting that initial crop establishment was primarily governed by inherent seed vigour and the existing soil moisture conditions at sowing rather than by post-sowing irrigation practices. Irrigation was found to be the major factor influencing delays in vegetative branching, flower initiation, and maturity. The I_2 irrigation level recorded the maximum delay, indicating that greater moisture availability enhanced vegetative growth by reducing moisture stress, thereby slowing the progression through various phenological stages. A similar trend was observed with nutrient application treatments, wherein the KNO_3 + humic acid treatment (T_5) exhibited significantly delayed phenological development compared to the other treatments. This may be attributed to improved nutrient availability, enhanced metabolic activity resulting from nutrient application, and better canopy development. In contrast, the control treatment attained flowering and maturity earlier, possibly due to accelerated crop completion under nutrient and moisture stress conditions. Overall, the phenological development of linseed was predominantly influenced by the independent effects of irrigation and nutrient management, while interaction effects were minimal (Hunt, 1990; Taiz *et al.*, 2015; Sarkar and Sarkar, 2017).

Table 4.2.5(a): Effect of seed priming, humic acid, and sulphur application on crop phenology of linseed different irrigation intervals (2022-23 and 2023-24).

Treatment	Days taken for emergence		Days for branching		Days taken for 50% flowering		Days taken for maturity	
	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24
Main plot: Irrigation level (I)								
I ₀	8.22	8.86	57.62	57.20	95.17	94.78	123.52	126.22
I ₁	8.39	8.52	64.57	64.27	104.63	101.08	136.01	138.25
I ₂	8.41	8.86	75.05	70.97	112.15	108.42	144.90	147.54
SEm±	0.11	0.08	0.62	0.56	0.85	0.77	0.33	0.58
CD (P=0.05)	NS	NS	2.42	2.19	3.33	3.01	1.25	2.36
Sub plot: Nutrient application (T)								
T ₀	10.39	11.00	61.78	60.60	97.28	93.59	132.56	133.71
T ₁	8.17	9.00	63.89	62.56	101.18	99.53	133.96	136.71
T ₂	8.85	9.44	62.67	61.44	101.39	98.35	133.44	136.17
T ₃	8.88	8.67	64.67	62.49	104.46	102.09	134.63	136.88
T ₄	7.46	7.89	68.67	66.34	106.92	104.62	136.08	139.09
T ₅	7.21	7.33	70.78	70.18	111.54	108.96	137.71	140.22
T ₆	7.42	7.89	67.78	65.42	105.11	102.83	135.30	138.59
SEm±	0.19	0.22	0.45	0.42	0.37	0.56	0.70	0.83
CD (P=0.05)	0.54	0.63	1.29	1.19	1.11	1.59	2.00	2.38
Interaction I × T								
SEm±	0.32	0.38	0.78	0.72	1.04	1.16	1.17	1.44
CD (P=0.05)	0.93	1.10	NS	2.91	NS	NS	NS	NS
Interaction T × I								
SEm±	0.29	0.21	1.63	1.47	2.21	2.00	0.82	1.55
CD (P=0.05)	0.98	1.12	NS	2.42	NS	NS	NS	NS

Note:

- 1- I₀: No post sowing irrigation, I₁: Post sowing irrigation one, I₂: Post sowing irrigation two,
- 2- T₀: Control, T₁: Potassium Nitrate, T₂: Sulphur, T₃: Humic acid, T₄: KNO₃ + S, T₅: KNO₃ + HA, T₆: Sulphur + HA.

Fig 4.2.5 (a): Effect of seed priming, humic acid, and sulphur application on crop phenology of linseed different irrigation intervals (2022-23).

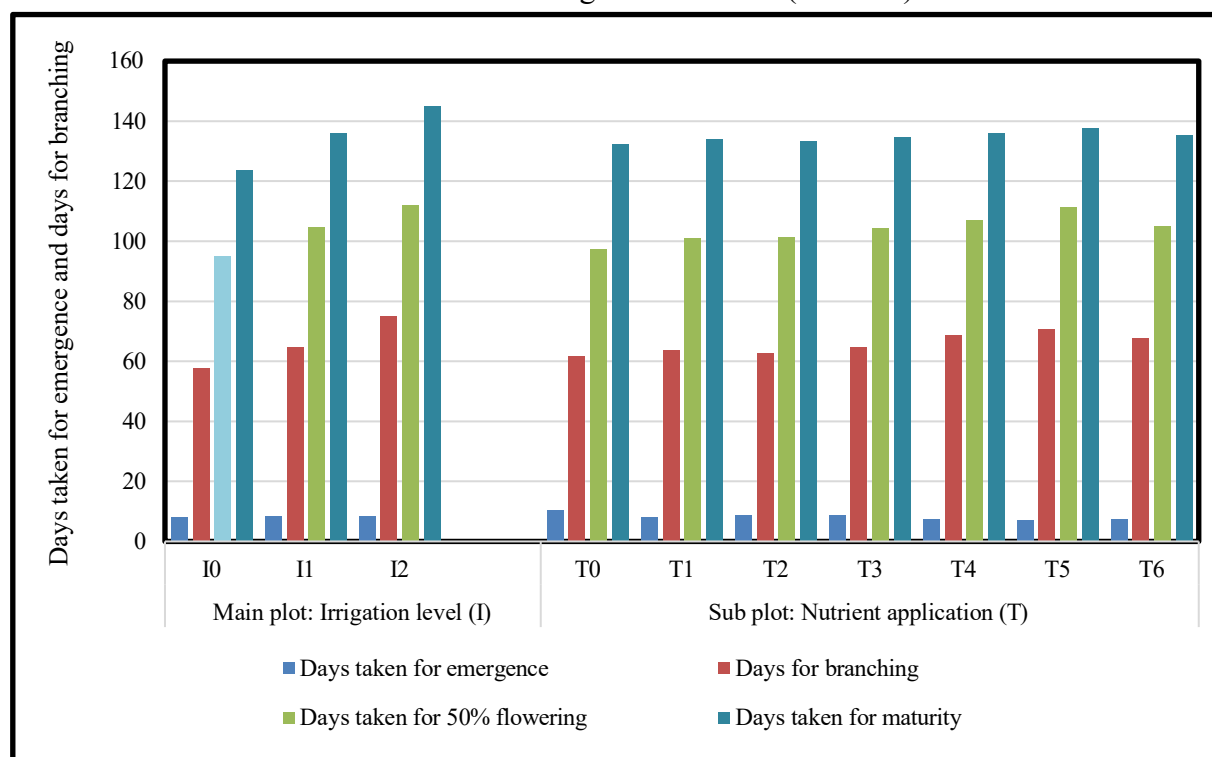


Fig 4.2.5 (b): Effect of seed priming, humic acid, and sulphur application on crop phenology of linseed different irrigation intervals (2023-24).

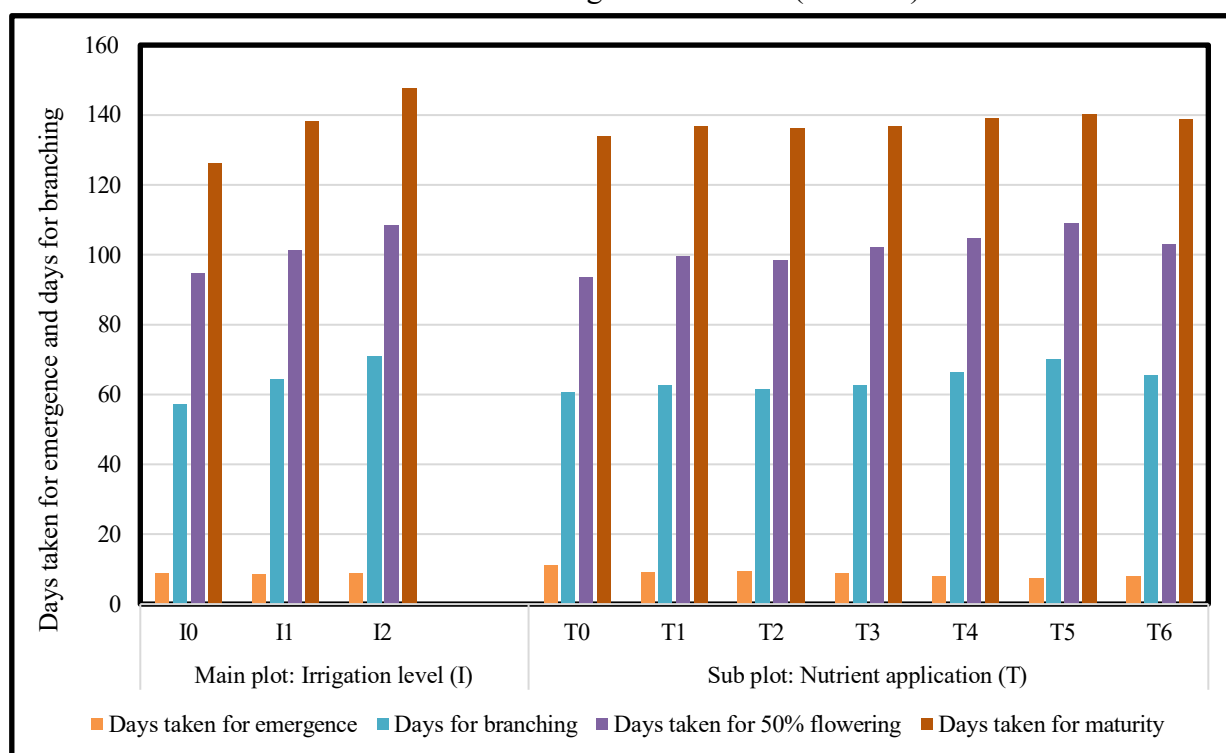


Table 4.2.5 (b): Interactive effect of seed priming, humic acid, and sulphur application on days taken for emergence and branching of linseed different irrigation intervals (2022-23 and 2023-24).

A. Days taken for emergence

Irrigation intervals	I ₀	I ₁	I ₂	Mean	I ₀	I ₁	I ₂	Mean
	2022–23				2023–24			
T ₀	10.50	10.33	10.33	10.39	11.67	10.67	10.67	11.00
T ₁	7.63	7.56	9.33	8.17	8.33	8.33	10.33	9.00
T ₂	7.56	9.67	9.33	8.85	8.33	10.33	9.67	9.44
T ₃	9.67	9.33	7.63	8.88	10.00	7.67	8.33	8.67
T ₄	7.51	7.19	7.67	7.46	8.33	7.33	8.00	7.89
T ₅	7.11	7.19	7.33	7.21	7.33	7.33	7.33	7.33
T ₆	7.56	7.48	7.22	7.42	8.00	8.00	7.67	7.89
Mean	8.22	8.39	8.41	8.34	8.86	8.52	8.66	8.75
SEM±			0.32			0.38		
CD (P=0.05)			0.93			1.10		

B. Days taken for branching

Irrigation intervals	I ₀	I ₁	I ₂	Mean
T ₀	53.90	59.90	68.01	60.60
T ₁	56.22	62.90	68.56	62.56
T ₂	55.29	60.53	68.49	61.44
T ₃	53.21	63.90	70.34	62.49
T ₄	60.17	67.10	71.77	66.34
T ₅	62.21	70.13	78.19	70.18
T ₆	59.40	65.43	71.43	65.42
Mean	57.20	64.27	70.97	64.81
SEM±		0.72		
CD (P=0.05)		2.07		

4.3.0 Physiological parameters:

4.3.1 Effect of seed priming, humic acid, and sulphur application on relative water content of linseed under different irrigation intervals.

The data presented in Table 4.3.1.a revealed that relative water content (RWC) of linseed was significantly influenced by irrigation levels at 45 DAS, 90 DAS, and at harvest during both the years (2022–23 and 2023–24).

Among the irrigation treatments, I₂ recorded the highest relative water content at all growth stages during both years of experimentation and remained statistically at par with I₁, whereas both treatments showed significantly higher RWC than the rainfed treatment (I₀). The comparatively lower RWC observed under I₀ indicated greater moisture stress, reduced leaf hydration, and restricted water uptake. Thus, the higher RWC under irrigated conditions reflected improved plant water status due to better soil moisture availability.

Nutrient management treatments and their interaction with irrigation levels were found to be non-significant at all stages of crop growth during both years. This suggests that nutrient applications did not exert any independent influence on relative water content under the prevailing experimental conditions. The non-significant interaction effect further indicated that the regulation of plant water status by irrigation occurred independently of nutrient management practices. Overall, soil moisture availability remained the primary factor governing plant water relations in linseed, whereas nutrient-induced effects on RWC were comparatively negligible (Blum, 2011; Taiz *et al.*, 2015).

Table 4.3.1.a: Effect of seed priming, humic acid, and sulphur application on relative water content of linseed different irrigation intervals (2022-23 and 2023-24).

Relative water content (%)							
Treatment	45 DAS			90 DAS		At harvest	
	2022-23	2023-24		2022-23	2023-24	2022-23	2023-24
Main plot: Irrigation level (I)							
I ₀	53.75	50.61		58.05	54.28	59.60	55.54
I ₁	68.42	64.43		67.93	63.51	69.74	64.98
I ₂	71.28	67.13		68.93	64.45	70.77	65.96
SEm±	1.18	1.13		0.51	0.48	0.53	0.50
CD (P=0.05)	4.64	4.43		2.01	1.90	2.07	1.97
Sub plot: Nutrient application (T)							
T ₀	61.25	57.68		63.58	59.46	65.29	60.86
T ₁	64.59	60.83		64.90	60.68	66.63	62.09
T ₂	64.21	60.46		64.33	60.16	66.06	61.57
T ₃	64.71	60.92		64.96	60.74	66.69	62.14
T ₄	65.04	61.27		65.51	61.25	67.25	62.67
T ₅	66.80	62.90		66.17	61.87	67.93	63.29
T ₆	64.77	61.01		65.34	61.10	67.08	62.52
SEm±	1.40	1.32		0.80	0.75	0.82	0.76
CD (P=0.05)	NS	NS		NS	NS	NS	NS
Interaction I × T							
SEm±	2.42	2.29	2.24	1.39	1.30	1.43	1.32
CD (P=0.05)	NS	NS	NS	NS	NS	NS	NS
Interaction T × I							
SEm±	1.621	1.556	1.354	1.284	1.395	1.322	4.156
CD (P=0.05)	NS	NS	NS	NS	NS	NS	NS

Note:

- 1- I₀: No post sowing irrigation, I₁: Post sowing irrigation one, I₂: Post sowing irrigation two,
- 2- T₀: Control, T₁: Potassium Nitrate, T₂: Sulphur, T₃: Humic acid, T₄: KNO₃ + S, T₅: KNO₃ + HA, T₆: Sulphur + HA.

Fig 4.3.1(a): Effect of seed priming, humic acid, and sulphur application on relative water content of linseed different irrigation intervals (2022-23).

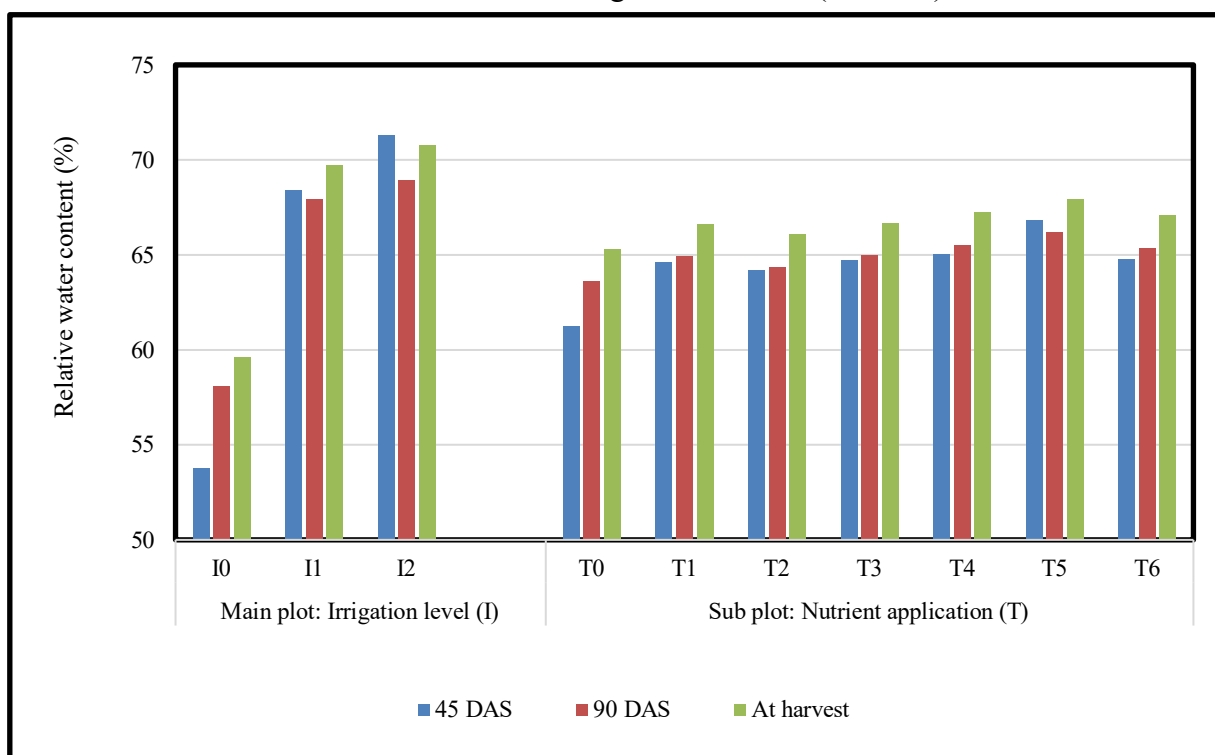
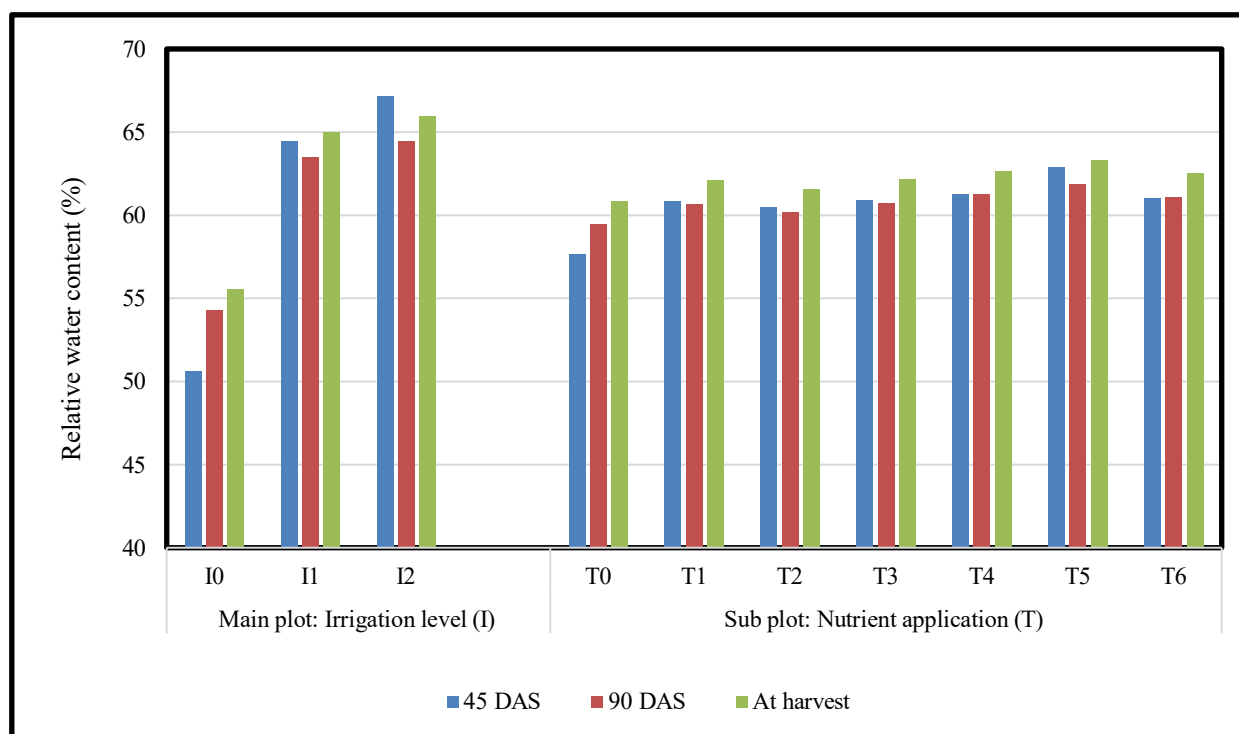


Fig 4.3.1(b): Effect of seed priming, humic acid, and sulphur application on relative water content of linseed different irrigation intervals (2023-24).



4.3.2 Effect of seed priming, humic acid, and sulphur application on membrane stability index of linseed under different irrigation intervals.

The results are presented in Table 4.3.2.a indicated that irrigation levels significantly influenced the membrane stability index (MSI) of linseed at 45 DAS, 90 DAS, and at harvest during both years (2022–23 and 2023–24).

The irrigation treatments that provided the greatest MSI throughout all growth stages and during both growing seasons were treatments I_2 (i.e., received two irrigations after sowing). For instance, MSI at 45 DAS were found to be 56.03% and 61.42% for I_2 during 2022-23 and 2023-24, respectively; while these values were significantly greater than I_0 and I_1 based on the differences exceeding the critical difference values for each year (i.e., 4.49, $P = 0.05$ and 3.69, $P = 0.05$). Similarly, by 90 D.A.S. and at harvest, I_2 consistently provided greater MSI than I_0 and I_1 , which illustrates that adequate irrigation can improve the integrity of cell membranes.

At all times in both years, the lowest membrane stability index was always recorded in plants that received no irrigation after sowing (I_0), as indicated by the increase in membrane injury due to stress from lack of moisture.

With respect to the treatments of nutrients being applied, the MSI of each of the eight treatments represented significant differences at 45 DAS and 90 DAS for both years, due to all treatments showing variation greater than the respective CD ($p = 0.05$) for both the 45 DAS and 90 DAS measurements. The combination of KNO_3 and humic acid (T_5) had the greatest MSI at 45 DAS (67.94% and 56.69%) and at 90 DAS (58.23% and 55.54%) for the 2022–23 and 2023–24 seasons, respectively, and were significantly greater than the control (T_0) and the other treatments applied individually.

The Treatments had significantly different Effects on the Membrane Stability Index (MSI) in the 2022-23. Treatment 5 (T_5) had the Highest MSI (60.97%), being statistically superior to Treatments 0, 1, and 2 according to the Critical Difference (CD) of 5.18. There was no significant difference between the Nutrient Treatments at harvest in the 2023-24 period, indicating that there is a Convergence of Treatment Effects at Maturity.

The Interaction Effect between Irrigation Levels and Nutrient Application ($I \times T$) on the MSI at all Growth Stages over both Years was also non-significant, indicating that the MSI was Consistent Regardless of Irrigation Regime.

At each developmental stage, both years displayed a marked effect of varying irrigation levels on MSI, with I_2 recording the highest values followed by I_1 and I_0 consistently incurred lower MSI values; therefore, it is concluded that there was improved membrane damage through increase lipid peroxidation as a result of moisture stress and oxidative injuries due an abundance of soil moisture on Day 45 after seeding (DAS)

as compared to when there was a lower amount of soil moisture during that time relative to higher atmospheric demand. The improved performance of MSI under I_1 and I_2 can be attributed to higher levels of cellular water content; lower thermal and chemical oxidative stress than would occur under similar pressures and high atmospheric demand in both years was due to improved soil moisture conditions than would be found under dry conditions of I_0 . The same trend has been noted under all years. Comparing all nutrient treatments for the combined treatment of KNO_3 + humic acid (T_5) shows that increased biomass production from improved SSI resulted from improvement of membrane stability through media (therefore mitigating thermal and water stress) from improved nutrient availability. While the response patterns were similar for both years, seasonal temperature and humidity were also related to absolute values; thus, irrigation (degree and timings) was the most important factor in regulating membrane stability (Blum, 2011; Taiz *et al.*, 2015).

Table 4.3.2.a: Effect of seed priming, humic acid, and sulphur application on membrane stability index of linseed different irrigation intervals (2022-23 and 2023-24).

Membrane stability index (%)						
Treatment	45 DAS		90 DAS		At harvest	
	2022- 23	2023-24	2022-23	2023-24	2022-23	2023-24
Main plot: Irrigation level (I)						
I ₀	49.13	41.07	43.17	40.32	45.86	43.29
I ₁	54.29	47.65	54.14	51.08	56.53	52.67
I ₂	56.03	61.42	63.00	58.83	66.17	61.61
SEm±	1.14	0.94	1.30	0.50	1.12	2.39
CD (P=0.05)	4.49	3.69	5.09	1.96	4.41	9.39
Sub plot: Nutrient application (T)						
T ₀	43.69	46.38	49.42	46.30	51.20	47.87
T ₁	47.65	48.41	51.87	48.32	54.64	51.01
T ₂	44.14	47.18	50.31	46.78	52.26	49.73
T ₃	54.44	49.80	52.67	49.67	56.38	52.60
T ₄	58.46	51.62	56.94	52.65	59.88	55.79
T ₅	67.94	56.69	58.23	55.54	60.97	56.82
T ₆	55.74	50.27	54.61	51.28	57.97	53.86
SEm±	1.80	1.89	1.78	1.92	1.81	2.20
CD (P=0.05)	5.15	5.42	5.11	5.50	5.18	NS
Interaction I × T						
SEm±	3.11	3.27	3.08	3.32	3.13	3.82
CD (P=0.05)	NS	NS	NS	NS	NS	NS
Interaction T×I						
SEm±	4.159	9.081	5.892	5.595	8.959	8.277
CD (P=0.05)	NS	NS	NS	NS	NS	NS

Note:

- 3- I₀: No post sowing irrigation, I₁: Post sowing irrigation one, I₂: Post sowing irrigation two,
- 4- T₀: Control, T₁: Potassium Nitrate, T₂: Sulphur, T₃: Humic acid, T₄: KNO₃ + S, T₅: KNO₃ + HA, T₆: Sulphur + HA.

Fig 4.3.2(a): Effect of seed priming, humic acid, and sulphur application on membrane stability index of linseed different irrigation intervals (2022-23).

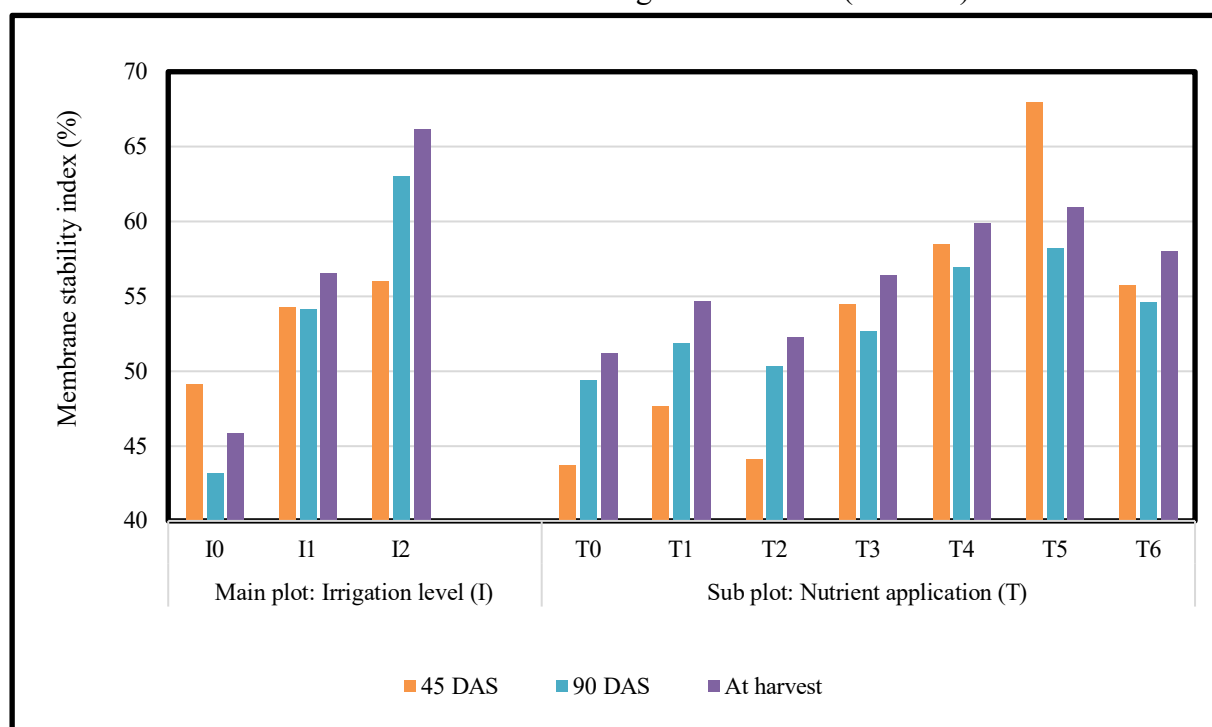
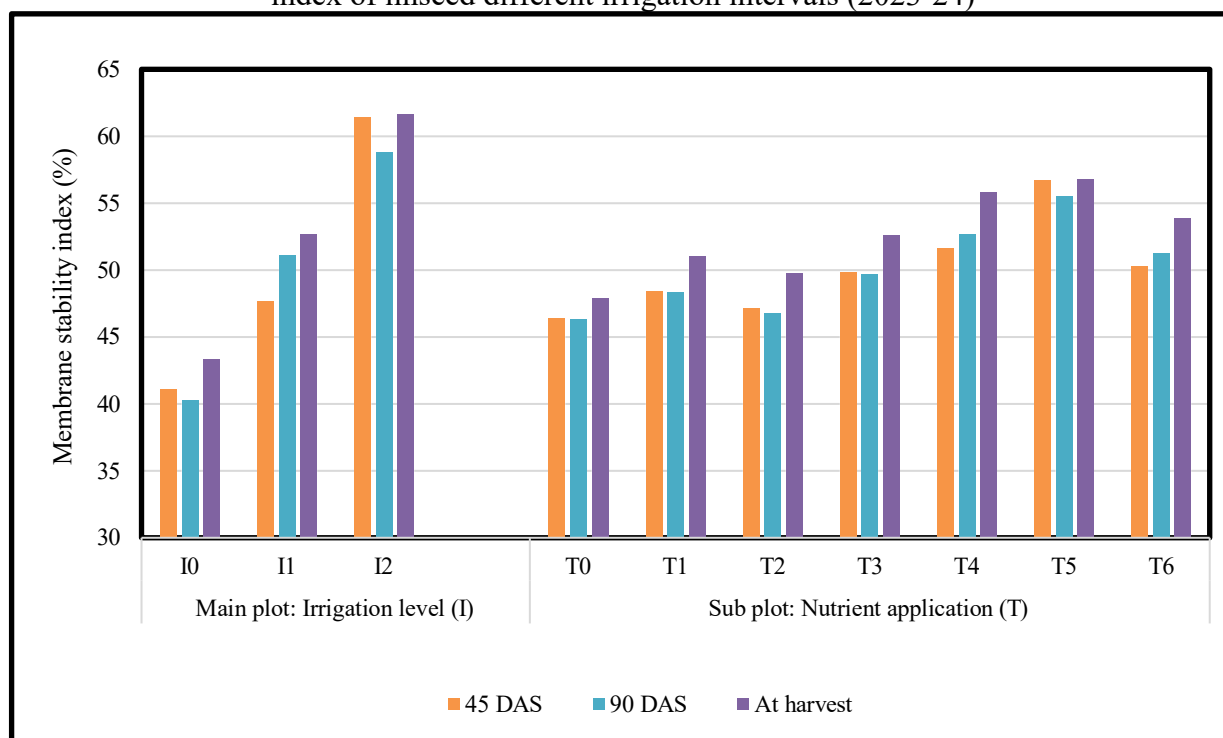


Fig 4.3.2(b): Effect of seed priming, humic acid, and sulphur application on membrane stability index of linseed different irrigation intervals (2023-24)



4.3.3 Effect of seed priming, humic acid, and sulphur application on membrane injury index of linseed under different irrigation intervals. (graph)

The data presented in Table 4.3.3.a showed that irrigation levels markedly influenced the membrane injury index (MII) of linseed at different stages of crop growth during both the years (2022–23 and 2023–24).

Out of all irrigation treatments available, the treatment that involved no irrigation after sowing (I_0) showed the highest level of damage to plant membranes which suggests a greater amount of damage took place on the plant's membranes due to moisture stress than all of the other treatments. In comparison, the treatment with two post-sowing irrigations (I_2) demonstrated the lowest level of membrane damage at every growth stage.

The treatment that involved two post-sowing irrigations (I_2) at 45 days after sowing (DAS) during 2023-2024 (represented as 38.48%) was significantly better than the treatment that had no post-sowing irrigation at this growth stage and exceeded the critical difference value (CD) of 3.69 for $p = 0.05$, while the results for the same growth stage during 2022-2023 did not show a statistically significant difference.

The membrane injury index for linseed was affected by both the irrigation and nutrient treatments applied at later growth stages in both years of the experiment. At 45 days after sowing (DAS), differences in the membrane injury index across the various irrigation treatments were largely not significant due to the favourable weather conditions and residual soil moisture, leading to no stress being experienced at early growth stages. However, at 90 DAS and at harvest, higher levels of irrigation (I_2 and I_1) resulted in significantly lower membrane injury index compared to I_0 . Therefore, it may be concluded that adequate irrigation leads to increased stability of cell membranes due to improved plant water status, particularly during periods of increasing temperatures and higher evaporative demands during periods without rainfall. As seen by higher membrane injury under I_0 , it suggests that moisture-induced stress increases the permeability of membranes resulting in cellular damage. Nutrient applications, especially combined applications of KNO_3 and humic acid, decrease the membrane injury index resulting in enhanced tolerance to stress due to improved osmotic regulation, antioxidant activity, and nutrient balance. There was no significant interaction between irrigation and nutrient treatments; therefore, the beneficial effect of nutrients on membrane stability was consistent across irrigation levels. The present data support earlier findings (Yadav and Meena, 2019; Kumar *et al.*, 2021b; Sharma *et al.*, 2018) that adequate irrigation and integrated nutrient management reduce stress-related cellular damage.

Table 4.3.3.a: Effect of seed priming, humic acid, and sulphur application on membrane injury index of linseed different irrigation intervals (2022-23 and 2023-24).

Membrane injury index (%)						
Treatment	45 DAS		90 DAS		At harvest	
	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24
Main plot: Irrigation level (I)						
I ₀	50.72	58.83	56.73	59.58	54.04	56.61
I ₁	45.61	52.25	45.76	48.82	43.37	47.23
I ₂	43.19	38.48	36.90	41.07	33.73	38.29
SEm±	1.57	0.94	1.30	0.50	1.12	2.39
CD (P=0.05)	NS	3.69	5.09	1.96	4.41	9.39
Sub plot: Nutrient application (T)						
T ₀	56.21	53.52	50.48	53.60	48.70	52.03
T ₁	52.25	51.49	48.03	51.58	45.25	48.89
T ₂	55.76	52.72	49.59	53.12	47.65	50.17
T ₃	45.46	50.10	47.22	50.23	43.52	47.30
T ₄	40.86	48.28	42.96	47.25	40.02	44.11
T ₅	30.85	43.21	41.67	44.36	38.93	43.08
T ₆	44.16	49.64	45.29	48.63	41.93	46.04
SEm±	5.62	1.89	1.78	1.92	1.81	2.20
CD (P=0.05)	16.13	5.42	5.11	5.50	5.18	NS
Interaction I × T						
SEm±	9.74	3.27	3.08	3.32	3.13	3.82
CD (P=0.05)	NS	NS	NS	NS	NS	NS
Interaction T × I						
SEm±	2.268	1.896	0.914	1.472	1.474	1.079
CD (P=0.05)	NS	NS	NS	NS	NS	NS

Note:

- 1- I₀: No post sowing irrigation, I₁: Post sowing irrigation one, I₂: Post sowing irrigation two,
- 2- T₀: Control, T₁: Potassium Nitrate, T₂: Sulphur, T₃: Humic acid, T₄: KNO₃ + S, T₅: KNO₃ + HA, T₆: Sulphur + HA.

Fig 4.3.3(a): Effect of seed priming, humic acid, and sulphur application on membrane injury index of linseed different irrigation intervals (2022-23)

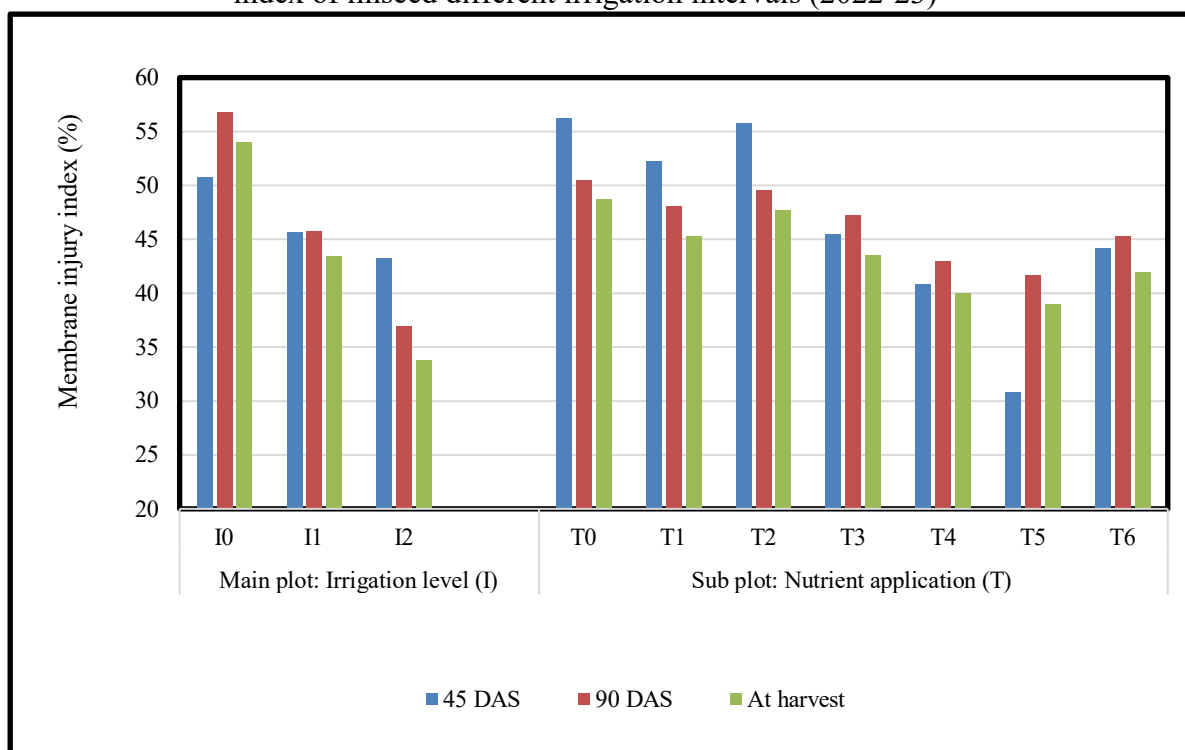
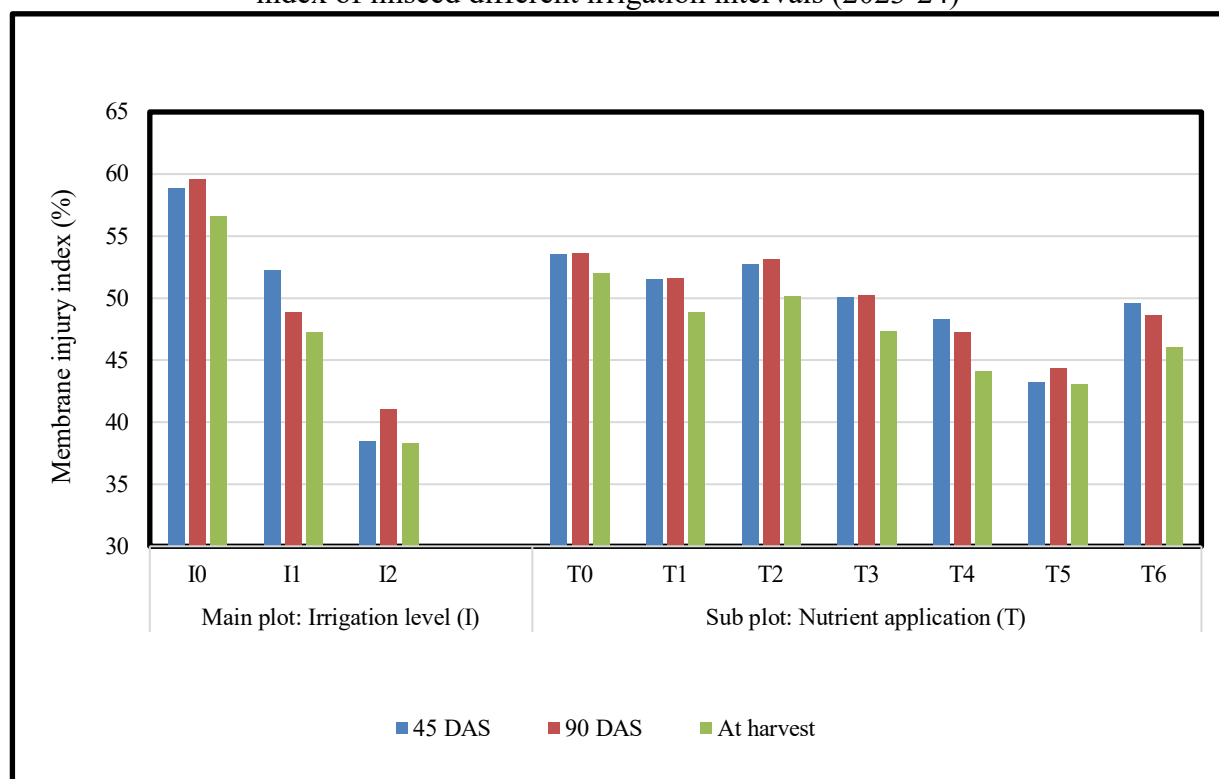


Fig 4.3.3(b): Effect of seed priming, humic acid, and sulphur application on membrane injury index of linseed different irrigation intervals (2023-24)



4.4 Biochemical parameter

4.4.1 Effect of seed priming, humic acid, and sulphur application on chlorophyll a of linseed under different irrigation intervals.

The data presented in the table indicate that chlorophyll a content (mg g^{-1}) of linseed was not significantly influenced by irrigation levels, nutrient application, or their interactions at 45 DAS, 90 DAS, and at harvest during both years of experimentation (2022–23 and 2023–24).

Effect of irrigation levels

Irrigation levels did not show a significant effect on chlorophyll a content at any stage of crop growth during either year, as the differences among treatments were statistically non-significant. At 45 DAS, chlorophyll a content ranged from 1.29 to 1.35 mg g^{-1} during 2022–23 and 1.28 to 1.43 mg g^{-1} during 2023–24. Similar non-significant variations were observed at 90 DAS and at harvest, indicating that variation in post-sowing irrigation frequency did not markedly influence chlorophyll a content of linseed.

Effect of nutrient application

The application of nutrients did not significantly affect the levels of chlorophyll a at any of the time points in either year. Although T₄ (KNO₃ and sulphur) and T₅ (KNO₃ and humic acid) produced marginally higher amounts of chlorophyll a than all other treatments, the experiments were considered to have similar amounts of chlorophyll a since all treatments increased less than their respective CD ($p = 0.05$). The control treatment (T₀) consistently produced lower amounts of chlorophyll a than the experimental treatments; however, the difference was not statistically significant.

At both the 45 DAS and 90-DAS, as well as at harvest, the combined influence of irrigation treatments and nutrient applications on chlorophyll a content in linseed was non-significant. The study did not find significant differences in the level of chlorophyll a in linseed plants among levels of irrigation due to the consistent amount of chlorophyll produced during both growing seasons of the study. These results suggest that, even though the environmental conditions have changed during the two years of the study, the ability of linseed to produce chlorophyll has remained constant. There were numerically higher levels of chlorophyll a for linseed under irrigation levels I₁ and I₂, but the differences were not statistically significant. Likewise, our results indicated that all species had similar amounts of chlorophyll a across all treatments based on nutrient applied during each of the sampling times at each location, but combined treatment effects of seed priming, humic acid and sulphur had slightly greater amounts than nutrient only application indicating greater quantities; possible increased nutrition from longer lasting nutrients. Lack of interaction effects also indicates that chlorophyll a was less impacted when comparing different irrigation and nutrient management (other than to remain consistent). Previous studies have shown that

levels of chlorophyll a are relatively constant regardless of presence of either temporary (low moisture) or moderate (long-term) to extreme (high moisture) environmental times (Sharma *et al.*, 2018; Kumar *et al.*, 2021b; and Yadav and Meena 2019

Table 4.4.1.a: Effect of seed priming, humic acid, and sulphur application on chlorophyll (a) of linseed different irrigation intervals (2022-23 and 2023-24).

Chlorophyll a (mg g⁻¹)						
Treatment	45 DAS		90 DAS		At harvest	
	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24
Main plot: Irrigation level (I)						
I ₀	1.35	1.28	1.61	1.33	1.73	1.42
I ₁	1.34	1.32	1.55	1.54	1.66	1.65
I ₂	1.29	1.43	1.48	1.59	1.58	1.71
SEm±	0.03	0.04	0.06	0.07	0.06	0.08
CD (P=0.05)	NS	NS	NS	NS	NS	NS
Sub plot: Nutrient application (T)						
T ₀	1.30	1.25	1.54	1.17	1.65	1.25
T ₁	1.39	1.33	1.61	1.52	1.73	1.63
T ₂	1.29	1.31	1.50	1.51	1.61	1.61
T ₃	1.31	1.35	1.50	1.55	1.61	1.66
T ₄	1.44	1.38	1.55	1.56	1.66	1.67
T ₅	1.30	1.44	1.59	1.56	1.70	1.67
T ₆	1.27	1.35	1.52	1.54	1.62	1.65
SEm±	0.04	0.06	0.06	0.11	0.07	0.14
CD (P=0.05)	NS	NS	NS	NS	NS	NS
Interaction I × T						
SEm±	0.07	0.10	0.11	0.18	0.12	0.25
CD (P=0.05)	NS	NS	NS	NS	NS	NS
Interaction T × I						
SEm±	0.079	0.096	0.153	0.169	0.164	0.230
CD (P=0.05)	NS	NS	NS	NS	NS	NS

Note:

- 1- I₀: No post sowing irrigation, I₁: Post sowing irrigation one, I₂: Post sowing irrigation two,
- 2- T₀: Control, T₁: Potassium Nitrate, T₂: Sulphur, T₃: Humic acid, T₄: KNO₃ + S, T₅: KNO₃ + HA, T₆: Sulphur + HA.

Fig 4.4.1.a: Effect of seed priming, humic acid, and sulphur application on chlorophyll (a) of linseed different irrigation intervals (2022-23).

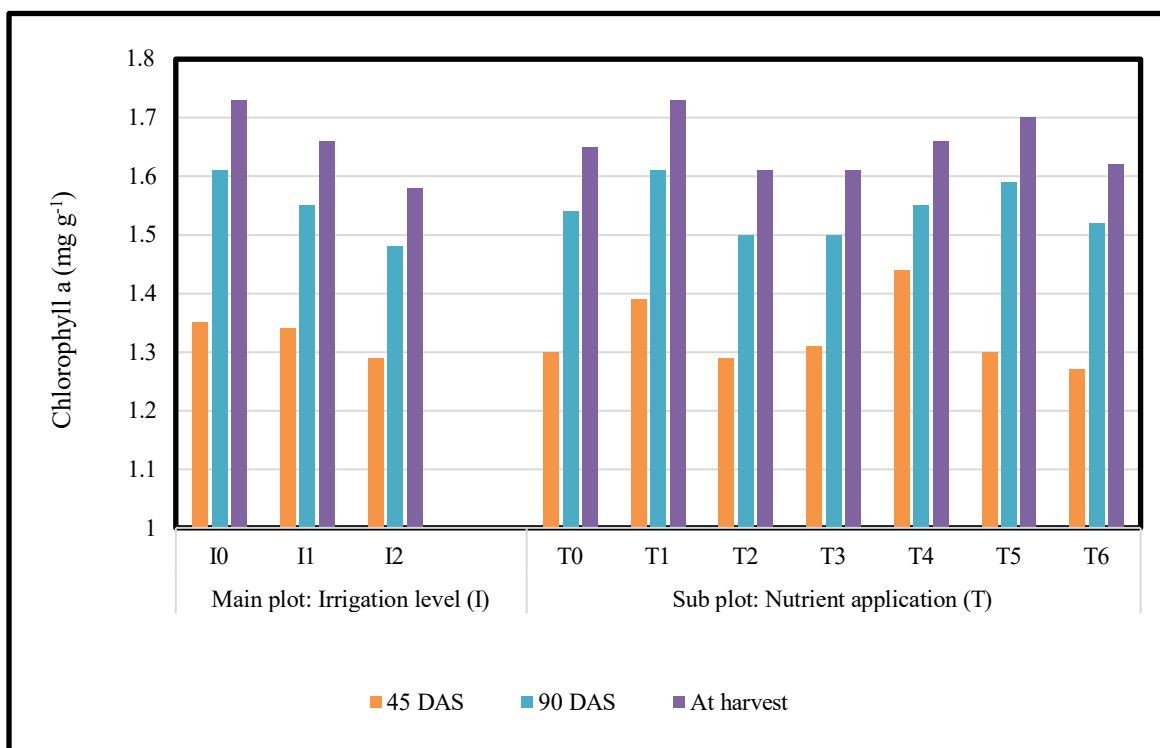
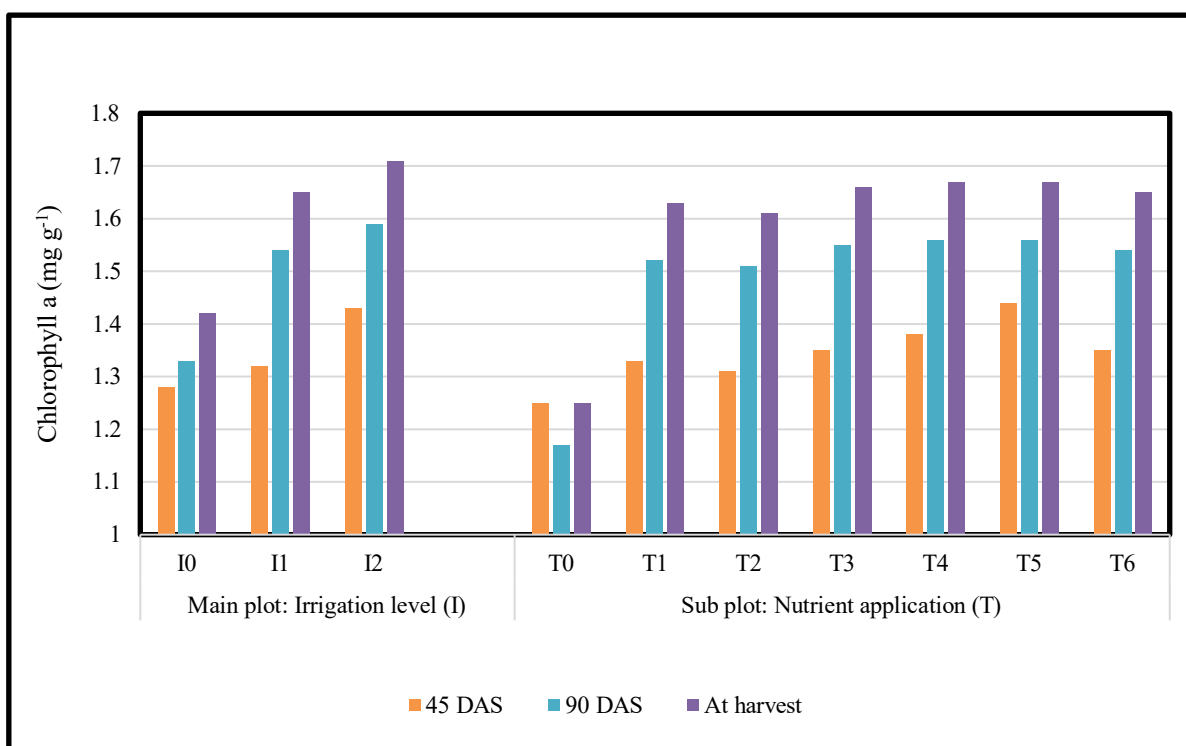


Fig 4.4.1(b): Effect of seed priming, humic acid, and sulphur application on chlorophyll (a) of linseed different irrigation intervals (2023-24)



4.4.2 Effect of seed priming, humic acid, and sulphur application on chlorophyll (b) of linseed under different irrigation intervals.

The data presented in Table 4.4.2 (a) show that chlorophyll b content (mg g^{-1}) of linseed was not significantly affected by irrigation levels, nutrient application, or their interactions at 45 DAS, 90 DAS, and at harvest during both years of experimentation (2022–23 and 2023–24).

Effect of irrigation levels

At all stages of growth for both years of the study, irrigation levels had no significant impact on chlorophyll b content because the average difference in treatment was not statistically different. For the 2022–23 growing season, at 45 days after sowing, chlorophyll b content ranged from 1.44 to 1.62 mg/g and for the 2023–24 growing season ranged from 1.44 to 1.67 mg/g . The same results were found at 90 days after sowing and at harvest, as no major treatment differences were noted between I_2 (two irrigations after planting) and I_0 regardless of the numerically higher chlorophyll b values associated with I_2 .

Effect of nutrient application

Overall, nutrient application did not have any significant influence on chlorophyll b concentration throughout any of the growth stages for either year. For two out of the growth stages (flowering and mature green), higher numerical chlorophyll b concentrations were measured with the use of combined nutrient treatments of T_4 (KNO_3 + sulphur) and T_5 (KNO_3 + humic acid); however, these differences did not reach statistical significance (i.e. $\text{CD } p = 0.05$). T_0 (control) had lower chlorophyll b concentrations compared to the combined treatments; however, these differences were also not statistically significant.

The interaction effects irrigation level and nutrient application ($I \times T$ and $T \times I$) were not significant at any growth stage for both years of study, which indicates that the interaction of the two treatments had no effect on chlorophyll b levels.

At 45 days after sowing (DAS), at 90 DAS and at harvest there were no significant differences in chlorophyll b concentration in linseed due to irrigation levels, treatments or the interaction of these factors in either of the two years, hence we can conclude that chlorophyll b concentration was not significantly influenced by changes in moisture or nutrient management based on the environmental conditions prevailing at the time. Despite chlorophyll b concentrations being numerically higher under increased irrigation levels (I_1 and I_2), especially later in the growing season, the differences were not statistically significant, indicating that the level of moisture stress suffered under I_0 was not severe enough to reduce chlorophyll b formation. The combination of seed priming treatments with Humic Acid and Sulphur has resulted in slightly higher levels of chlorophyll b probably because of better nutrient availability, and therefore, improved photosynthetic activity but these differences were not significant. It can also be seen from the lack of significant interaction effects that chlorophyll b was fairly constant and less affected by

moderate changes in irrigation and nutrients than by severe amounts of either. This goes along with previous reports stating that chlorophyll b is stable under mild moisture stress but only shows a clear response to moisture stress when it is under severe moisture stress (Sharma *et al.*, 2018; Kumar *et al.*, 2021b; Yadav and Meena, 2019).

Table 4.4.2.a: Effect of seed priming, humic acid, and sulphur application on chlorophyll (b) of linseed different irrigation intervals (2022-23 and 2023-24).

Chlorophyll b (mg g⁻¹)						
Treatment	45 DAS		90 DAS		At harvest	
	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24
Main plot: Irrigation level (I)						
I ₀	1.44	1.44	1.48	1.53	1.58	1.63
I ₁	1.51	1.57	1.54	1.66	1.65	1.78
I ₂	1.62	1.67	1.64	1.76	1.76	1.88
SEm±	0.05	0.04	0.11	0.06	0.11	0.07
CD (P=0.05)	NS	NS	NS	NS	NS	NS
Sub plot: Nutrient application (T)						
T ₀	1.33	1.51	1.55	1.57	1.66	1.68
T ₁	1.47	1.52	1.51	1.60	1.62	1.71
T ₂	1.48	1.53	1.64	1.59	1.75	1.70
T ₃	1.61	1.51	1.46	1.55	1.56	1.65
T ₄	1.60	1.62	1.54	1.73	1.65	1.85
T ₅	1.61	1.63	1.61	1.89	1.72	2.02
T ₆	1.56	1.59	1.57	1.63	1.68	1.74
SEm±	0.07	0.08	0.11	0.09	0.12	0.09
CD (P=0.05)	NS	NS	NS	NS	NS	NS
Interaction I × T						
SEm±	0.12	0.13	0.19	0.15	0.20	0.16
CD (P=0.05)	NS	NS	NS	NS	NS	NS
Interaction T × I						
SEm±	0.130	0.119	0.280	0.158	0.301	0.176
CD (P=0.05)	NS	NS	NS	NS	NS	NS

Note:

I₀: No post sowing irrigation, I₁: Post sowing irrigation one, I₂: Post sowing irrigation two, T₀: Control, T₁: Potassium Nitrate, T₂: Sulphur, T₃: Humic acid, T₄: KNO₃ + S, T₅: KNO₃ + HA, T₆: Sulphur + HA.

Fig 4.4.2 (a) Effect of seed priming, humic acid, and sulphur application on chlorophyll (b) of linseed under different irrigation intervals (2022-23)

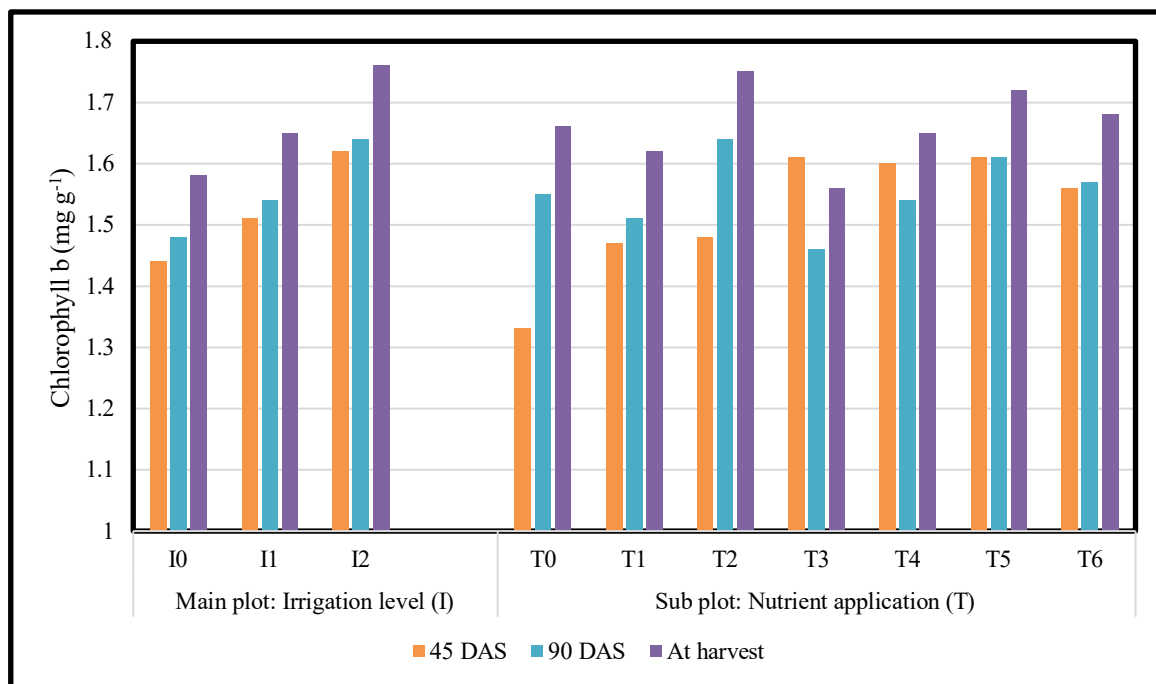
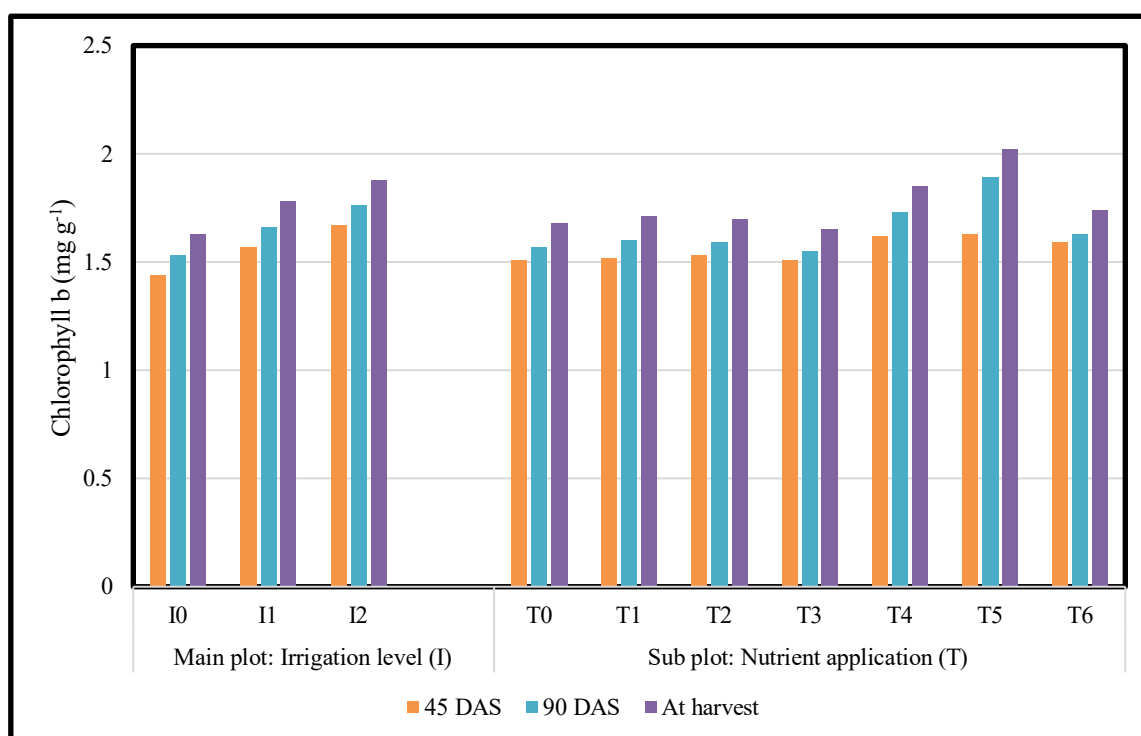


Fig 4.4.2 (b) Effect of seed priming, humic acid, and sulphur application on chlorophyll (b) of linseed under different irrigation intervals (2023-24).



4.4.3 Effect of seed priming, humic acid, and sulphur application on total chlorophyll of linseed under different irrigation intervals.

The data presented in Table 4.4.3 (a) indicate that total chlorophyll content (mg g^{-1}) of linseed was partially influenced by irrigation levels and nutrient application, while their interaction effects were non-significant during both years of experimentation (2022–23 and 2023–24).

Effects of irrigation levels

The total chlorophyll content of the plants was statistically different among irrigation treatments within each growing season. For the 2022–23 season, there were no significant differences in total chlorophyll content as determined by irrigation treatments and measurement dates. The chlorophyll measurements for the 2023–24 growing season were different at the 45 DAS and harvest, but did not differ at the 90 DAS

The greatest total chlorophyll content at 45 DAS (2023–24 growing season) was with I_2 (3.10 mg g^{-1}) and was statistically significant when compared to I_0 (2.72 mg g^{-1}). I_1 had a total chlorophyll content that was not significantly different than I_2 . At 2023–24 harvest, I_2 also had the greatest chlorophyll content (3.59 mg g^{-1}) and was statistically different than I_0 (3.05 mg g^{-1}). The total chlorophyll content from plants treated with I_1 were not statistically different than the content of plants treated with I_2 .

Effect of nutrient application

The application of nutrients significantly affected total chlorophyll concentration at 45 days after sowing (DAS) in 2022-23, with treatment T_4 ($\text{KNO}_3 + \text{S}$) having the greatest concentration of 3.04 mg g^{-1} , which was significantly higher than the control treatment (T_0), since the difference was greater than the least significant difference (LSD) (0.18). However, the remainder of the treatments were not significantly different from each other.

At 90 das and harvest time of 2022-23, the application of nutrients had no significant effect on total chlorophyll concentration; however, in 2023-24, the application of nutrients resulted in significantly different total chlorophyll concentrations both at 90 DAS and at harvest time. At 90 das, treatment T_5 ($\text{KNO}_3 + \text{humic acid}$) exhibited the greatest total chlorophyll concentration of 3.45 mg g^{-1} and was found to be significantly different from the control, as the difference exceeded the LSD (0.29). Treatment T_5 also exhibited the greatest total chlorophyll concentration at harvest (3.69 mg g^{-1}), and was significantly higher than T_0 , again exceeding the LSD (0.31).

The irrigation level and fertilizer application ($I \times T$ and $T \times I$) interaction effects were not significant at any stage of crop development across the two years of study. Therefore, the combined effect of irrigation and nutrient treatments does not affect total chlorophyll content. At both 45 and 90 days after sowing for each year, there was no significant difference in the total chlorophyll content of linseed for the different

levels of irrigation. This indicates that there was uniformity in pigment development throughout early and mid-stages of growth. However, at the time of harvest, the two irrigation levels (I₁ and I₂) during 2023-24, had significantly more total chlorophyll than I₃. This indicates that appropriate soil moisture throughout the later stages of crop growth assisted in maintaining chlorophyll stability. The application of nutrients had a statistically significant effect on total chlorophyll at both 45 days after sowing (2022-23) and 90 days after sowing and harvest (2023-24). In addition, treatments involving seed priming, humic acid, and sulphur (in particular T₅) had significantly more total chlorophyll than any of the other treatments. It is likely that these treatments improved nutrient uptake, facilitated the synthesis of chlorophyll, and delayed leaf senescence. At every growth phase, the interaction effect of irrigation and fertiliser application (nutrients) type in this study was not determined. The results therefore, indicate that total chlorophyll level is primarily affected by the individual effect of water supply and treatment. These findings correspond with previous research (Sharma *et al.*, 2018; Kumar *et al.*, 2021b; Yadav and Meena, 2019) that suggests that providing an adequate level of irrigation and using an integrated nutrient application programme will assist in maintaining chlorophyll levels and improving photosynthesis efficiency in oilseed crops.

Table 4.4.3.a: Effect of seed priming, humic acid, and sulphur application on total chlorophyll of linseed at different intervals (2022-23 and 2023-24).

Total chlorophyll (mg g⁻¹)						
Treatment	45 DAS		90 DAS		At harvest	
	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24
Main plot: Irrigation level (I)						
I ₀	2.78	2.72	3.09	2.85	3.31	3.05
I ₁	2.85	2.90	3.09	3.20	3.30	3.43
I ₂	2.91	3.10	3.12	3.35	3.34	3.59
SEm±	0.06	0.04	0.09	0.05	0.10	0.05
CD (P=0.05)	NS	0.16	NS	0.19	NS	0.21
Sub plot: Nutrient application (T)						
T ₀	2.63	2.77	2.96	2.74	3.17	2.93
T ₁	2.85	2.85	3.12	3.12	3.34	3.34
T ₂	2.77	2.84	3.14	3.09	3.36	3.31
T ₃	2.93	2.86	3.10	3.10	3.32	3.31
T ₄	3.04	3.00	3.10	3.28	3.31	3.51
T ₅	2.90	3.07	3.20	3.45	3.42	3.69
T ₆	2.83	2.94	3.08	3.18	3.30	3.39
SEm±	0.06	0.07	0.10	0.10	0.11	0.11
CD (P=0.05)	0.18	NS	NS	0.29	NS	0.31
Interaction I × T						
SEm±	0.11	0.13	0.18	0.17	0.19	0.19
CD (P=0.05)	NS	NS	NS	NS	NS	NS
Interaction T×I						
SEm±	0.166	0.105	0.240	0.130	0.258	0.144
CD (P=0.05)	NS	NS	NS	NS	NS	NS

Note:

- 1- I₀: No post sowing irrigation, I₁: Post sowing irrigation one, I₂: Post sowing irrigation two,
- 2- T₀: Control, T₁: Potassium Nitrate, T₂: Sulphur, T₃: Humic acid, T₄: KNO₃ + S, T₅: KNO₃ + HA, T₆: Sulphur + HA.

Fig 4.4.3(a): Effect of seed priming, humic acid, and sulphur application on total chlorophyll different irrigation intervals (2022-23).

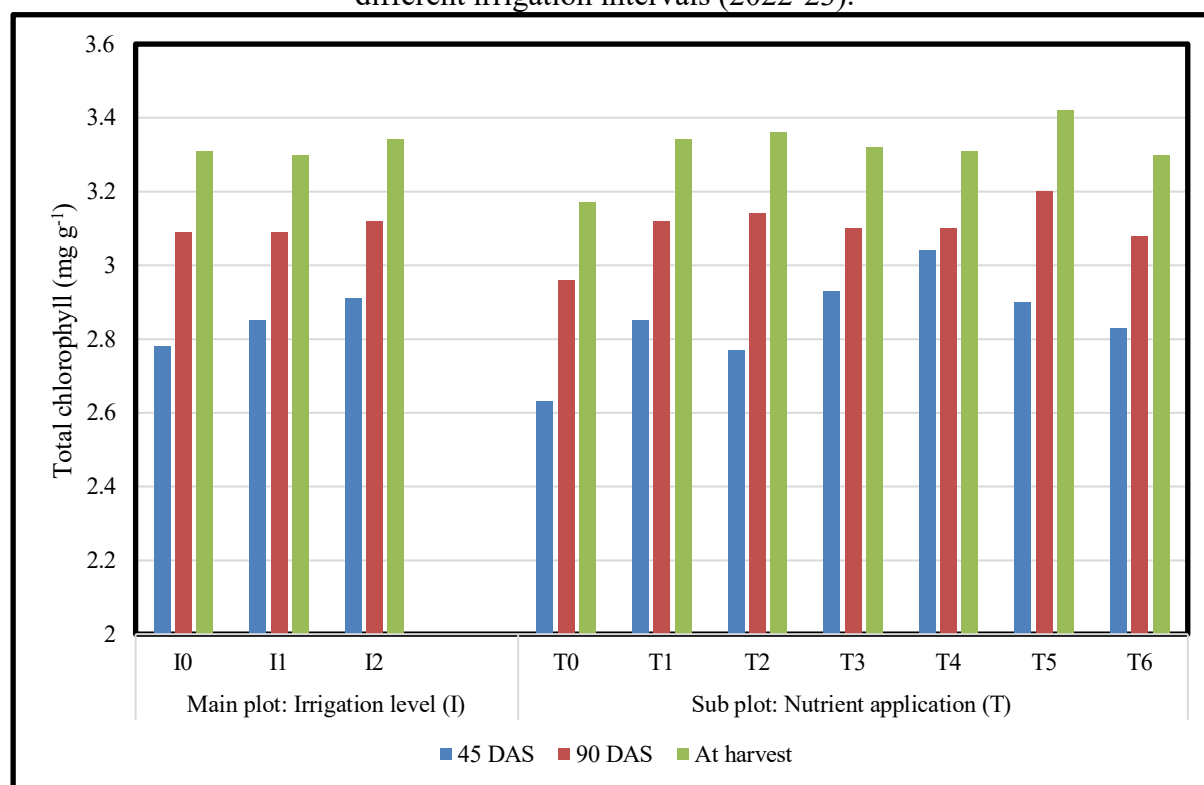
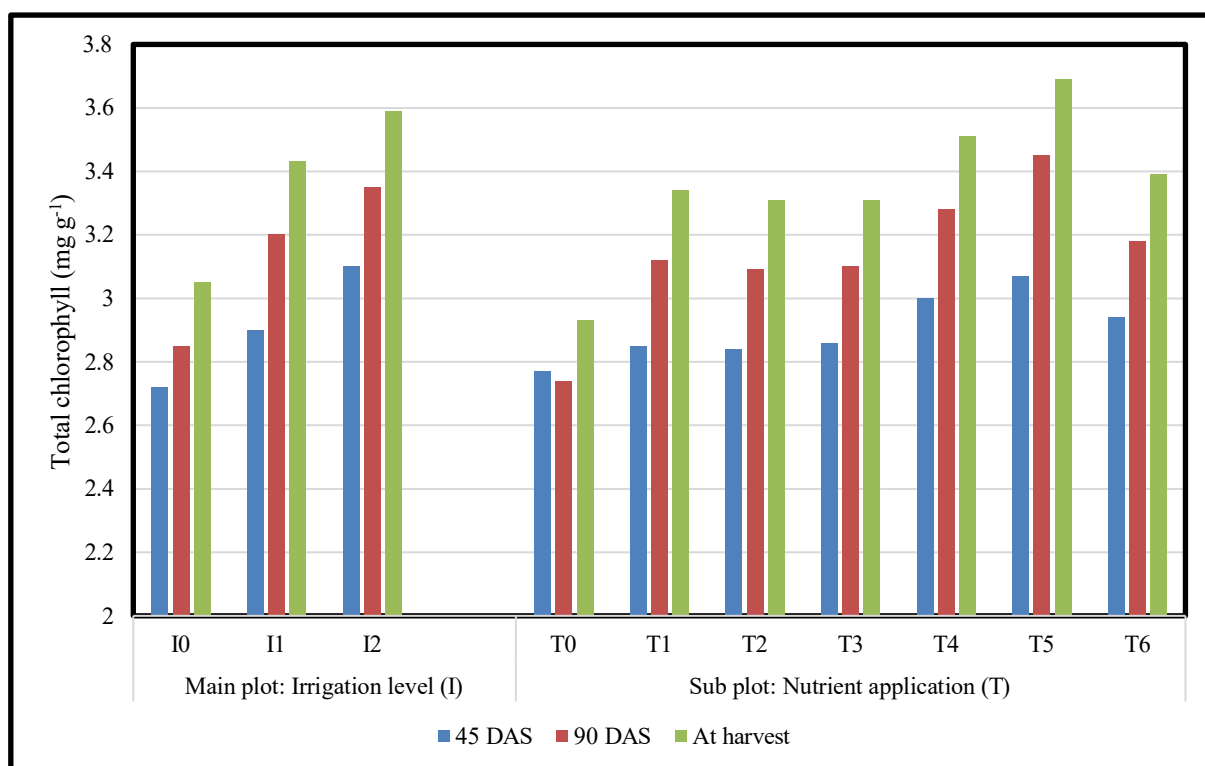


Fig 4.4.3(b): Effect of seed priming, humic acid, and sulphur application on total chlorophyll different irrigation intervals (2022-23).



4.4.4 Effect of seed priming, humic acid, and sulphur application on proline content of linseed under different irrigation intervals.

The data presented in Table 4.4.4 (a) indicate that proline content ($\mu\text{g g}^{-1}$) of linseed was significantly influenced by irrigation levels at certain growth stages, whereas nutrient application and interaction effects did not show significant influence during both years of experimentation (2022–23 and 2023–24).

Effect of irrigation levels

There was no apparent effect of irrigation on the proline content at the 45DAS, 90DAS, and harvest stages for 2022-23 as there were no significant differences between the treatments ($P > .05$). The irrigation treatment was significant at the 45-day and 90-day stages for the 2023–24 crop year, but not at the harvest stage. At the 45-day stage of the 2023–24 crop year, the I_0 treatment had the highest proline content ($2.07 \mu\text{g g}^{-1}$), significantly higher than the I_2 treatment ($1.52 \mu\text{g g}^{-1}$), as this exceeded the CD (critical difference) value of 0.23. The I_1 treatment was statistically similar to the I_0 and I_2 treatments. At the 90-day stage of the 2023–24 crop year, the I_0 treatment had the highest proline content ($3.50 \mu\text{g g}^{-1}$) compared to the I_2 treatment ($2.16 \mu\text{g g}^{-1}$) as this exceeded the 0.46 CD value. Increased proline accumulation as compared to the other irrigation treatments due to moisture stress conditions is evident based on these results. At harvest, the proline content of I_0 was higher than the other irrigation levels; however, there were no significant differences ($P > .05$) among irrigation levels in either 2022-23 or 2023-24.

Effect of nutrient application

There is no significant effect of nutrient application on the proline content at any growth stage in either year has been demonstrated, since there was no statistically significant difference among treatment means. However, on a numerical basis, proline levels were generally greater with the control treatment (T_0) compared to treatments with combined nutrient applications (T_4 and T_5), suggesting that improved nutrient status may have significantly reduced proline accumulation due to stress. This indicates that balanced nutrition, including potassium nitrate and even better when combined with humic acid or sulphur, has the potential to lower stress intensity due to improved efficiency of water and nutrient uptake in plants, which maintains cellular turgor and stability of metabolic functions (Narayan *et al.*, 2023; Canellas and Olivares, 2014). The combined nutrient treatment T_6 (S + HA) shows moderate to low concentrations (lower than T_0) of proline, which shows the treatment was able to moderate stress in plants. These results show the beneficial role of humic acid and sulphur, active ingredients both sought after in drought-stressed plants, in overcoming drought-induced stress by mitigating stress-related metabolic pathways and promoting maintenance of physiological stability.

Proline content in linseed didn't differ significantly among irrigation treatments at 45 DAS across both seasons, perhaps because irrigation stress was absent at that time due to excellent early-season weather

conditions with moderate temperatures and good soil moisture. However, with further development of the crop to 90 DAS and at harvest, there was significant accumulation of proline compared to the lower irrigation levels (I_0), indicating the ability of the linseed plants to make osmotic adjustments due to the increase in moisture stress due to high growing temperatures and increased evaporative demand during later growth phases. Irrigation levels (I_1 and I_2) decreased the proline content which indicates lower intensity of stress with sufficient moisture in the soil. The control treatment (T_0) had much higher proline levels than the treatment with nutrients, which indicated that the control treatment was under greater constraint than the other treatments. Conversely, the integrated treatments were lower in proline than the control treatment, meaning the plants were under less physiological stress than the control treatment and would therefore require more effort to recover from the stress than the integrated treatments. The lack of significance in the interaction between treatments implied that the accumulation of proline was based on the moisture and the overall stress level of the plants and not from their treatment. This result helps support previous results indicating that proline accumulates under drought and decreases as moisture and nutrient availability improve (Bates *et al.*, 1973; Farooq *et al.*, 2009; Sharma *et al.*, 2018).

Table 4.4.4.a: Effect of seed priming, humic acid, and sulphur application on proline content of linseed different irrigation intervals (2022-23 and 2023-24).

Treatment	Proline content ($\mu\text{g g}^{-1}$)					
	45 DAS		90 DAS		At harvest	
	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24
Main plot: Irrigation level (I)						
I ₀	1.55	2.07	2.36	3.50	3.07	4.74
I ₁	1.42	1.87	2.13	2.81	3.35	3.90
I ₂	1.24	1.52	2.09	2.16	3.02	3.12
SEm $\pm$	0.12	0.06	0.21	0.12	0.25	0.14
CD (P=0.05)	NS	0.23	NS	0.46	NS	0.56
Sub plot: Nutrient application (T)						
T ₀	1.93	2.01	3.05	3.29	4.18	4.49
T ₁	1.38	1.86	2.21	2.90	3.17	4.01
T ₂	1.37	1.93	2.20	2.99	3.16	4.12
T ₃	1.37	1.83	2.43	2.91	3.43	4.02
T ₄	1.29	1.71	1.53	2.63	2.35	3.69
T ₅	1.21	1.64	1.49	2.37	2.29	3.36
T ₆	1.29	1.76	2.45	2.69	3.47	3.75
SEm $\pm$	0.16	0.11	0.54	0.39	0.66	0.47
CD (P=0.05)	NS	NS	NS	NS	NS	NS
Interaction I $\times$ T						
SEm $\pm$	0.27	0.19	0.94	0.67	1.14	0.82
CD (P=0.05)	NS	NS	NS	NS	NS	NS
Interaction T $\times$ I						
SEm $\pm$	0.315	0.151	0.545	0.309	0.665	0.375
CD (P=0.05)	NS	NS	NS	NS	NS	NS

Note:

- 1- I₀: No post sowing irrigation, I₁: Post sowing irrigation one, I₂: Post sowing irrigation two,
- 2- T₀: Control, T₁: Potassium Nitrate, T₂: Sulphur, T₃: Humic acid, T₄: KNO₃ + S, T₅: KNO₃ + HA, T₆: Sulphur + HA.

Fig 4.4.4(a): Effect of seed priming, humic acid and sulphur application on proline content of linseed different irrigation intervals (2022-23)

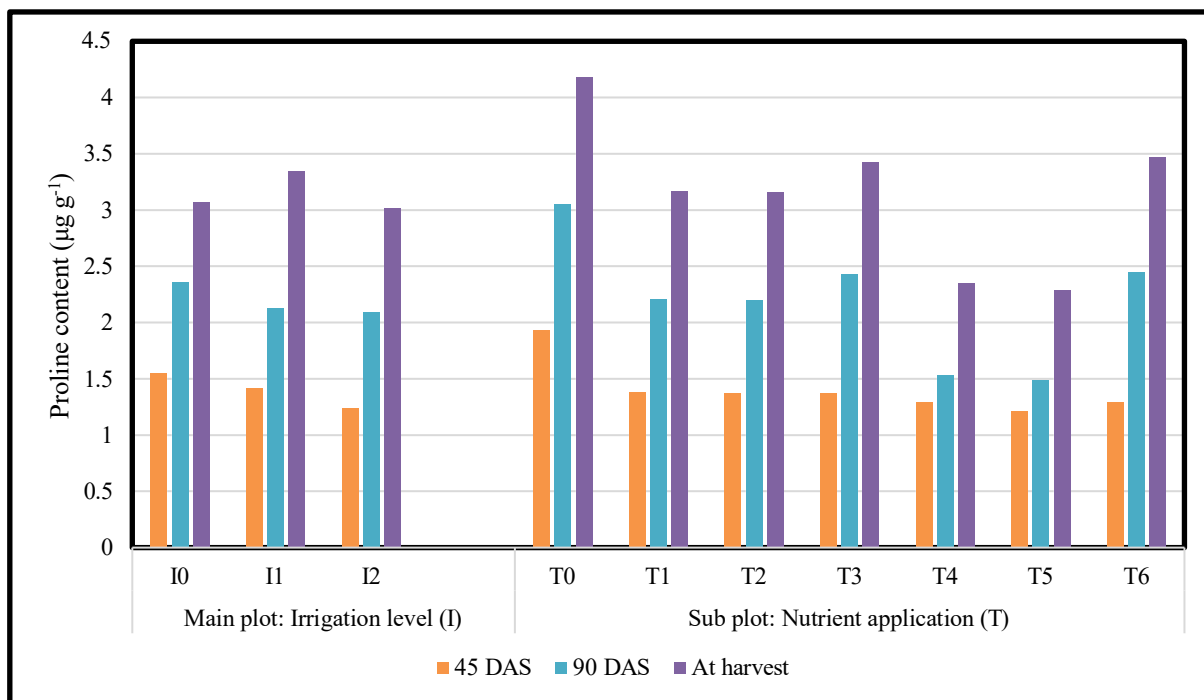
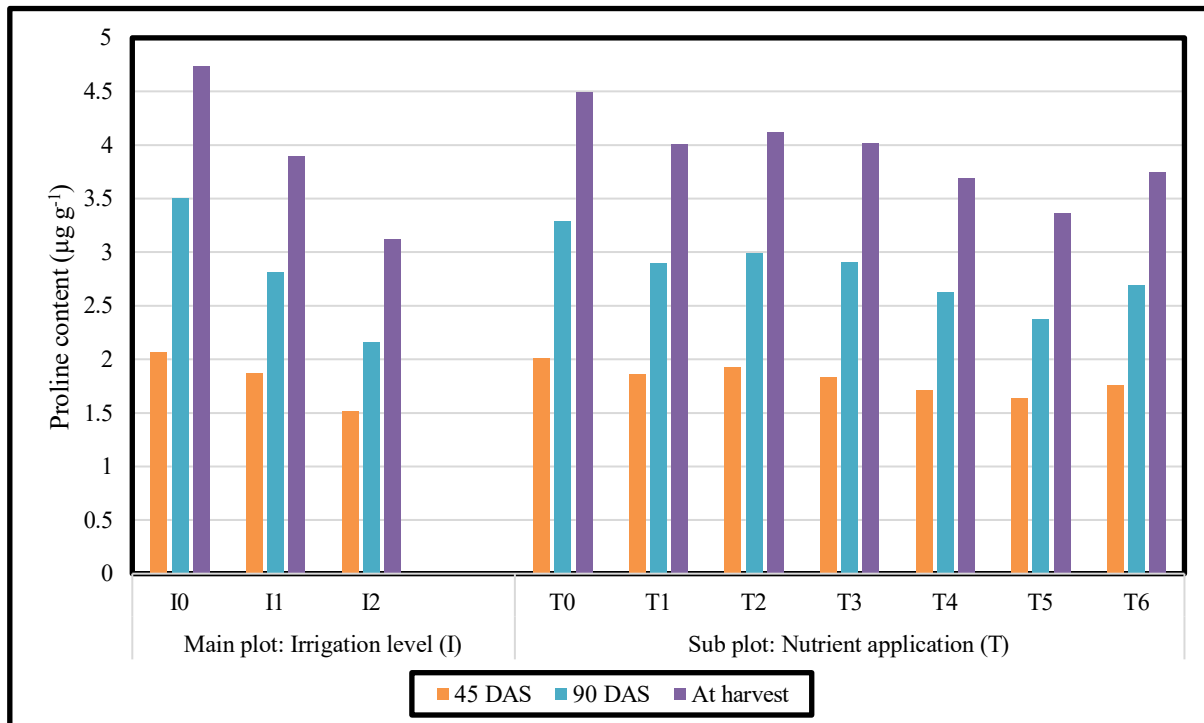


Fig 4.4.4(b): Effect of seed priming, humic acid and sulphur application on proline content of linseed different irrigation intervals (2023-24)



4.5 Yield and yield attributes

4.5.1 Effect of seed priming, humic acid, and sulphur application on the number of primary and secondary branches of linseed under different irrigation intervals.

The data presented in Table 4.5.1 (a) indicate that the number of primary and secondary branches of linseed was significantly influenced by nutrient application, whereas irrigation levels and interaction effects did not exert a significant influence during both years of experimentation (2022–23 and 2023–24).

Effect of irrigation levels

Irrigation treatments were not found to have any significant influence on the number of primary or secondary branches in either year because the differences between treatments were not statistically significant; although numerically, I_2 (two irrigations after sowing) had the most branches compared to I_0 . The primary branch number average values ranged from 5.59 to 6.07 in 2022-23 and 5.22 to 5.68 in 2023-24; while secondary branches averaged 35.38 to 39.14 in 2022-23 and 32.25 to 34.62 in 2023-24 with all values not being significantly different at the $P = 0.05$ level compared with one another.

Effect of nutrient application

Nutrient application had an impact on both the primary and secondary branches throughout both periods of the study. In comparison to the control (T_0) and the other treatments, the maximum number of primary branches for both years (2022-23 and 2023-24) occurred in T_5 (KNO_3 + humic acid), with 7.58 and 7.10 branches/plant, respectively (differences of 1.44 and 1.30 were observed, greater than CD).

T_5 also produced the highest number of secondary branches (51.56 and 39.89 branches/plant during 2022-23 and 2023-24, respectively) and was significantly greater than T_0 and single nutrient treatments. T_4 (KNO_3 + sulphur) ranked second and did not statistically differ from T_5 for both branches but was significantly greater than T_0 .

The control treatment (T_0) recorded the lowest number of both primary and secondary branches in both years.

The interaction effects of irrigation levels and nutrient application ($I \times T$ and $T \times I$) were found to be non-significant for both primary and secondary branches during both years of experimentation, indicating that the effect of nutrient application on branching was independent of irrigation levels.

This observation indicates a synergistic role of potassium, humic acid, and sulphur in stimulating nutrient uptake and hormonal balance, which leads to enhanced vegetative growth and shoot differentiation (Bhat *et al.* 2022 and Sharma *et al.* 2023). Potassium nitrate promotes endogenous activity of cytokinins that stimulate cell division in meristematic regions, and humic acid enhances root absorption capability, and sulphur helps in protein synthesis; together, it is responsible for structural growth. The combined

application of nutrients improved secondary branching as well. T₅ and T₄ had an increase of greater than 24 secondary branching in 2022 - 23 than the control. The increases in lateral branches directly relate to yield potential (more branching means more capsules and seeds). Irrigation levels had no significant effect on the number of primary and secondary branches of linseed in either year, suggesting that the prevailing soil moisture and favourable weather conditions were adequate for supporting branching of linseed under lower irrigation levels. Factors such as genetic potential and availability of assimilates regulate branching in linseed, as opposed to marginal variations in moisture supply at later developmental stages, which would account for there being no significant effect of irrigation. Nutrient application results would show a significant difference between the integrated and individual treatments, with the highest number of primary and secondary branches resulting from the combined application of seed priming, humic acid, and sulphur (T₅).

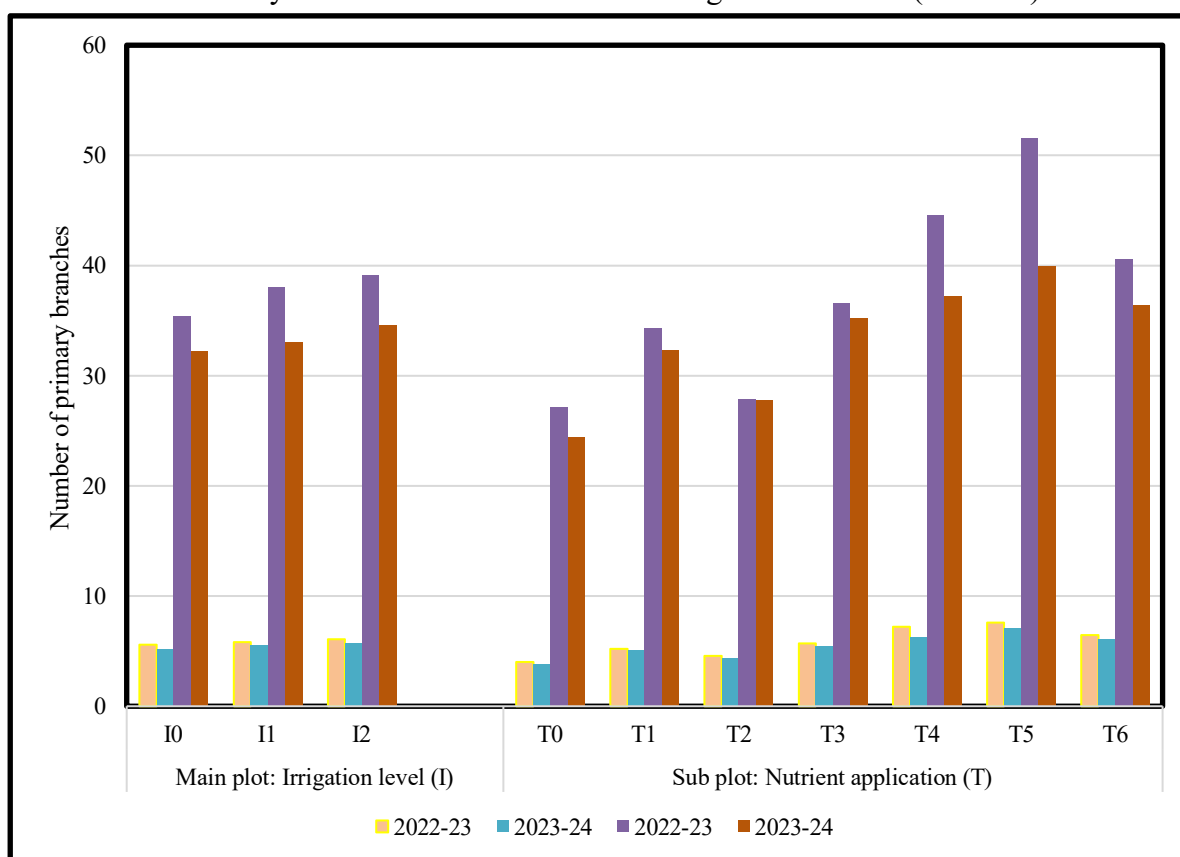
Table 4.5.1.a: Effect of seed priming, humic acid, and sulphur application on the number of primary and secondary branches of linseed at different irrigation intervals (2022-23 and 2023-24).

Treatment	Number of primary branches		Number of secondary branches	
	2022-23	2023-24	2022-23	2023-24
Main plot: Irrigation level (I)				
I ₀	5.59	5.22	35.38	32.25
I ₁	5.81	5.50	38.00	33.08
I ₂	6.07	5.68	39.14	34.62
SEm±	0.35	0.24	2.58	2.77
CD (P=0.05)	NS	NS	NS	NS
Sub plot: Nutrient application (T)				
T ₀	4.03	3.85	27.11	24.41
T ₁	5.20	5.07	34.33	32.33
T ₂	4.57	4.38	27.89	27.78
T ₃	5.71	5.48	36.56	35.22
T ₄	7.22	6.29	44.56	37.22
T ₅	7.58	7.10	51.56	39.89
T ₆	6.46	6.08	40.56	36.37
SEm±	0.50	0.45	4.78	3.48
CD (P=0.05)	1.44	1.30	13.70	9.99
Interaction I × T				
SEm±	0.87	0.79	8.27	6.03
CD (P=0.05)	NS	NS	NS	NS
Interaction T × I				
SEm±	0.93	0.64	6.83	7.33
CD (P=0.05)	NS	NS	NS	NS

Note:

- 1- I₀: No post sowing irrigation, I₁: Post sowing irrigation one, I₂: Post sowing irrigation two,
- 2- T₀: Control, T₁: Potassium Nitrate, T₂: Sulphur, T₃: Humic acid, T₄: KNO₃ + S, T₅: KNO₃ + HA, T₆: Sulphur + HA.

Fig 4.5.1 (a): Effect of seed priming, humic acid, and sulphur application on the number of primary and secondary branches of linseed different irrigation intervals (2022-23).



4.5.2. Effect of seed priming, humic acid, and sulphur application on Number of capsule plant⁻¹, Seed yield capsule⁻¹, and test weight of linseed (2022-23 and 2023-24).

The data presented in Table 4.5.2 (a) indicate that yield attributes of linseed were significantly influenced by nutrient application, whereas irrigation levels and interaction effects did not exert a significant influence during both years of experimentation (2022–23 and 2023–24).

Effect of irrigation levels

The effects of the different irrigation levels on capsule number per plant, seed yield per capsule, and test weight were statistically insignificant over both years, but as compared to I₀ and I₁, numerically larger values for all three yield parameters were found under irrigation condition I₂; irrigation condition I₂ allowed two post-sowing irrigations, and I₁ had only one post-sowing irrigation.

For the year 2022-23, the average capsule number per plant was 144.48 to about 162.95, the average seed yield per capsule was 8.84 to 9.36 g, and the average test weight was from 6.33 g to 7.00 g. Other than the non-significant trends observed in 2022-23, the trends regarding irrigation frequency did not significantly affect these yield parameters during this time either.

Effect of nutrient application

The results of the experiments indicated that the application of nutrients had a strong impact on capsules per plant and the overall seed yield obtained per capsule for both years of trial. The highest number of capsules per plant was observed in T₅ (combination of KNO₃ and humic acid), with 212.22 in 2022 and 175.11 in 2023, both of which are significantly higher than those found in the control (T₀) or any other treatment used in this experiment, due to being greater than the corresponding critical differences (52.65 and 43.50).

In addition, the T₅ group had the greatest seed yield per capsule at 10.49 g and 9.89 g during 2022-23 and 2023-24, respectively, and again, both of these values were statistically different from all other treatments because they were greater than the critical differences (1.53 g and 0.93 g). The second highest treatment was T₄ (KNO₃ combined with sulphur), which was equal to Treatment 5 and statistically higher than the other single-nutrient treatments and the control.

For the test weight of the seed yield per capsule, nutrient application had no effect on test weight in 2022-23. However, for the second year of experimenting (2023-24) T₅ had the highest test weight (7.31 g), which was statistically higher than that of the control or other treatments because it was greater than the critical difference of 0.56 g. In addition, the control (T₀) had the lowest test weight in both years.

The interaction effects of irrigation levels and nutrient application (I × T and T × I) were found to be non-significant for all yield attributes during both years of study, indicating that the effects of nutrient application on capsules per plant, seed yield per capsule, and test weight were independent of irrigation levels. The number of capsules per plant, the number of seed yield per capsule, and the test weight of linseed were not

significantly influenced by the level of irrigation applied to the crops in the two years studied, which implies that moisture availability is sufficient to allow for appropriate reproductive development of the crop under irrigation systems with the irrigation level. Yield factors of linseed are comparatively less sensitive to moderate changes in the amount of irrigation provided to crops when the crop has received some hydro-thermal stress as a result of residual soil moisture and reasonable climate conditions during the floral and fruiting phases of the crop.

Table 4.5.2.a: Effect of seed priming, humic acid, and sulphur application on the number of capsule plant⁻¹, Seed yield capsule⁻¹, and test weight of linseed at different irrigation intervals (2022-23 and 2023-24).

Treatment	No. of capsules per plant		Seed yield per capsule (g)		Test weight (g)	
	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24
Main plot: Irrigation level (I)						
I ₀	144.48	131.43	8.84	8.46	6.33	6.31
I ₁	154.19	138.25	8.99	8.64	6.94	6.49
I ₂	162.95	142.46	9.36	8.92	7.00	6.61
SEm±	8.78	3.69	0.22	0.22	0.29	0.14
CD (P=0.05)	NS	NS	NS	NS	NS	NS
Sub plot: Nutrient application (T)						
T ₀	102.56	99.93	7.60	7.36	6.48	5.47
T ₁	141.22	128.22	8.89	8.41	6.88	6.11
T ₂	126.11	112.44	8.37	7.95	7.10	5.93
T ₃	149.67	135.96	9.14	8.70	6.78	6.64
T ₄	186.11	160.37	9.62	9.39	6.41	7.01
T ₅	212.22	175.11	10.49	9.89	7.02	7.31
T ₆	159.22	149.63	9.32	9.00	6.61	6.82
SEm±	18.36	15.17	0.53	0.32	0.33	0.20
CD (P=0.05)	52.65	43.50	1.53	0.93	NS	0.56
Interaction I × T						
SEm±	31.80	26.27	0.92	0.56	0.57	0.34
CD (P=0.05)	NS	NS	NS	NS	NS	NS
Interaction T × I						
SEm±	23.23	9.74	0.591	0.584	0.662	0.358
CD (P=0.05)	NS	NS	NS	NS	NS	NS

Note:

- 1- I₀: No post sowing irrigation, I₁: Post sowing irrigation one, I₂: Post sowing irrigation two,
- 2- T₀: Control, T₁: Potassium Nitrate, T₂: Sulphur, T₃: Humic acid, T₄: KNO₃ + S, T₅: KNO₃ + HA, T₆: Sulphu + HA.

Fig 4.5.2(a): Effect of seed priming, humic acid, and sulphur application on Number of capsule plant⁻¹, Seed yield capsule⁻¹ and test weight of linseed different irrigation intervals (2022-23).

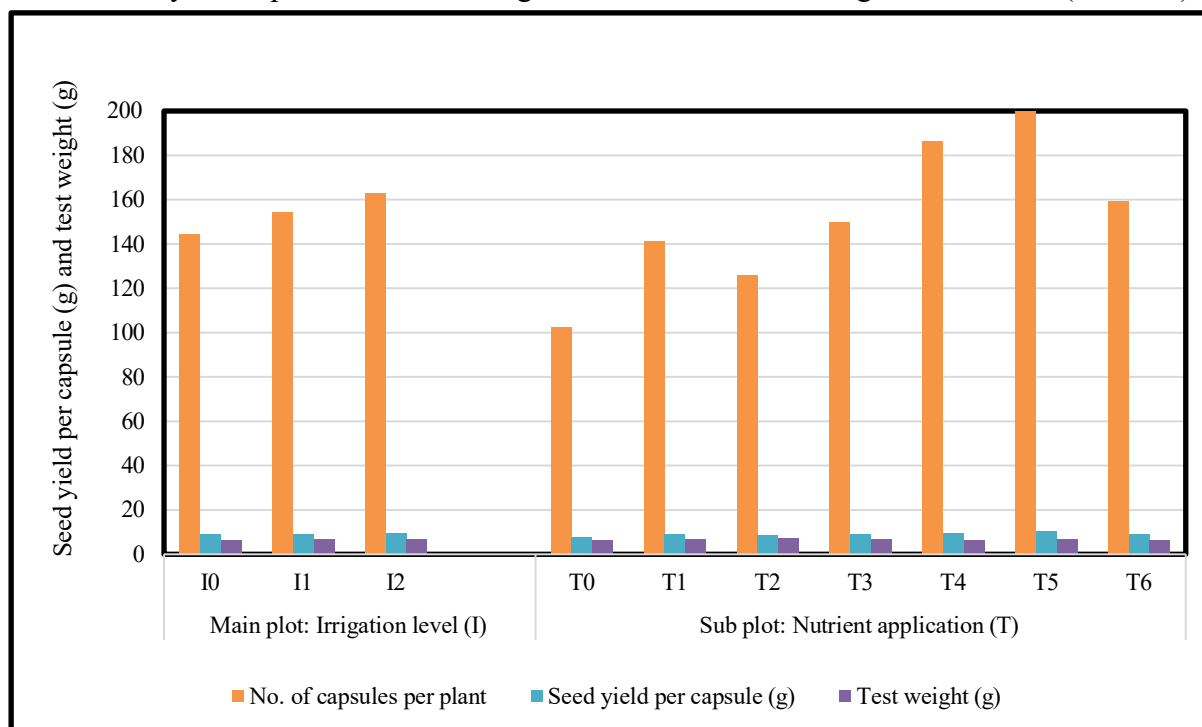
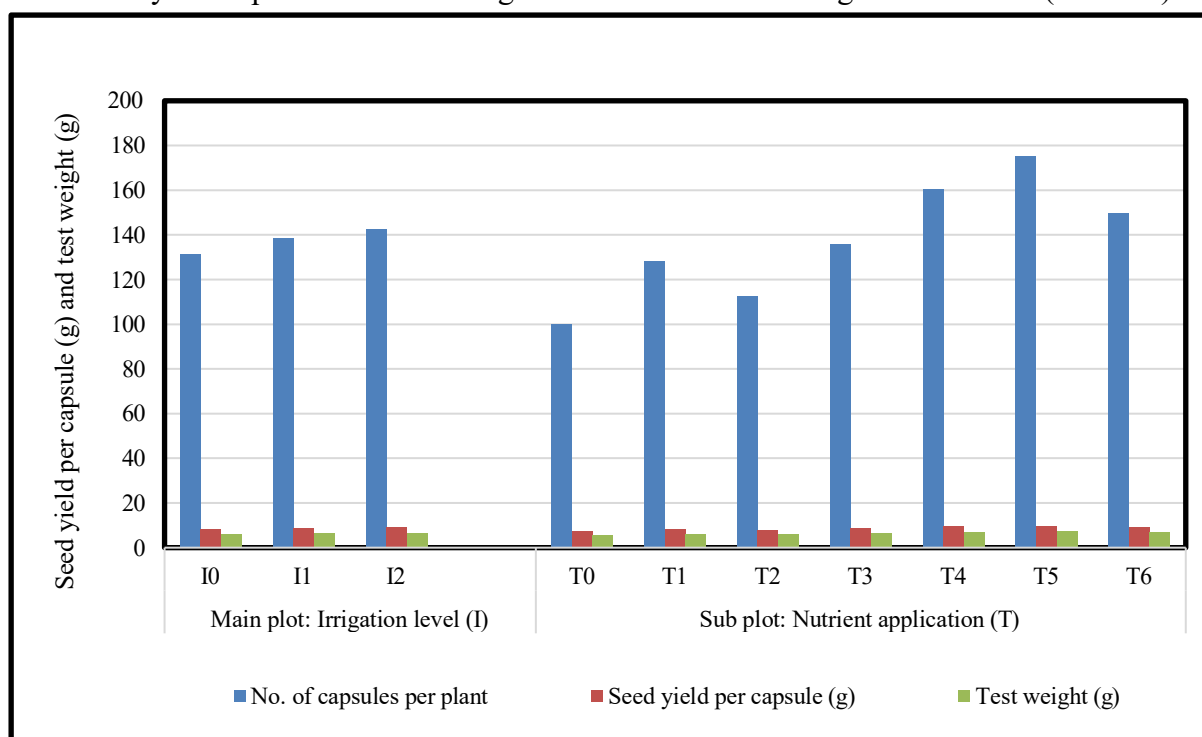


Fig 4.5.2(b): Effect of seed priming, humic acid, and sulphur application on Number of capsule plant⁻¹, Seed yield capsule⁻¹ and test weight of linseed different irrigation intervals (2023-24).



4.5.3 Effect of seed priming, humic acid, and sulphur application on seed, oil, and biological yield and harvest index of linseed under different irrigation intervals.

The data presented in Table 4.5.3 (a) indicate that yield of linseed were significantly influenced by nutrient application, whereas irrigation levels and interaction effects did not exert a significant influence during both years of experimentation (2022–23 and 2023–24).

Seed yield (q ha^{-1})

The data regarding seed yield of linseed as affected by irrigation levels and nutrient application treatments are presented in Table 4.5.3.a. A critical examination of the data indicated that seed yield showed an increasing trend with successive increase in irrigation levels during both years of investigation. However, the effect of irrigation levels on seed yield was found to be non-significant during 2022–23. In contrast, during 2023–24, irrigation levels significantly influenced seed yield, wherein the highest seed yield (12.40 q ha^{-1}) was recorded under two post-sowing irrigations applied at 35 and 65 DAS (I_2). This treatment was followed by one post-sowing irrigation at 35 DAS (I_1), while the lowest seed yield was recorded under no post-sowing irrigation (I_0). The improvement in seed yield under higher irrigation levels may be ascribed to better moisture availability during the critical stages of crop growth, which possibly favoured nutrient absorption, photosynthetic activity and translocation of assimilates towards reproductive structures, thereby improving seed development and final yield. On the other hand, limited soil moisture under lower irrigation regimes might have restricted physiological activities, resulting in comparatively lower seed production.

The data further revealed that nutrient application treatments exerted a significant influence on seed yield during both years of study. Among different treatments, seed priming with KNO_3 in combination with soil application of humic acid (T_5) resulted in the highest seed yield (13.49 and 13.13 q ha^{-1} during 2022–23 and 2023–24, respectively), and remained significantly superior over the control treatment. The treatments comprising KNO_3 + sulphur (T_4) and sulphur + humic acid (T_6) also produced higher seed yields and performed statistically similar to each other. The superior performance of T_5 may be attributed to the combined influence of KNO_3 and humic acid on crop growth and development. Seed priming with KNO_3 might have improved seedling establishment and nutrient utilization, whereas humic acid possibly enhanced root proliferation, nutrient availability and metabolic efficiency of the crop. Such favourable effects may have led to better growth and yield-contributing characters, ultimately resulting in enhanced seed yield. In contrast, the lowest seed yield recorded under the control treatment (T_0) might be due to the absence of nutrient supplementation, which may have limited crop growth and reduced assimilate production for seed formation.

The interaction effect between irrigation levels and nutrient application treatments was found to be non-significant during both years of investigation, indicating that the response of nutrient treatments remained

relatively consistent across different irrigation regimes.

Oil yield (q ha^{-1})

Oil yields had a similar trend to seed yields, as both increased with increasing irrigation level. The highest oil yields were produced under I_2 (4.58 and 4.40 q ha^{-1}). As shown above, irrigation level has a significant effect on oil yield; this was very evident in the 2023-2024 growing season. The application of fertilizer had a significant impact on oil yield for each year of study. The highest yields were achieved with treatment T_5 ($\text{KNO}_3 + \text{Humic Acid}$) (5.41 and 5.19 q ha^{-1}), followed closely by treatment T_4 ($\text{KNO}_3 + \text{Sulphur}$). Improvement in oil yield can likely be attributed to increased seed yield and improved oil accumulation, due to adequate nutrient supply. The 2023-24 season had a significant interaction effect on oil yield, demonstrating that the nutrient treatment responded positively to optimum irrigation conditions.

Biological yield (q ha^{-1})

The data related to biological yield of linseed as influenced by irrigation levels and nutrient application treatments have been presented in Table 4.5.3.a. A perusal of the data indicated that biological yield increased with increase in irrigation levels during both years of experimentation. Significantly higher biological yield was obtained under two post-sowing irrigations applied at 35 and 65 DAS (I_2) during both years of study. However, treatments receiving one post-sowing irrigation (I_1) and no post-sowing irrigation (I_0) did not differ significantly from each other. The improvement in biological yield under I_2 may be attributed to the availability of adequate soil moisture throughout the crop growth period, which possibly maintained better plant growth and favoured dry matter production. Adequate moisture availability during the active growth phase might have facilitated efficient nutrient utilization and enhanced vegetative development, thereby contributing towards greater biomass accumulation. On the contrary, restricted moisture availability under lower irrigation levels may have adversely affected plant growth and dry matter production.

A further examination of the data revealed that nutrient application treatments significantly influenced biological yield during both years of investigation. Among the different treatments, seed priming with KNO_3 along with soil application of humic acid (T_5) recorded the highest biological yield (36.71 and 36.62 q ha^{-1} during 2022–23 and 2023–24, respectively). This treatment was followed by $\text{KNO}_3 + \text{sulphur}$ (T_4), sulphur + humic acid (T_6), humic acid alone (T_3), KNO_3 alone (T_1) and sulphur alone (T_2), whereas the control treatment (T_0) registered the lowest biological yield during both years. During the first year, T_4 and T_6 as well as T_1 and T_2 remained statistically at par, while in the second year all treatments behaved differently in a statistical sense. The higher biological yield recorded under T_5 may be due to the combined effect of KNO_3 and humic acid in

improving crop growth. Priming with KNO_3 might have supported better crop establishment and nutrient utilization during the early growth stages, whereas humic acid may have promoted root activity and nutrient availability, resulting in better plant growth and biomass accumulation. The comparatively lower biological yield observed under the control treatment might be associated with limited nutrient availability and comparatively poor crop growth.

The interaction effect between irrigation levels and nutrient application treatments was found to be significant for biological yield only during 2023–24, suggesting that the magnitude of response to nutrient treatments differed under varying irrigation conditions during that year. This variation may be attributed to differences in moisture availability, which likely influenced the efficiency of nutrient utilization and dry matter accumulation under different treatment combinations.

Harvest index (%)

An increasing amount of irrigation led to an increase in the harvest index, but the harvest index was not statistically different between the irrigation levels in either of the years studied. The effect of irrigation was primarily on total biomass production and not on the distribution of biomass for economic yield. The harvest index was significantly affected by nutrient applications in both years. The highest harvest index was obtained from T_5 (KNO_3 and humic acid), with harvest indices of 36.75% and 35.87%, indicating superior efficiency in the movement of assimilates to seed formation. Harvest indices for T_4 and T_6 were also higher than for the control. The seed yield, oil yield, and biological yield and harvest index of linseed from both years only noticed very small differences across the different irrigation levels, indicating that the levels of rainfall and soil moisture were largely adequate to meet the water requirements of the crop, and any additional irrigations had little impact on yield. The I_2 irrigation treatment had slightly higher values than I_1 , reflecting a greater amount of moisture supporting biomass and seed filling; however, most of the differences between the irrigation treatments were not statistically significant. Unlike the irrigation, treatment applications had a considerable effect on all measures of yield, with the combination of seed priming, humic acid, and sulphur (T_5) consistently providing the highest seed yield, oil yield, and biological yield, along with a relatively higher harvest index compared to the other treatments. Improved nutrient availability, root growth, photosynthetic efficiency, and distribution of assimilates toward economic yield are some of the reasons why these yields have increased. The larger contribution of integrated nutrient management under these specific climatic conditions, rather than irrigation, is validated by earlier studies with linseed and other oil yield crops (Sharma *et al.*, 2018; Yadav and Meena, 2019; Kumar *et al.*, 2021).

Table 4.5.3.a: Effect of seed priming, humic acid, and sulphur application on seed yield, oil yield, biological yield, and harvest index of different irrigation intervals (2022-23 and 2023- 24).

Treatment	Seed yield (q ha ⁻¹)		Oil yield (q ha ⁻¹)		Biological yield (q ha ⁻¹)		Harvest index (%)	
	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24
Main plot: Irrigation level (I)								
I ₀	12.28	12.07	4.31	4.16	35.42	35.03	34.65	34.44
I ₁	12.45	12.17	4.43	4.24	35.48	35.19	35.06	34.55
I ₂	12.61	12.40	4.58	4.40	35.87	35.59	35.15	34.85
SEm±	0.07	0.03	0.03	0.02	0.07	0.09	0.24	0.17
CD (P=0.05)	NS	0.13	0.10	0.08	0.28	0.37	NS	NS
Sub plot: Nutrient application (T)								
T ₀	11.34	11.09	3.50	3.34	33.97	33.74	33.40	32.86
T ₁	12.09	11.89	4.13	3.99	35.44	34.99	34.11	33.98
T ₂	11.97	11.77	3.93	3.80	35.19	34.40	34.01	34.21
T ₃	12.51	12.31	4.47	4.31	35.64	35.34	35.10	34.84
T ₄	13.01	12.81	4.93	4.77	36.19	36.06	35.96	35.54
T ₅	13.49	13.13	5.41	5.19	36.71	36.62	36.75	35.87
T ₆	12.72	12.50	4.69	4.48	35.98	35.72	35.36	34.99
SEm±	0.11	0.09	0.04	0.04	0.10	0.11	0.33	0.28
CD (P=0.05)	0.30	0.26	0.13	0.11	0.29	0.32	0.95	0.82
Interaction I × T								
SEm±	0.18	0.16	0.08	0.06	0.17	0.19	0.57	0.49
CD (P=0.05)	NS	NS	NS	NS	NS	0.55	NS	NS
Interaction T × I								
SEm±	0.591	0.584	0.240	0.217	0.192	0.247	0.662	0.358
CD (P=0.05)	NS	NS	NS	NS	NS	NS	1.165	NS

Note:

- 1- I₀: No post sowing irrigation, I₁: Post sowing irrigation one, I₂: Post sowing irrigation two,
- 2- T₀: Control, T₁: Potassium Nitrate, T₂: Sulphur, T₃: Humic acid, T₄: KNO₃ + S, T₅: KNO₃ + HA, T₆: Sulphur + HA.

Fig 4.5.3(a): Effect of seed priming, humic acid and sulphur application on seed yield, oil yield and biological yield and harvest index of linseed different irrigation intervals (2022-23).

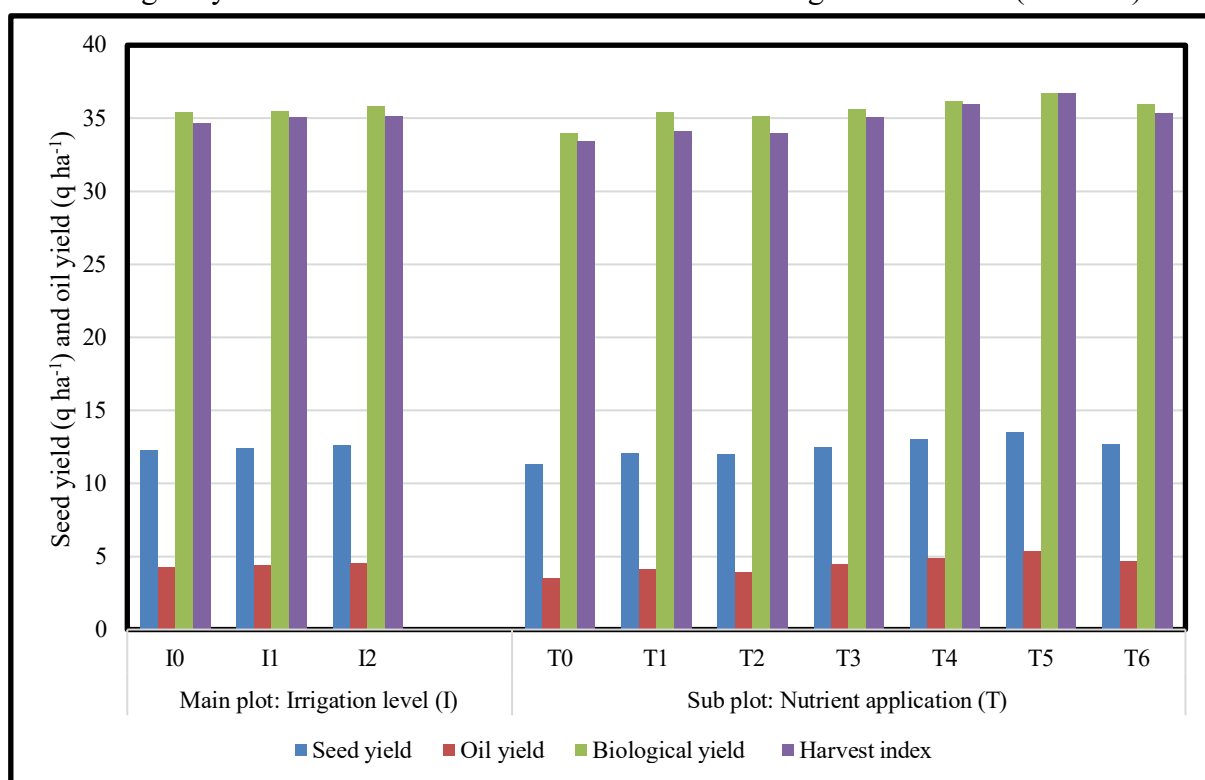
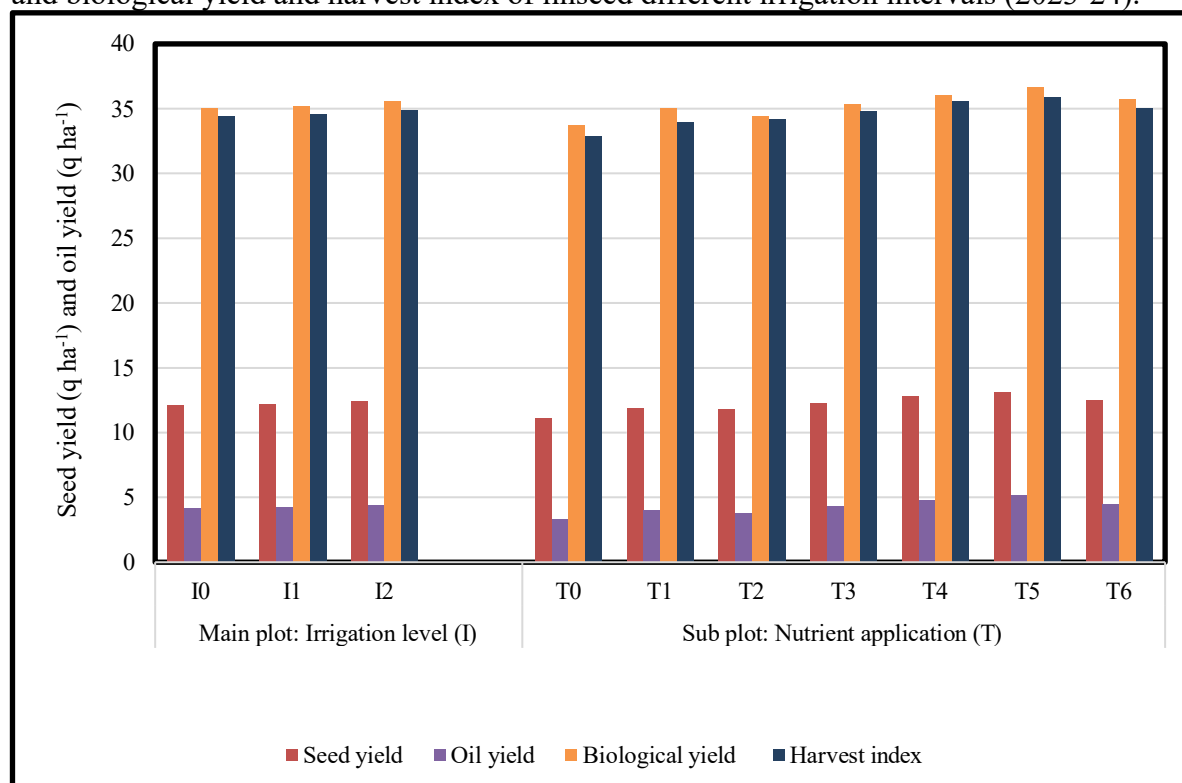


Fig 4.5.3(b): Effect of seed priming, humic acid and sulphur application on seed yield, oil yield and biological yield and harvest index of linseed different irrigation intervals (2023-24).



4.5.4 Effect of seed priming, humic acid, and sulphur application on oil content in seed of linseed under different irrigation intervals.

The amount of oil present in linseed seed was found to be heavily affected by the number of irrigations applied throughout both years of experimentation (2022-23 and 2023-24). The highest oil content was obtained from I₂, which consisted of two post-sowing irrigations, in both years of measurement. The oil content measured for I₂ was 36.15% and 35.35% for the years 2022-23 and 2023-24, respectively.

The only other irrigation treatments outperformed by I₂ were I₁ (one post-sowing irrigation) and I₀ (no post-sowing). The lowest amount of oil was recorded for I₀, which had 34.90% and 34.28%, respectively, for the years 2022-23 and 2023-24. The statistical analysis performed on the data showed there were significant differences between the different levels of irrigation (CD (P=0.05)), based on the values of 0.35 and 0.32 for the two years.

The treatments significantly influenced oil content in linseed seed during both study years. The highest oil content was found with T₅ (KNO₃ + humic acid) treatment, 40.11% and 39.51% for years 2022–23 and 2023–24, respectively; it was significantly greater than other nutrient treatments or controls. The next highest oil content was obtained from T₄ (KNO₃ + sulphur), at 37.91% and 37.25%, respectively, with T₆ (sulphur + humic acid) being the next highest. The lowest oil content was in the control treatments of T₀ (30.86% and 30.15%). All nutrient treatments were significantly different statistically, as indicated by CD (P=0.05) values of 0.78 and 0.66 for years 2022–23 and 2023–24, respectively. The interaction effect between irrigation levels and nutrient application on oil content was found to be statistically non-significant during both years of experimentation. Irrigation levels significantly affected the oil content in linseed seeds in both years, and irrigation level two (I₂) produced more oil than irrigation level one (I₁), which resulted in less stress on the plant and more nutrients being transferred to developing seeds, ultimately promoting oil formation. Some oil content produced by irrigation level zero (I₀) could have been due to mild moisture stress which is known to inhibit fatty acid development. Fertilizer type had a significant and repeated effect on oil content; the integrated method of using humic acid, sulphur and seed priming (T₅) had the highest amount of oil per seed diameter in both years. According to the result it is concluded that improved oilseed performance comes from the functionality of sulphur for oilseed metabolism (mainly the production of fatty acids) and the beneficial effects of humic compounds concerning how efficiently a plant can uptake nutrients and perform physiological activities. Irrigation treatments had no interactive effects with the nutrient treatment indicating that the integrated management of nutrients provides a consistent benefit to oil content of the oilseeds regardless of which irrigation regime the crops are grown in. This is supported by previous studies (Tripathi *et al.*, 2017; Sharma *et al.*, 2018 and Kumar *et al.*, 2021b) that highlight both adequate moisture and sulphur nutrition influence enhancing oil content of linseed oils and/or crops.

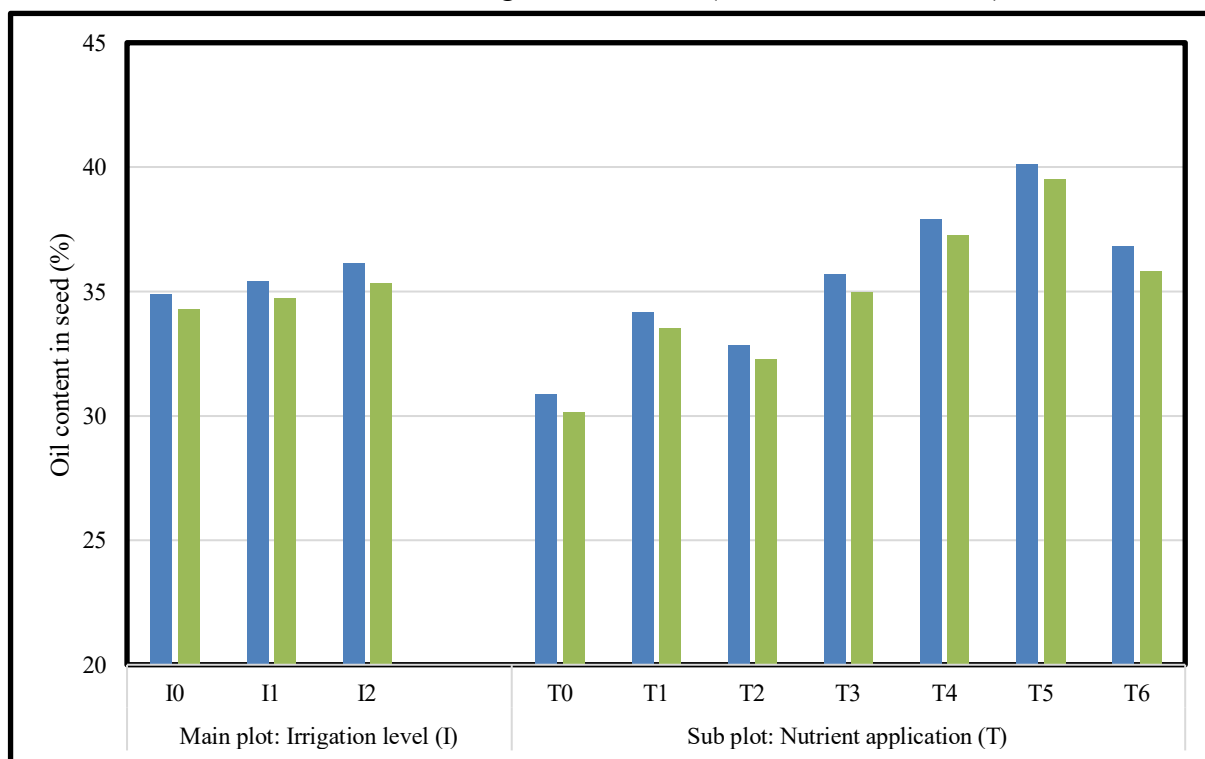
Table 4.5.4.a: Effect of seed priming, humic acid and sulphur application on oil content in seed of linseed under different irrigation intervals during *Rabi* season of year 2022-23 and 2023-24.

Treatment	Oil content in seed (%)	
	2022-23	2023-24
Main plot: Irrigation level (I)		
I ₀	34.90	34.28
I ₁	35.41	34.73
I ₂	36.15	35.35
SEm±	0.09	0.08
CD (P=0.05)	0.35	0.32
Sub plot: Nutrient application (T)		
T ₀	30.86	30.15
T ₁	34.16	33.52
T ₂	32.83	32.27
T ₃	35.70	34.99
T ₄	37.91	37.25
T ₅	40.11	39.51
T ₆	36.83	35.83
SEm±	0.27	0.23
CD (P=0.05)	0.78	0.66
Interaction I × T		
SEm±	0.47	0.40
CD (P=0.05)	NS	NS
Interaction T × I		
SEm±	0.240	0.217
CD (P=0.05)	NS	NS

Note:

I₀: No post sowing irrigation, I₁: Post sowing irrigation one, I₂: Post sowing irrigation two,
T₀: Control, T₁: Potassium Nitrate, T₂: Sulphur, T₃: Humic acid, T₄: KNO₃ + S, T₅: KNO₃ + HA, T₆:
Sulphu + HA.

Fig 4.5.4.a: Effect of seed priming, humic acid and sulphur application on oil content in seed of linseed at different irrigation intervals (2022-23 and 2023-24).



4.6 Soil moisture parameter

4.6.1 Effect of seed priming, humic acid, and sulphur application on soil moisture content in the soil profile up to 30 cm only at sowing of linseed under different irrigation intervals.

Soil moisture content (mm) was measured in the soil profile (to a depth of 30 cm) at the time of sowing of linseed in the *Rabi* seasons of 2022-23 and 2023-24 to establish the uniformity of initial soil moisture status for comparing treatments across both years. The results demonstrate that the soil moisture content did not differ significantly across irrigation levels, nutrient application treatments, or interactions in both years of the study.

Over the two years of study, soil moisture readings ranged from 70.13 mm to 70.65 mm (2022 to 2023) and from 68.22 mm to 68.81 mm (2023 to 2024), respectively. Although there were numerical differences between I_1 , I_2 , and I_0 soil moisture levels with multiple measurements over two growing seasons, no statistically significant differences could be identified using an analysis of variance (ANOVA) at the 5% probability level. This indicates that the uniformity of initial soil moisture conditions, rather than any treatment applied to irrigated crops, defined the pre-irrigation soil moisture characteristics of the 0 cm to 60 cm profile.

The study results show that different methods of applying nutrients did not significantly affect soil moisture content just before irrigation in either of the years studied. Soil moisture ranged from 69.65–71.37 mm for the years 2022–2023 and 67.33–69.47 mm for the years 2023–2024, while the highest numerical values were found with T_5 (KNO_3 + humic acid) and T_2 (sulphur).

The soil moisture content in the soil profile up to 60 cm depth at the time of sowing was not significantly affected by the levels of irrigation, application of nutrients, and their interaction effects during both the years of experimentation (2022-23 and 2023-24). The non-significant differences among the irrigation treatments (I_0 , I_1 , and I_2) reveal that the soil moisture content at sowing was more or less the same for all the plots, regardless of the irrigation treatment to be followed. This is because of the similar antecedent soil moisture conditions at the time of sowing, as no irrigation had been applied after sowing. Likewise, nutrient application treatments involving seed priming, humic acid, sulphur, and their combinations did not exert a significant effect on soil moisture content at sowing. This may be due to the fact that nutrient amendments primarily influence soil physical and biological properties gradually over the crop growth period, rather than causing immediate changes in soil moisture status at the initial stage. Since soil moisture was measured before the commencement of irrigation treatments, the influence of nutrient-induced improvements in soil water retention or root activity was not yet evident. Furthermore, the non-significant interaction effects ($I \times T$) suggest that irrigation levels and nutrient applications acted

independently and did not differentially affect soil moisture availability at sowing. Similar observations have been reported in earlier studies, in which uniform soil moisture conditions at sowing resulted in non-significant treatment effects, underscoring that initial soil water status is largely determined by pre-sowing rainfall, soil texture, and field preparation practices rather than by treatment-induced factors (Hillel, 1998; Michael, 2012).

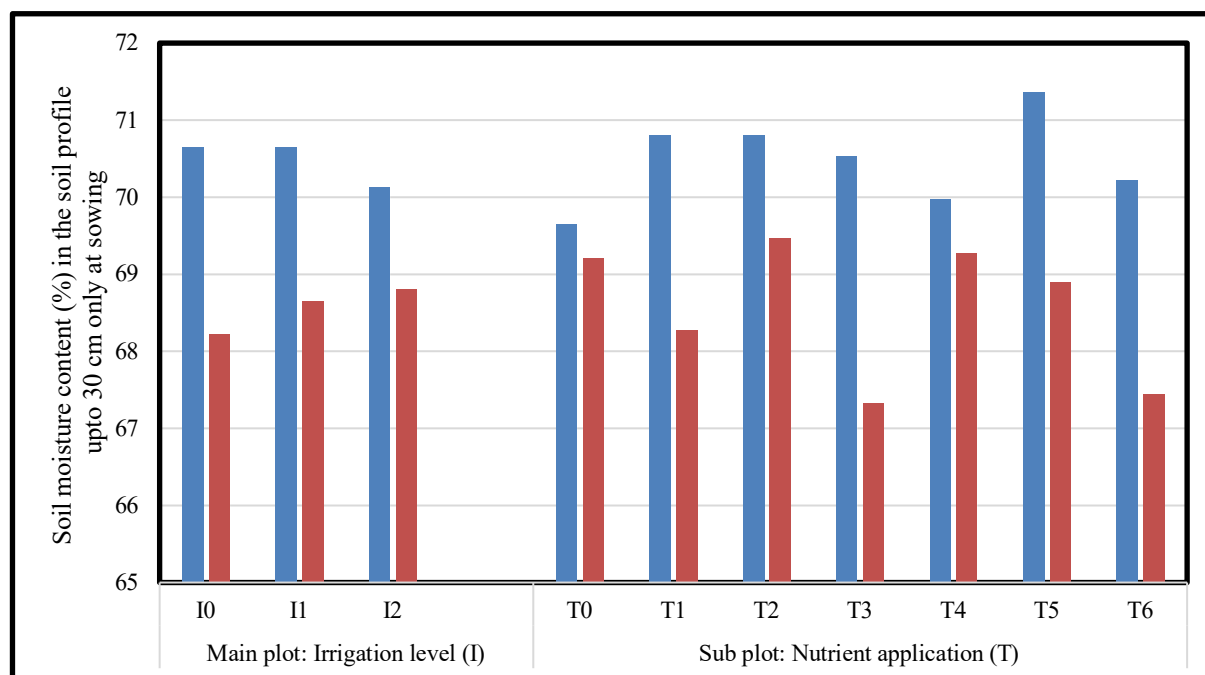
Table 4.6.1.a: Effect of seed priming, humic acid, and sulphur application on soil moisture content in the soil profile up to 30 cm only at sowing of linseed under different irrigation intervals during the *Rabi* season of the year (2022-23 and 2023-24).

Treatment	Soil moisture content in the soil profile up to 30 cm at the time of sowing (mm)	
	2022-23	2023-24
Main plot: Irrigation level (I)		
I ₀	70.65	68.22
I ₁	70.65	68.65
I ₂	70.13	68.81
SEm±	0.483	0.484
CD (P=0.05)	NS	NS
Sub plot: Nutrient application (T)		
T ₀	69.65	69.21
T ₁	70.80	68.27
T ₂	70.80	69.47
T ₃	70.54	67.33
T ₄	69.97	69.28
T ₅	71.37	68.90
T ₆	70.22	67.45
SEm±	0.89	0.87
CD (P=0.05)	NS	NS
Interaction I × T		
SEm±	1.54	1.51
CD (P=0.05)	NS	NS
Interaction T × I		
SEm±	1.276	1.286
CD (P=0.05)	NS	NS

Note:

- 1- I₀: No post sowing irrigation, I₁: Post sowing irrigation one, I₂: Post sowing irrigation two,
- 2- T₀: Control, T₁: Potassium Nitrate, T₂: Sulphur, T₃: Humic acid, T₄: KNO₃ + S, T₅: KNO₃ + HA, T₆: Sulphur + HA.

Fig 4.6.1.a: Effect of seed priming, humic acid, and sulphur application on soil moisture content in the soil profile up to 30 cm only at sowing of linseed under different irrigation intervals during *Rabi* season of year (2022-23 and 2023-24).



4.6.2 Effect of seed priming, humic acid, and sulphur application on soil moisture storage in the soil profile up to 60 cm only before each irrigation of linseed under different irrigation.

The data are presented in Table 4.6.2.a indicate that soil moisture content in the 0–60 cm soil profile measured before the first and second irrigation of linseed was significantly influenced by irrigation levels, whereas the effects of nutrient application treatments and their interactions with irrigation levels were largely non-significant during both years of study (2022–23 and 2023–24).

Irrigation scheduling affected soil moisture levels significantly before the first and second irrigations in both seasons. Irrespective of season, as the level of irrigation increased, moisture levels before the first irrigation varied significantly, with the lowest and highest values occurring between 110.86 and 136.37 mm in 2022-23; 111.02 and 134.08 mm in 2023-24. No irrigations have occurred since sowing, with the greatest increase in moisture observed when irrigated twice compared to once or not at all. Statistically, all moisture levels between irrigation levels differed greatly, with CD values of 3.22 mm for 2022-23 and 4.25 mm for 2023-24. Similarly, before the second irrigation, soil moisture level varied from 108.22 to 133.27 mm in 2022-23 and from 114.85 to 129.75 mm in 2023-24, again with I₂ having significantly more moisture than I₁ or I₀, with the difference being 1.79 mm for 2022-23 and 4.03 mm for 2023-24, which provides clear evidence of the cumulative effects of increased irrigation frequency on soil moisture storage in the root zone of the plant.

However, with respect to the effect of different nutrient application treatments on soil moisture content, there was no statistically significant difference among treatments before either irrigation during both experimental years, except before the second irrigation in 2023–24, where there was a mean difference among treatments. The integrated nutrient treatment produced higher soil moisture content numerically compared to the other treatments, particularly for T₅ (KNO₃ and humic acid) and T₄ (KNO₃ and sulfur); however, these differences were not generally statistically significant at the 5% probability level, as no minimum significant difference existed.

Before the second irrigation in 2023–24, T₅ had a mean soil moisture value of 126.35 mm, which was significantly greater than the control; this may indicate a cumulative effect of nutrient amendments on soil moisture retention under optimal seasonal conditions for the experiment.

Before the onset of the two irrigation events in each year, there were no significant interaction effects (I × T) between irrigation levels and nutrient applied treatment. This indicates that the nutrient applied treatments did not differentially alter soil moisture availability as a function of irrigation schedule. Irrigation levels had a marked effect on soil moisture content in the 0-60 cm soil profile of the linseed crops during both years investigated. The moisture content recorded under the treatment of I₂ was greater than that of I₁, which was in turn greater than that of I₀ in both years, indicating that the frequent application

of irrigation (I) maintained higher soil water reserve as compared with I₀. The nutrient application treatments (nutrients only and Irrigation + nutrients), and their interactions with irrigation levels, did not have a consistent or significant effect on the moisture content of the pre-irrigation soils, indicating that applying nutrients to the soils at this stage had little or no impact on moisture depletion. Overall, the irrigation scheduled timing was the primary driver of the pre-irrigation soil moisture content available for linseed crop growth. Among the irrigation treatments, the increase in soil moisture storage was substantial with the rise in the level of irrigation. Before the first irrigation, the maximum soil moisture was noticed in I₂, followed by I₁, whereas the minimum soil moisture was measured in I₀ in both years. The same trend was noticed before the second irrigation, where I₁ and I₂, although receiving equal irrigation at 35 DAS, showed substantial differences in soil moisture content. This suggests that the soil moisture condition at the time of observation was not dependent solely on the irrigation applied but also on the subsequent depletion of moisture. Variation in soil moisture observed by before the second irrigation can be attributed to crop evapotranspiration demand, root water extraction, and soil-plant-atmosphere interactions that occurred during the period between irrigation and observation. Soil moisture measurement was conducted after a certain period of time after irrigation, and thus equal irrigation did not necessarily lead to equal soil moisture distribution in the treatments. This phenomenon of soil moisture dynamics under similar irrigation conditions has also been observed by Doorenbos and Kassam (1979), Hillel (1998), and Michael (2012), who highlighted the importance of atmospheric demand and crop water use in determining soil moisture depletion.

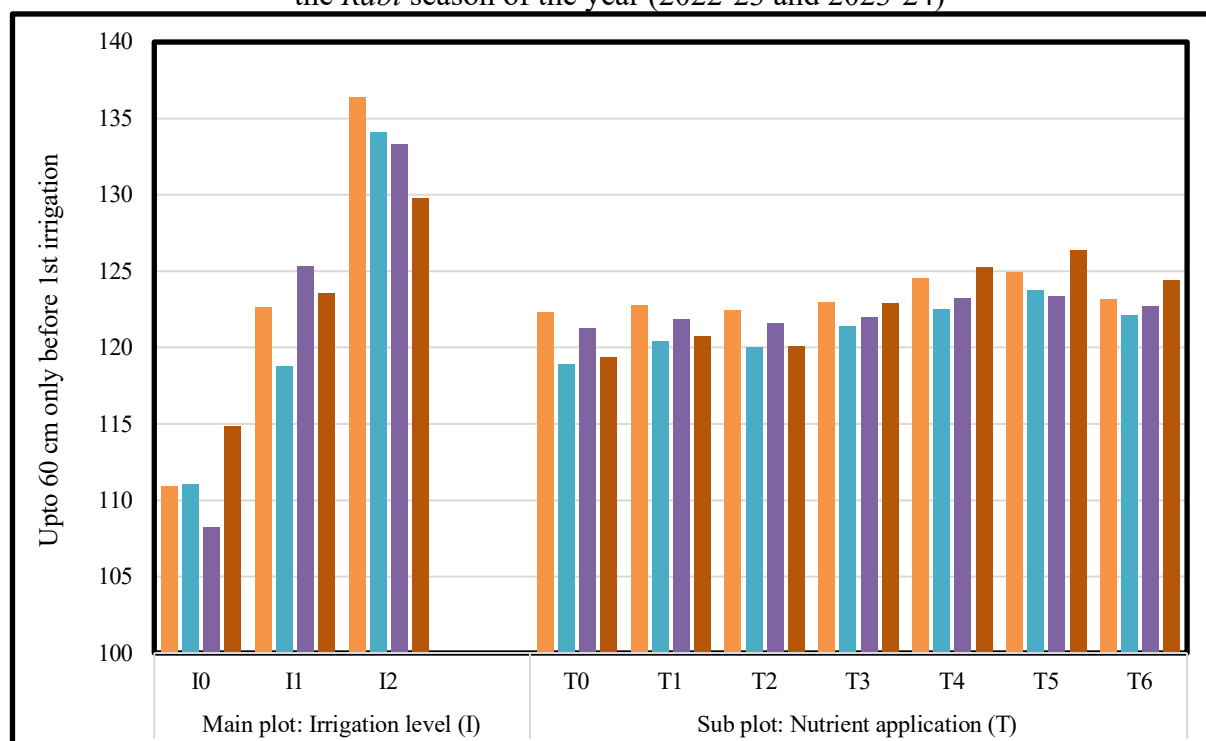
Table 4.6.2.a: Effect of seed priming, humic acid, and sulphur application on soil moisture content in the soil profile up to 60 cm only before each irrigation of linseed under different irrigation intervals during the *Rabi* season of the year (2022-23 and 2023-24).

Soil moisture storage (mm)				
Treatment	Up to 60 cm only before 1 st irrigation		Up to 60 cm only before the 2 nd irrigation	
	2022-23	2023-24	2022-23	2023-24
Main plot: Irrigation level (I)				
I ₀	110.86	111.02	108.22	114.85
I ₁	122.62	118.75	125.33	123.54
I ₂	136.37	134.08	133.27	129.75
SEm±	0.82	1.08	0.46	1.03
CD (P=0.05)	3.22	4.25	1.79	4.03
Sub plot: Nutrient application (T)				
T ₀	122.29	118.90	121.22	119.36
T ₁	122.78	120.38	121.84	120.70
T ₂	122.41	120.01	121.59	120.09
T ₃	122.91	121.38	121.97	122.90
T ₄	124.54	122.50	123.22	125.24
T ₅	124.92	123.73	123.35	126.35
T ₆	123.16	122.10	122.72	124.38
SEm±	1.44	1.13	1.59	1.08
CD (P=0.05)	NS	NS	NS	3.11
Interaction I × T				
SEm±	2.50	1.96	2.76	1.88
CD (P=0.05)	NS	NS	NS	NS
Interaction T × I				
SEm±	2.170	2.863	1.226	2.715
CD (P=0.05)	NS	NS	NS	NS

Note:

- 1- I₀: No post sowing irrigation, I₁: Post sowing irrigation one, I₂: Post sowing irrigation two,
- 2- T₀: Control, T₁: Potassium Nitrate, T₂: Sulphur, T₃: Humic acid, T₄: KNO₃ + S, T₅: KNO₃ + HA, T₆: Sulphur + HA.

Fig 4.6.2.a: Effect of seed priming, humic acid, and sulphur application on soil moisture content in the soil profile up to 60 cm only before each irrigation of linseed under different irrigation intervals during the *Rabi* season of the year (2022-23 and 2023-24)



4.6.3 Effect of seed priming, humic acid, and sulphur application on soil moisture storage in the soil profile up to 60 cm, only after each irrigation of linseed under different irrigation intervals.

Table 4.6.3.a displays data indicating that both seasons (2022-23 and 2023-24), soil moisture content was significantly affected by the irrigation level, both after the first and second irrigation, with the ascending order of I_0 , I_1 , to I_2 having a large and marked increase. After the first irrigation, the plant available soil moisture content went from I_0 (144.25 - 310.48) and I_1 (141.37 - 306.43), which evidences the large influence of irrigation levels on moisture content due to large statistically significant CD values at the 5 percent level. Also, soil moisture storage was always greater in I_2 than in I_1 and I_0 , with very statistically substantial differences due to large statistically significant CD values.

Among the irrigation treatments, the highest soil moisture storage was recorded by I_2 , followed by I_1 , while the lowest values were recorded by I_0 in both irrigation sessions of 2022-23 and 2023-24. The substantial increase in soil moisture content in the higher levels of irrigation indicates the direct role of irrigation frequency and amount in soil profile replenishment. The treatments of nutrient application had a variable effect on the storage of soil moisture. There was a significant effect of the treatments after the first irrigation in 2022-23 and after the second irrigation in both years, with relatively higher soil moisture in the treatments involving the combined application of seed priming, humic acid, and sulphur. The soil's improved physical characteristics, enhanced capacity to hold water, and improved soil structure based on added organic matter and nutrients, as well as agglomeration of the soil, are reasons this occurred. Nutritional application separately showed a lack of interaction with irrigation; thus, no effect on irrigation moisture; irrigation showed no effect on water retention after nutrients were added.

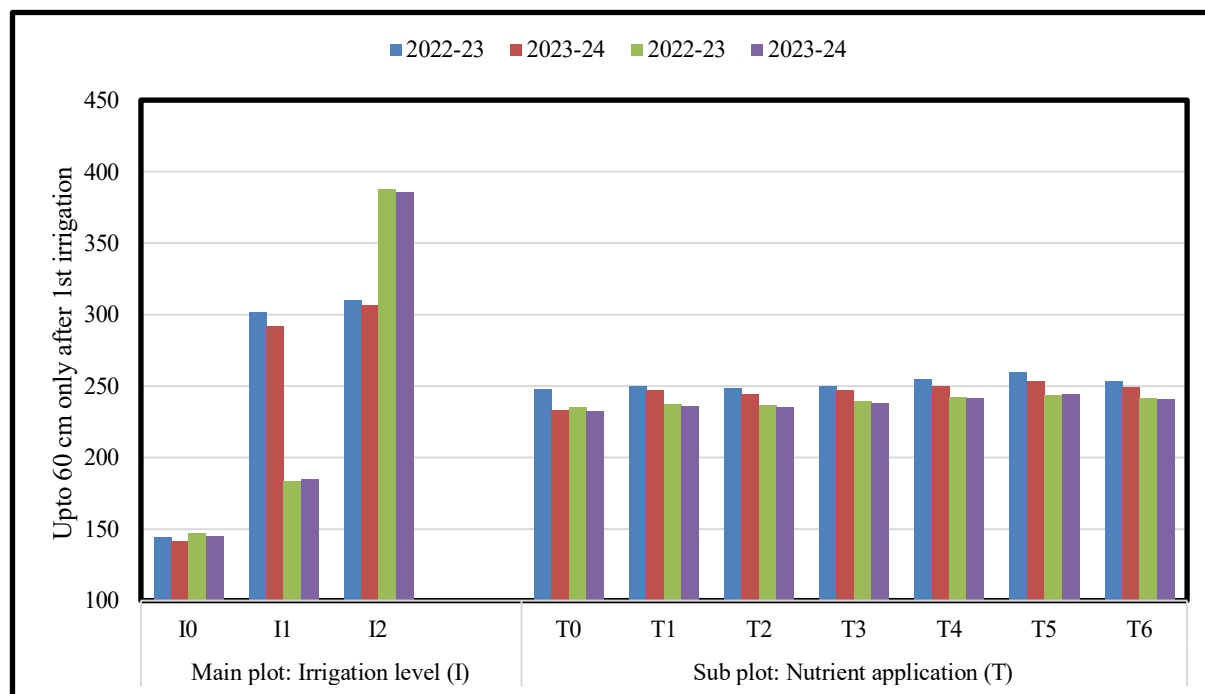
Table 4.6.3.a: Effect of seed priming, humic acid, and sulphur application on soil moisture content in the soil profile up to 60 cm only after each irrigation of linseed under different irrigation intervals during the *Rabi* season of the year (2022-23 and 2023-24).

Soil moisture storage (mm)				
Treatment	Up to 60 cm only after 1 st irrigation		Up to 60 cm only after the 2 nd irrigation	
	2022-23	2023-24	2022-23	2023-24
Main plot: Irrigation level (I)				
I ₀	144.25	141.37	147.53	144.90
I ₁	301.88	291.75	183.36	184.90
I ₂	310.48	306.43	387.34	385.59
SEm±	3.02	3.17	2.06	1.51
CD (P=0.05)	11.84	12.44	8.08	5.94
Sub plot: Nutrient application (T)				
T ₀	248.22	233.16	235.38	232.75
T ₁	249.80	247.31	237.34	236.18
T ₂	248.94	244.54	236.63	235.21
T ₃	250.25	247.58	239.36	238.43
T ₄	254.82	250.19	242.25	241.77
T ₅	259.90	253.76	243.42	244.16
T ₆	253.47	249.10	241.51	240.74
SEm±	2.30	5.85	1.36	1.81
CD (P=0.05)	6.59	NS	3.91	5.20
Interaction I × T				
SEm±	3.98	10.13	2.36	3.14
CD (P=0.05)	NS	NS	NS	NS
Interaction T × I				
SEm±	7.98	8.38	5.44	3.98
CD (P=0.05)	NS	NA	NS	NS

Note:

I₀: No post sowing irrigation, I₁: Post sowing irrigation one, I₂: Post sowing irrigation two,
T₀: Control, T₁: Potassium Nitrate, T₂: Sulphur, T₃: Humic acid, T₄: KNO₃ + S, T₅: KNO₃ + HA, T₆:
Sulphu + HA.

Fig 4.6.3.a Effect of seed priming, humic acid, and sulphur application on soil moisture content in the soil profile up to 60 cm, only after each irrigation of linseed under different irrigation intervals.



4.6.4 Effect of seed priming, humic acid, and sulphur application on soil moisture content in the soil profile up to 60 cm only after 10 mm of rain of linseed under different irrigation intervals.

Soil moisture content in the soil profile up to 60 cm depth measured after 10 mm rainfall differed significantly among irrigation levels during both years (Table 4.6.4 a). The highest soil moisture content was recorded under I_2 (331.97 and 325.36 mm during 2022–23 and 2023–24, respectively), which was significantly superior to I_1 and I_0 , as the differences exceeded the critical difference values of 7.71 mm (2022–23) and 5.68 mm (2023–24). Treatment I_1 also maintained significantly higher soil moisture than I_0 in both years.

Nutrient application treatments exerted a significant influence on soil moisture content after rainfall. Treatment T_5 recorded the maximum soil moisture content (285.43 and 281.35 mm during 2022–23 and 2023–24, respectively) and was significantly superior to the control (T_0), as the differences exceeded the CD values of 8.38 mm and 9.22 mm during the respective years. Other nutrient treatments remained statistically at par with one another but maintained higher soil moisture than the control. The interaction effect between irrigation levels and nutrient application treatments was found to be non-significant during both years, indicating that the response of soil moisture content to nutrient application was consistent across irrigation regimes.

In the soil profile to a 60 cm. depth, following 10 mm of rainfall, soil moisture content was significantly affected by irrigation levels and nutrient application treatments during both (2022-23) and (2023-24) *Rabi* seasons (Table 4.6.4.a) with I_2 having the highest soil moisture content, then I_1 , and I_0 always having the lowest values during both 2022-23 and 2023-24. This trend shows that the plots receiving a greater amount of irrigation retained more moisture within the soil profile after rainfall than would have been retained in either of the other two levels of irrigation, which also is likely due to both better antecedent soil moisture conditions and enhanced soil moisture infiltration. Soil moisture content after rain was significantly affected by nutrient application methods. The seed priming, humic acid or sulphur applications, particularly in combination with others created higher moisture content in the soil than did the control treatments. The form of humic substances in the soil and the sulphur-mediated physical conditioning of soil improved its structure and increased the amount of organic matter in it, giving it greater capacity to retain moisture once water has been applied. Nutrient applications impacted on soil moisture content after rainfall regardless of the level of irrigated water applied in a given year, and so explain how the moisture content of the soil after rainfall will almost always be determined by the past irrigation history of the site, but nutrient applications would help retain those moisture levels long-term, without interacting with irrigated water level.

Table 4.6.4 (a): Effect of seed priming, humic acid, and sulphur application on soil moisture content in the soil profile up to 60 cm only after 10 mm rainfall of linseed under different irrigation intervals during the *Rabi* season of the year (2022-23 and 2023-24).

Treatment	Soil moisture content in the soil profile up to 60 cm only after 10 mm of rain (mm)	
	2022-23	2023-24
Main plot: Irrigation level (I)		
I ₀	233.52	230.02
I ₁	273.30	267.70
I ₂	331.97	325.36
SEm±	1.96	1.45
CD (P=0.05)	7.71	5.68
Sub plot: Nutrient application (T)		
T ₀	266.58	262.59
T ₁	279.79	274.52
T ₂	278.90	273.79
T ₃	280.69	275.01
T ₄	283.66	277.15
T ₅	285.43	281.35
T ₆	282.15	276.11
SEm±	2.92	3.22
CD (P=0.05)	8.38	9.22
Interaction I × T		
SEm±	5.06	5.57
CD (P=0.05)	NS	NS
Interaction T × I		
SEm±	5.187	3.814
CD (P=0.05)	NS	NS

Note:

- 1- I₀: No post sowing irrigation, I₁: Post sowing irrigation one, I₂: Post sowing irrigation two,
- 2- T₀: Control, T₁: Potassium Nitrate, T₂: Sulphur, T₃: Humic acid, T₄: KNO₃ + S, T₅: KNO₃ + HA, T₆: Sulphur + HA.

Fig 4.6.4 (a): Effect of seed priming, humic acid, and sulphur application on soil moisture content in the soil profile up to 60 cm only after 10 mm rainfall of linseed under different irrigation intervals during the *Rabi* season of the year (2022-23 and 2023-24).

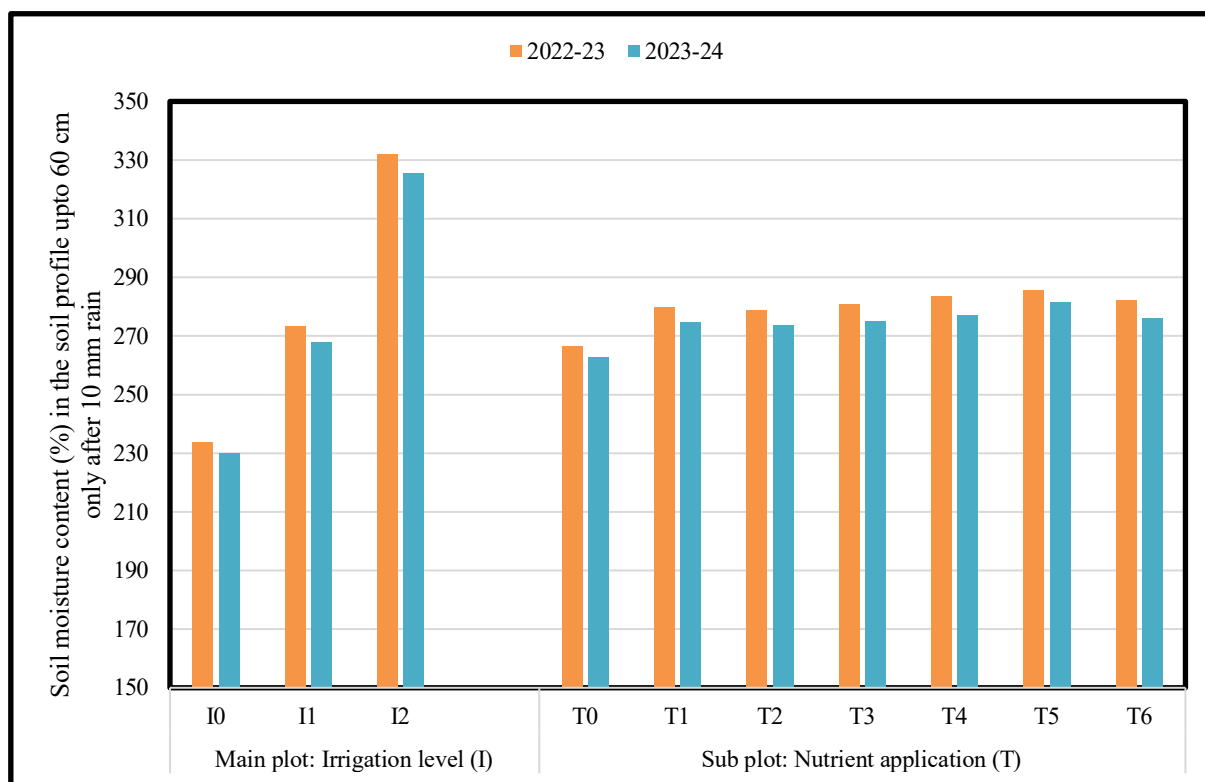


Table 4.6.4 (b): Interactive of seed priming, humic acid and sulphur application on soil moisture content in the soil profile up to 60 cm only after 10 mm rain of linseed under variable of water regime during *Rabi* season of pooled of both the years.

Soil moisture content (mm) in the soil profile up to 60 cm only after 10 mm rain				
	I₀	I₁	I₂	Mean
T ₀	202.49	267.97	323.30	264.59
T ₁	235.86	269.63	325.98	277.16
T ₂	235.33	268.82	324.88	276.34
T ₃	236.38	270.08	327.08	277.85
T ₄	237.43	272.52	331.26	280.40
T ₅	237.72	273.03	339.43	283.39
T ₆	237.19	271.48	328.73	279.13
Mean	231.77	270.50	328.67	
SEm±	4.04			
LSD (P=0.05)	11.58			

4.6.5 Effect of seed priming, humic acid, and sulphur application on soil moisture content in the soil profile up to 30 cm only after crop harvest of linseed under different irrigation intervals.

Soil moisture content in the soil profile up to 30 cm depth measured after crop harvest on linseed crop varied significantly with the levels of irrigation during both the *Rabi* seasons of 2022-23 and 2023-24 (Table 4.6.5.a). Maximum soil moisture content was observed under I_2 treatment, i.e., 89.29 and 84.56 mm during 2022-23 and 2023-24, respectively. This moisture content under I_2 was significantly higher than I_1 and I_0 , as the differences were much higher than the critical difference of 2.00 mm and 1.48 mm, respectively. Treatment I_1 possessed significantly higher soil moisture content than I_0 , which proved the residual effect of the second higher level of irrigation on the soil moisture status.

Nutrient application treatments had no significant effect on the post-harvest soil moisture content in both the years. Although T_5 recorded numerically higher soil moisture content of 83.81 and 79.71 mm during 2022-23 and 2023-24, respectively, it was statistically at par with all other nutrient treatments including control. The interaction effect between irrigation levels and nutrient application was found to be non-significant for all the years. This indicates that nutrient treatments did not have differential impacts on the retention of soil moisture under different levels of irrigation.

Thus, the higher the level of irrigation, the higher the residual soil moisture content can be attributed, as it has a stimulating effect on soil water recharge during crop growth, resulting in higher soil moisture at and even after harvest time. The lack of significance of the application of nutrient treatments at crop harvest time suggests, however, that even though it has a stimulating effect on soil moisture content, it has only a slight effect at and even after crop harvest time, considering the conditions applied. Moreover, it can be inferred from the lack of significance of the interaction effect that soil moisture at crop harvest time is independent of soil moisture history, with its determination being controlled only by irrigation history.

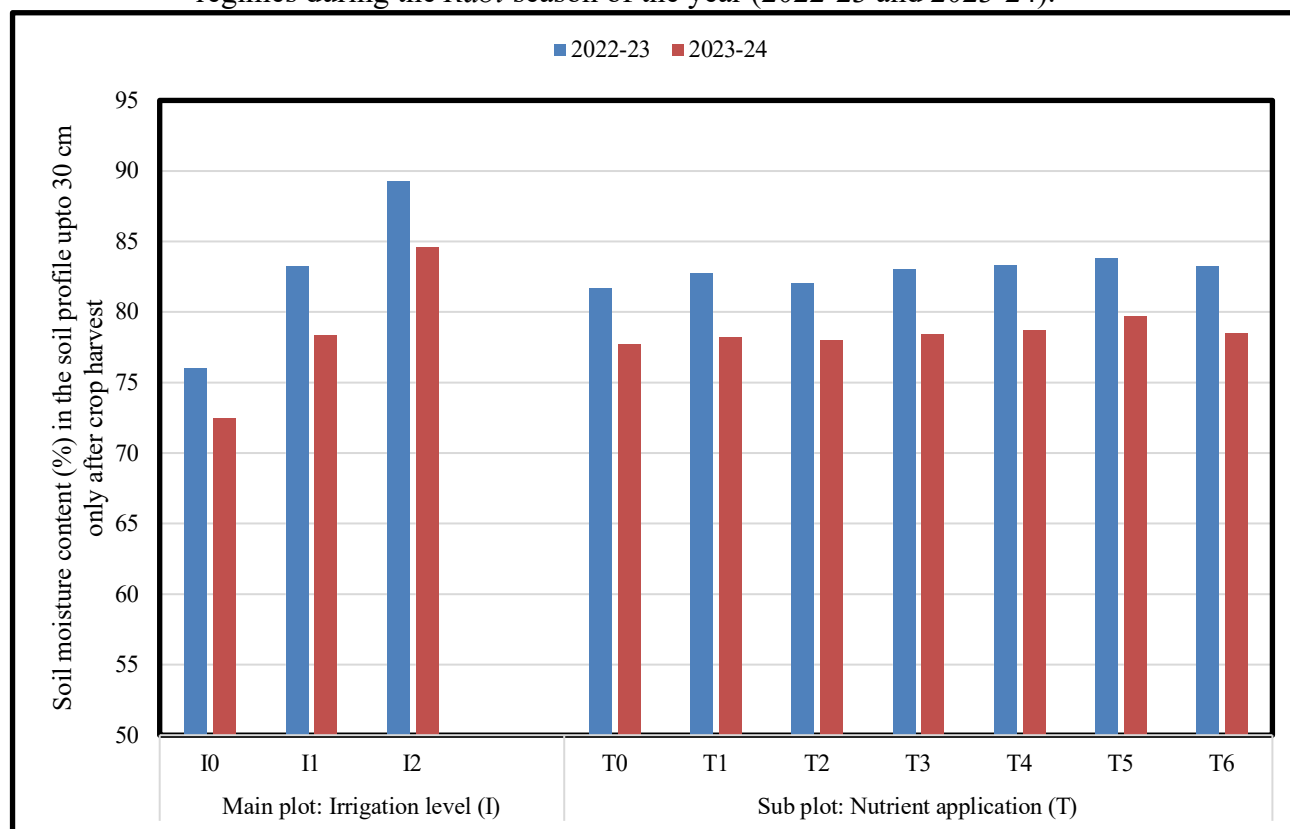
Table 4.6.5 (a): Effect of seed priming, humic acid, and sulphur application on soil moisture content in the soil profile up to 30 cm only after crop harvest of linseed under different irrigation intervals during the *Rabi* season of the year (2022-23 and 2023-24).

Treatment	Soil moisture content in the soil profile up to 30 cm only after crop harvest (mm)	
	2022-23	2023-24
Main plot: Irrigation level (I)		
I ₀	76.00	72.43
I ₁	83.23	78.38
I ₂	89.29	84.56
SEm±	0.51	0.38
CD (P=0.05)	2.00	1.48
Sub plot: Nutrient application (T)		
T ₀	81.68	77.72
T ₁	82.72	78.21
T ₂	82.01	78.00
T ₃	83.06	78.41
T ₄	83.33	78.69
T ₅	83.81	79.71
T ₆	83.26	78.48
SEm±	0.86	0.77
CD (P=0.05)	NS	NS
Interaction I × T		
SEm±	1.49	1.34
CD (P=0.05)	NS	NS
Interaction T × I		
SEm±	1.348	0.982
CD (P=0.05)	NS	NS

Note:

I₀: No post sowing irrigation, I₁: Post sowing irrigation one, I₂: Post sowing irrigation two,
T₀: Control, T₁: Potassium Nitrate, T₂: Sulphur, T₃: Humic acid, T₄: KNO₃ + S, T₅: KNO₃ + HA, T₆: Sulphur + HA.

Table 4.6.5 (a): Effect of seed priming, humic acid, and sulphur application on soil moisture content in the soil profile up to 30 cm only after crop harvest of linseed under variable water regimes during the *Rabi* season of the year (2022-23 and 2023-24).



4.7 Economics

Over two consecutive years (2022–23 and 2023–24), economic analysis revealed variations in gross return, net return and benefit:cost ratio under different irrigation and nutrient management treatments. For irrigation levels, treatment I₂ recorded the highest gross return (₹1,00,880 and ₹99,200 ha⁻¹ during 2022–23 and 2023–24, respectively), followed by I₁ (₹99,600 and ₹97,360 ha⁻¹) and I₀ (₹98,240 and ₹96,560 ha⁻¹). Gross return increased with increase in seed yield, indicating direct dependence of economic return on yield performance. However, due to comparatively higher cultivation cost under higher irrigation levels, maximum net return was observed under I₀ (₹60,940 and ₹54,160 ha⁻¹ during 2022–23 and 2023–24, respectively), followed by I₁ and I₂. The benefit:cost ratio also followed a similar trend with higher values recorded under I₀.

Among nutrient treatments, T₅ recorded the highest gross return (₹1,07,920 and ₹1,05,920 ha⁻¹ during 2022–23 and 2023–24, respectively), followed by T₄ and T₆, mainly due to superior seed yield under these treatments. Treatment T₅ also recorded higher net return and benefit:cost ratio, indicating better economic viability under integrated nutrient application. Lower economic returns were recorded under T₀ due to comparatively lower seed yield.

Differences in cost of cultivation between experimental years were primarily due to variation in labour requirement and expenditure incurred on intercultural operations, harvesting and threshing during respective crop seasons, resulting in year-to-year variation in cultivation cost.

4.7 (a) Influence of treatments on Linseed economics under different irrigation intervals.

Treatment	Cost of Cultivation		Gross return (Rs ha ⁻¹)		Net return (Rs ha ⁻¹)		B: C ratio	
	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24
Main plot: Irrigation level (I)								
I ₀	37300	42400	98240	96560	60940	54160	2.63	2.28
I ₁	41600	43900	99600	97360	58000	53460	2.39	2.22
I ₂	43900	45900	100,880	99200	56980	53300	2.30	2.16
Sub plot: Nutrient application (T)								
T ₀	38200	41300	90720	89440	52520	48140	2.37	2.17
T ₁	39100	42000	96720	94880	57620	52880	2.47	2.26
T ₂	43800	46700	95760	94080	51960	47380	2.19	2.01
T ₃	39300	42100	100080	98240	60780	56140	2.55	2.33
T ₄	44100	46900	104080	102240	59980	55340	2.36	2.18
T ₅	41000	44000	107920	105920	66920	61920	2.63	2.41
T ₆	43900	46800	101760	99920	57860	53120	2.32	2.14

SUMMARY AND CONCLUSION

This research was conducted in the agricultural field of Lovely Professional University, Phagwara, Punjab during the *rabi* seasons of 2022-23 and 2023-24 to quantify the impact of various nutrient management practices (seed priming, humic acid, and sulphur) and irrigation scheduling on linseed (*Linum usitatissimum* L.) growth, yield, and oil quality. The experimental layout was a split-plot design with three irrigation levels in main plots (I_0 : no irrigation post sowing, I_1 : one irrigation, I_2 : two irrigations) and seven nutrient management treatments in sub-plot (T_0 : control, T_1 : KNO_3 15 mM, T_2 : Sulphur @ 60 kg ha⁻¹, T_3 : Humic acid @ 12 kg ha⁻¹, T_4 : KNO_3 + Sulphur, T_5 : KNO_3 + Humic acid, T_6 : Sulphur + Humic acid). The analysis of the results was conducted using a range of morphological, physiological, biochemical, and yield parameters to advise on sustainable, economically viable methods of linseed production.

5.1 Growth parameter

- 1.1 Plant height was observed to be significantly affected by different irrigation levels and nutrient application at different growth stages during both years. According to CD ($P = 0.05$), two irrigations after sowing, i.e., I_2 , significantly influenced plant height compared to I_0 and I_1 at 60 DAS, 90 DAS, and harvest, whereas at 30 DAS, there were no significant differences. In the case of nutrients, it was found that T_5 (KNO_3 + humic acid) was significant for greater plant height compared to the control and other treatments at all stages. The interaction effects of $I \times T$ and $T \times I$ were mostly non-significant.
- 1.2 The fresh weight of linseed was significantly affected by the differing levels of irrigation at the later stages of growth in the two years. As per CD ($P = 0.05$), the two irrigations (I_2) significantly influenced the fresh weight over I_0 at 60 DAS, 90 DAS, and at harvest, while the fresh weight at 30 DAS is found to be non-significant. The nutrient treatments T_5 with KNO_3 and humic acid significantly influenced the fresh weight compared to the control and other treatments at all stages of growth. The interaction effects $I \times T$ and $T \times I$ are found to be non-significant.
- 1.3 Dry matter accumulation was significantly influenced by irrigation levels at 60 DAS, 90 DAS, and at harvest during both years, while differences at 30 DAS were non-significant. As per CD ($P = 0.05$), two post-sowing irrigations (I_2) recorded significantly higher dry matter accumulation over I_0 and I_1 at later growth stages. Of the nutrient treatments, T_5 (KNO_3 + Humic Acid) showed significantly higher dry matter production than the control

and other treatments at all stages. The interactions were not significant at the early stages, but the treatments and interactions were significant at 90 DAS and harvest.

- 1.4 The irrigation levels significantly influenced the leaf area at 90 DAS and at harvest in both years, while differences at 30 and 60 DAS were nonsignificant according to CD ($P = 0.05$). Two post-sowing irrigations (I_2) recorded significantly higher leaf area over I_0 , staying at par with I_1 at later stages. In respect of nutrient treatments, T_5 (KNO_3 + humic acid) produced significantly higher leaf area than the control and other treatments during all growth stages. Interaction effects ($I \times T$ and $T \times I$) were nonsignificant.

5.2 Phenological parameter

- 1.5 Leaf area index, however, was found to have no significant effect with the different levels of irrigation at any stage of growth in both years, as the differences were non-significant, i.e., CD ($P=0.05$). Also, the leaf area index was seen to increase significantly with the application of the nutrient treatments but to a higher extent with T_5 , i.e., KNO_3 + Humic Acid, in comparison to the control, i.e., T_0 , and the remaining treatments, wherein the superiority of T_5 was evident statistically at various stages, i.e., 30, 60, 90 DAS, and harvest in both the years, with the interaction effect of $I \times T$ and $T \times I$ found nonsignificant.
- 1.6 The crop growth rate increased with increasing irrigation levels; this was much more pronounced with an increase in growth intervals. The crop growth rate of I_2 was also significantly higher compared to I_0 and I_1 at both intervals of time in both years according to CD ($P = 0.05$). Among the treatments of nutrients applied to the crops, the T_5 treatment of KNO_3 + Humic acid recorded a much faster crop growth rate compared to the control and other treatments at both intervals of time in both years. The interaction between irrigation and treatments ($I \times T$), as well as the interaction between treatments and irrigation ($T \times I$), was non-significant at 30-60 DAS but became significant at 60-90 days after sowing. The crop growth rate was much higher at 60-90 DAS compared to 30-60 days after sowing.
- 1.7 During 30–60 DAS, irrigation levels showed a significant effect on RGR, with I_2 and I_1 recording significantly higher values than I_0 as per CD ($P = 0.05$) in both years. However, no significant differences were observed during 60–90 DAS among irrigation levels. Nutrient application treatments and their interactions with irrigation did not exert any significant influence on RGR at either growth stage. Overall, RGR was mainly affected

by irrigation during the early growth period.

1.8 At 30–60 DAS, there was a highly significant effect of irrigation levels on net assimilation rate, where I_2 showed significant superiority over I_0 , while performing at par with I_1 as per CD at $P = 0.05$. Nutrient application was also found to show a highly significant effect during 30–60 DAS, where T_5 (KNO_3 + Humic acid) showed significant superiority over other treatments. However, at 60–90 DAS, all the effects of irrigation, nutrient, and interaction were found to be non-significant in both years. All interaction effects were also found to be non-significant throughout.

1.9 Days taken for emergence were not significantly affected by levels of irrigations, while days taken to branch, flower at 50 percent, and maturity were significantly influenced by higher levels of irrigations. I_2 recorded significantly higher days compared to I_0 and I_1 as per CD ($P = 0.05$). Nutrient application treatments significantly affected all the phenological stages of the crop, while T_5 recorded significantly earlier emergence with delayed flowering and maturity compared to the control. Interaction effects were found to be non-significant, except for days to emergence and branch in one of the years. Higher moisture and nutrient availability increased the period of the crop.

5.3 Physiological parameters

3.1. Irrigation levels exerted a significant effect on relative water content at 45 DAS, 90 DAS, and at harvest, with I_2 and I_1 recording significantly higher RWC than I_0 as per CD ($P = 0.05$) during both years. Although mean RWC values varied among nutrient treatments, differences due to nutrient application were statistically non-significant at all stages. Interaction effects between irrigation and nutrient treatments were also non-significant. Overall, improved soil moisture availability under higher irrigation regimes enhanced plant water status.

3.2 Levels of irrigation also significantly influenced MSI at 45 DAS, 90 DAS, and at harvest, where I_2 recorded significantly higher MSI than I_1 and I_0 as per CD at $P = 0.05$ during both years. Application of nutrients also greatly influenced MSI at 45 and 90 DAS, wherein T_5 [KNO_3 + humic acid] recorded the highest values, which were significantly superior over the control treatment. The effect of the application of nutrients at the harvest stage was non-significant during 2023-24. Interaction effect of irrigation and nutrients was non-significant at all stages.

3.3 The interaction effects of levels of irrigation significantly influenced the membrane injury

indices at 90 DAS and at harvest in I₂, where the recorded values of membrane injury were significantly lower than I₁ and I₀ as per CD ($P = 0.05$). Irrigation had a non-significant effect during 2022–23 at 45 DAS, while the effect was significant in 2023–24. Nutrient application significantly impacted membrane injury indices at 45 and 90 DAS, where T₅ recorded the lowest membrane injury; however, at harvest, nutrient application showed a non-significant impact in 2023–24. The interaction effects were found to be non-significant throughout.

5.4 Biochemical Parameters

- 4.1. Chlorophyll a content was not significantly affected by irrigation levels at all stages during both years. A light increasing trend was noticed for I₂ treatment during the later stages. Nutrient application level was found to be non-significant for all treatments; slightly higher chlorophyll concentrations were noticed for the T₄ and T₅ levels. Interaction between irrigation and nutrient levels was also found to be non-significant for all stages during the crop growth period.
- 4.2 Moreover, the chlorophyll b content was not significantly influenced by various levels of irrigation during any stage of growth in both years, where the CD value was not significant. Again, differences in the levels of nutrient application were not statistically significant; however, relatively higher values were recorded with T₅ and I₂. The interaction between the two factors was statistically not significant.
- 4.3 The total chlorophyll content indicated a significant effect of irrigation treatments only at 45 DAS (2023-24) and 90 DAS (2023-24) when I₂ had a higher value compared to I₁, with significant differences beyond CD ($P=0.05$). Nutrient application had a significant effect on total chlorophyll content at 45 DAS (2022-23) and 90 DAS (2023-24), with T₅ being superior to control. However, at harvest, all differences with respect to irrigation, nutrients, and their interaction were statistically non-significant. I x T was non-significant at all stages of both years.
- 4.4 Proline content increased significantly under lower irrigation levels, with I₀ recording higher values than I₂ at 45 DAS (2023–24) and 90 DAS (2023–24), as the differences exceeded the CD ($P=0.05$). Nutrient application did not exert a significant effect on proline accumulation at any stage during both years. The interaction between irrigation and nutrient treatments was non-significant, indicating that proline accumulation was

mainly governed by moisture stress conditions rather than nutrient combinations.

5.5 Yield and yield attributes

- 5.1. The effect on the number of primary and secondary branches was not significant with varying irrigation levels for the two years. Nutrient application, however, was significant, with T₅ showing the maximum number of primary and secondary branches, compared with the control according to CD, P=0.05. The interaction of the effect of irrigation and nutrients on the experiment was nonsignificant.
- 5.2 Irrigation levels did not exert a significant effect on the number of capsules per plant, seed yield per capsule, or test weight during both years, as differences were within the CD limits. In contrast, nutrient application had a significant influence on capsules per plant and seed yield per capsule, with T₅ being statistically superior to the control and most other treatments. Test weight was significantly affected by nutrient treatments only in 2023–24, where T₅ recorded the highest value. The I × T interaction remained non-significant, indicating independent effects of irrigation and nutrients on yield attributes.
- 5.3. Seed yield, oil yield, biological yield, and harvest index were not significantly affected by irrigation levels in 2022-23. In 2023-24, irrigation levels had significant effects on seed and oil yield; the values for I₂ were higher than those of I₀, i.e., Control, since the difference was higher than CD at P=0.05. Application of nutrients had significant effects on seed yield, oil yield, and biological yield for both years, and T₅ values were statistically the highest compared to the rest of the treatment and control values. The values of harvest index also had significant responses to the application of nutrients, i.e., maximum values for T₅, followed by the rest. Interaction values were mostly non-significant, indicating that irrigation levels acted independently.
- 5.4. The content of oil in seeds showed a remarkable increase every year based on levels of irrigation treatment; its highest value was noted under I₂, followed by other levels, which were beyond CD, using P=0.05 as a critical difference. Among the nutrient treatments, T₅ showed a remarkably higher value compared to all other treatments in both years, clearly surpassing the critical difference value, compared to other treatments, as its value is greater than others. The control treatment had the lowest value, recorded during both years. The interaction effects between irrigation and nutrient treatments were not significant, showing a clear effect of these treatments.

5.6 Soil moisture parameter

- 6.1. Soil moisture content in the 0-30 cm profiles at the time of sowing did not show any significant differences due to irrigation levels and nutrient treatments in both years because differences were less than CD ($P=0.05$). This implies that all the treatment plots had uniform moisture at the time of sowing. The results also indicate non-significant values of interaction effects, implying that all treatment combinations had equal moisture conditions.
- 6.2. The increase in soil moisture storage up to a depth of 60 cm was pronounced with the various levels of irrigation, with I₂ showing a high value before the 1st and 2nd irrigation during both years, as the differences were more than CD ($P=0.05$). Nutrient application levels had shown non-significant effects on the amount of soil moisture storage, except before the 2nd irrigation during 2023-24, when the difference was shown to be significant. The interaction effects (I x T) were found to be non-significant, revealing that the levels of irrigation were the governing factors for the soil moisture storage.
- 6.3. The storage of soil moisture up to 60 cm depth was substantially increased with a higher level of irrigation. Among the irrigation levels, I₂ recorded the highest storage of soil moisture after the 1st and 2nd irrigations carried out in both years, since the difference is larger than the CD with $P=0.05$. The treatments related to the application of nutrients have revealed variations; however, they were significant after the 1st irrigation in 2022-23, as well as after the 2nd irrigation in both years, whereas they were non-significant in other cases. Also, the interaction effects (I x T) were non-significant, which revealed that storage of soil moisture was influenced only by irrigation.
- 6.4. The soil moisture content up to 60cm depth, especially after the 10 mm of rain, differed significantly for the different levels of irrigation, with the highest recorded in the I₂ level during the two years, as the differences were all compared with the CD ($P=0.05$). The differences were also seen in the application of nutrient levels, with differences recorded in the application of the integrated nutrient compared with the control. The interaction effects, I x T, were however not significant for the factors under study on the soil moisture content.

5.7 Economics

7.1. Economic analysis revealed that irrigation and nutrient management significantly influenced economic parameters of linseed cultivation during both years. Among irrigation levels, I₂ recorded higher gross return due to increased seed yield; however, comparatively higher cultivation expenditure influenced the benefit:cost ratio under irrigation treatments. Among nutrient treatments, T₅ recorded higher gross return, net return and benefit:cost ratio owing to superior productivity and better economic efficiency. Differences in cost of cultivation between years were mainly due to variation in labour requirement, intercultural operations, harvesting, threshing and treatment input costs during respective crop seasons.

The results of the present investigation, entitled “Effect of seed priming, humic acid and sulphur application on growth, yield and oil quality of linseed under different irrigation intervals,” concluded that:

To study the efficacy of seed priming, humic acid, and sulphur application on the growth and yield of linseed.

As per the first objective, seed priming, humic acid and sulphur application significantly improved the growth and yield attributes of linseed. Integrated application of these treatments recorded superior performance over control and produced statistically significant results.

To evaluate the effect of different irrigation intervals on the growth, yield, and oil quality of linseed.

From this second objective, it is noted that various intervals in the irrigation process had a profound impact on the growth, yield, and quality of oil produced from linseed. Also, with more irrigation, the yield and oil produced showed improvement, indicating that linseed had a positive response to moist soil.

As per the third objective, economic analysis revealed that improved irrigation levels, along with nutrient application, increased the gross return, net return, and benefit-cost ratio, indicating they were economically sound and profitable.

Limitations of the study

Although the present investigation has given significant and consistent results, there are some limitations. The field experiments were conducted at one location in two consecutive *Rabi*

seasons; hence, the seasonal climatic variability in respect of temperature and rainfall might have influenced the findings. The responses are also specific to the soil type of the experimental site, and the performance of seed priming and humic acid and sulphur application may vary under different soil textures and fertility conditions. Additionally, although the combined application of KNO_3 and humic acid under two irrigations proved economically superior at the experimental site, the economic feasibility of these treatments may vary across regions due to variations in input costs, irrigation availability, and farmers' resource endowments.

Future research directions

Future studies may be carried out at the molecular and physiological levels to understand the basic mechanism of stress tolerance, nutrient uptake, and yield enhancement due to seed priming and humic acid application. Long-term studies may also be carried out for the cumulative effect of humic acid and sulphur application on the soil health, microbial activity, and nutrient dynamics of agroecosystems. Further, such treatments may be evaluated under micro-irrigation systems like drip irrigation to fully understand the water-use efficiency and sustainability pertaining to water-scarcity situations. Multi-location and multi-season trials under rainfed agro-ecological zones would further establish the scalability and applicability of the same.

Conclusion

The investigation clearly indicated that irrigation regimes and nutrient management practices significantly affected linseed growth and yield, oil quality, and physiological performance. Two post-sowing irrigations applied at the vegetative and flowering stages (I_2) consistently improved crop growth, soil moisture availability, and yield attributes over limited or no irrigation. Among nutrient treatments, the conjunctive application of potassium nitrate seed priming and humic acid (T_5) proved most effective in improving crop establishment, physiological stability, yield components, and seed and oil yield with more economic returns. Sulphur application also showed additional benefits, though integrated nutrient application was more beneficial than individual treatments. The interaction of I_2T_5 emerged as the best treatment combination, producing superior productivity coupled with more moisture conservation and higher benefit–cost ratio for both years. Thus, integration of two crucial irrigations with KNO_3 seed priming and humic acid application is recommended as a viable and profitable practice to improve linseed productivity under variable moisture regimes

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Appendix-I

Meteorological data for the year 2022-2023

SMW	Temp Max (°C)	Temp Min (°C)	RH Max (%)	RH Min (%)	Wind Speed (km/h)	Rainfall (mm)
42	31.71	20.29	53.71	43.43	2.14	0
43	29.57	18.29	54.29	43.71	3.29	0
44	28.71	18.43	53.14	44.29	2.57	0
45	27.86	15.00	53.43	44.14	2.00	0
46	26.57	13.71	56.86	47.29	2.43	0
47	23.57	13.14	56.71	46.14	1.86	0
48	23.29	11.29	67.86	56.43	1.00	0
49	27.29	10.86	88.00	59.57	4.00	0
50	26.57	10.86	89.14	70.43	7.71	0
51	24.00	9.43	91.57	75.43	4.57	0
52	21.43	8.86	93.71	80.00	7.57	0.29
1	14.40	5.50	94.10	81.90	6.60	0

Date	Temp Max (°C)	Temp Min (°C)	RH Max (%)	RH Min (%)	Wind Speed (km/h)	Rainfall (mm)
2	13.50	8.40	95.60	82.70	8.90	0.20
3	14.40	5.90	91.40	76.60	6.70	0
4	18.70	7.60	84.10	63.60	7.70	4.90
5	20.10	8.70	94.60	76.00	11.40	1.80
6	23.70	11.80	80.30	58.10	10.10	0
7	26.00	10.80	63.00	41.40	9.60	0
8	28.10	14.30	92.30	56.30	9.90	0
9	27.40	14.00	66.30	47.90	9.10	0
10	29.40	14.00	46.40	37.30	8.70	0
11	27.80	16.70	74.40	45.10	10.60	2.10
12	24.70	13.90	93.30	59.70	1.80	5.50
13	27.60	15.70	88.70	50.60	10.10	0.30

Meteorological data for the year 2023-2024

Date	Temp Max (°C)	Temp Min (°C)	RH Max (%)	RH Min (%)	Wind Speed (km/h)	Rainfall (mm)
43	30.64	13.53	92.90	45.55	4.45	0
44	29.96	13.17	93.35	46.48	4.01	0
45	26.0	12.6	92.41	57.14	5.6	0.1
46	27.3	9.9	93.43	47.81	4.3	0.0
47	24.3	10.3	92.7	49.45	4.8	0.05
48	23.85	10.65	92.22	59.40	4.4	0.9
49	23.15	6.79	94.52	49.94	5.4	1.4
50	25.51	4.35	94.05	51.93	4.06	1.2
51	21.40	4.56	94.31	58.67	3.70	0.0
52	16.61	7.99	94.59	73.48	2.05	0.05
1	11.64	6.28	94.71	86.28	2.99	0.02
2	11.8	6.15	94.42	78	3,28	0
3	13.14	6	93.85	79.28	3.13	0
4	15.85	5.7	94.14	73.42	4.7	0
5	17.14	9	93.42	73.14	4.9	1.3
6	20.8	2.9	93.4	52.0	5.2	0
7	23.5	7.2	92.1	53.5	7.1	0
8	22.9	5.9	90.9	43.9	8.1	0.2

Date	Temp Max (°C)	Temp Min (°C)	RH Max (%)	RH Min (%)	Wind Speed (km/h)	Rainfall (mm)
9	22.2	9.2	88.1	55.5	9.1	9.1
10	23.21	7.5	91.13	55.5	5.9	0
11	26.86	8.9	91.74	52.93	6.4	0
12	29.70	13.75	91.37	49.45	7.4	0
13	30.9	16.9	86.24	54.76	6.24	2.33
14	30.9	16.8	86.14	53.87	6.14	2.13

Appendix-ii

Calculation of fixed cost of cultivation (Rs ha⁻¹) of Linseed (LC 2069) 2022

S.No.	Particulars	Fixed cost of cultivation (Rs ha ⁻¹)			
		Input	Unit	Cost of labour (Rs day ⁻¹ or hour)	Total Cost (Rs ha ⁻¹)
1.	Field Preparation (Ploughing, Planking, and seed bed preparation)	1 Tractor (4 hr)	1	800 x 4	3200
2.	Seed cost	5	kg	200	1000
3.	Sowing	5	labour	500	2500
4.	Insecticide (Imidacloprid 17.8% SL)	1.5	L	860	1290
5.	Spraying insecticide, Thinning, and Weeding	16	Labour	500	8000
6.	Harvest and threshing	21	Labour	500	10,500
	Common Cost				26,490.00
	Miscellaneous (10% of common cost)				2649.00
	Total				29,139.00

Calculation of fixed cost of cultivation (Rs ha⁻¹) of Linseed (LC 2069) 2023

S.No.	Particulars	Fixed cost of cultivation (Rs ha ⁻¹)			
		Input	Unit	Cost of labour (Rs day ⁻¹ or hour)	Total Cost (Rs ha ⁻¹)
1.	Field Preparation (Ploughing, Planking, and seed bed preparation)	1 Tractor (4 hr)	1	800 x 4	3200
2.	Seed cost	5	kg	200	1000
3.	Sowing	5	labour	500	2500
4.	Insecticide (Imidacloprid 17.8% SL)	1.5	L	860	1290
5.	Spraying insecticide, Thinning, and Weeding	14	Labour	500	7000
6.	Harvest and threshing	18	Labour	500	9000
	Common Cost				23,990.00
	Miscellaneous (10% of common cost)				2399.00
	Total				26,389.00

Calculation of variable cost of cultivation (Rs ha⁻¹) of Linseed (2022 and 2023)

S.No.	Particulars	Quantity	Unit	Cost of Treatments (Rs ha ⁻¹)	Cost of Labour (Rs day ⁻¹)	Water rate (Rs month ⁻¹)	Total Cost	Grand Total
Main plot								
I0	Zero irrigation	-	-	-	-	-	-	-
I1	Vegetative stage	2	labour	-	500	50	1050	1050
I2	Vegetative + Seed filling stage	4	labour	-	500	50	2050	2050
Sub plot								
T0	Urea	163	Kg ha ⁻¹	5.36	500	-	1373.68	3433.68
	DAP	65	Kg ha ⁻¹	24	500	-	2060.00	
T1	Urea	163	Kg ha ⁻¹	5.36	500	-	1373.68	4055.68
	DAP	65	Kg ha ⁻¹	24	500	-	2060.00	
	KNO ₃	1.22	Kg ha ⁻¹	100	500	-	622.00	
T2	Urea	163	Kg ha ⁻¹	5.36	500	-	1373.68	6399.68
	DAP	65	Kg ha ⁻¹	24	500	-	2060.00	
	Sulphur	111.11	Kg ha ⁻¹	22.2	500	-	2966.64	
T3	Urea	163	Kg ha ⁻¹	5.36	500	-	1373.68	4025.19
	DAP	65	Kg ha ⁻¹	24	500	-	2060.00	
	Humic Acid	0.247	Kg ha ⁻¹	370.5	500	-	591.51	
T4	Urea	163	Kg ha ⁻¹	5.36	500	-	1373.68	6522.32
	DAP	65	Kg ha ⁻¹	24	500	-	2060.00	
	KNO ₃ + Sulphur	1.22 + 111.11	Kg ha ⁻¹	100+22.2	500	-	3088.64	
T5	Urea	163	Kg ha ⁻¹	5.36	500	-	1373.68	4806.68
	DAP	65	Kg ha ⁻¹	24	500	-	2060.00	
	KNO ₃ + HA	1.22 + 0.247	Kg ha ⁻¹	100+370.5	500	-	713.51	
T6	Urea	163	Kg ha ⁻¹	5.36	500	-	1373.68	6491.84
	DAP	65	Kg ha ⁻¹	24	500	-	2060.00	
	Sulphur + HA	111.11 + 0.247	Kg ha ⁻¹	22.2 + 370.5	500	-	3058.16	

The total cost incurred by the treatments (Rs ha⁻¹) of linseed in 2022

MAINP LOT	SUBPLOT	SOURCE COST	FIXED COC	INTEREST ON THE COLUMN (3+4@12% per annum)	INTEREST ON THE COLUMN (3+4@10% per annum)	Total cost of cultivation (3+4+5+6) ha ⁻¹
		3	4	5	6	7
I0	T0	3433.68	29,139	3469.04	2890.87	35268.59
	T1	4055.68	29,139	3543.68	2953.07	36027.43
	T2	6399.68	29,139	3824.96	3187.47	38887.11
	T3	4025.19	29,139	3540.02	2950.02	35990.23
	T4	6522.32	29,139	3839.68	3199.73	39036.73
	T5	4806.68	29,139	3633.8	3028.17	36943.65
	T6	6491.84	29,139	3836.02	3196.68	38999.54
I1	T0	1050 + 3433.68 = 4483.68	29,139	3594.48	2995.87	40,213.03
	T1	1050 + 4055.68 = 5105.68	29,139	3670.8	3058.07	40,973.55
	T2	1050 + 6399.68 = 7449.68	29,139	3951	3292.47	43,832.15
	T3	1050 + 4025.19 = 5075.19	29,139	3667.2	3055.02	41,484.92
	T4	1050 + 6522.32 = 7572.32	29,139	3966	3304.73	43,982.05
	T5	1050 + 4806.68 = 5856.68	29,139	3759.12	3133.17	41,887.97
	T6	1050 + 6491.84 = 7541.84	29,139	3962.4	3301.68	43,944.92
I2	T0	2050 + 3433.68 = 5483.68	29,139	3683.04	3074.87	41,380.59
	T1	2050 + 4055.68 = 6105.68	29,139	3759.36	3137.07	42,141.11
	T2	2050 + 6399.68 = 8449.68	29,139	4039.56	3371.47	44,999.71
	T3	2050 + 4025.19 = 6075.19	29,139	3755.52	3134.02	42,103.73
	T4	2050 + 6522.32 = 8572.32	29,139	4054.24	3383.73	45,149.29
	T5	2050 + 4806.68 = 6856.68	29,139	3847.92	3212.17	43,055.77
	T6	2050 + 6491.84 = 8541.84	29,139	4050.48	3380.68	45,112.00

The total cost incurred by the treatments (Rs ha⁻¹) of linseed in 2023

MAIN PLOT	SUBPLOT	SOURCE COST	FIXED COC	INTEREST ON THE COLUMN (3+4@12% per annum)	INTEREST ON THE COLUMN (3+4@10% per annum)	Total cost of cultivation (3+4+5+6) ha ⁻¹
		3	4	5	6	7
I0	T0	3,433.68	26,389.00	3,868.22	3,223.52	39,340.52
	T1	4,055.68	26,389.00	4,103.48	3,419.07	40,393.33
	T2	6,399.68	26,389.00	5,199.00	4,332.47	44,746.25
	T3	4,025.19	26,389.00	4,099.41	3,417.42	40,357.12
	T4	6,522.32	26,389.00	5,238.88	4,369.73	44,958.62
	T5	4,806.68	26,389.00	4,613.56	3,847.17	42,095.11
	T6	6,491.84	26,389.00	5,212.43	4,345.38	44,873.85
II	T0	1,050 + 3,433.68 = 4,483.68	26,389.00	4,617.64	3,850.20	39,340.52
	T1	1,050 + 4,055.68 = 5,105.68	26,389.00	4,852.90	4,045.75	40,393.33
	T2	1,050 + 6,399.68 = 7,449.68	26,389.00	5,948.42	4,959.15	44,746.25
	T3	1,050 + 4,025.19 = 5,075.19	26,389.00	4,848.83	4,042.10	40,357.12
	T4	1,050 + 6,522.32 = 7,572.32	26,389.00	5,988.30	5,009.00	44,958.62
	T5	1,050 + 4,806.68 = 5,856.68	26,389.00	5,362.98	4,486.45	42,095.11
	T6	1,050 + 6,491.84 = 7,541.84	26,389.00	5,961.75	4,981.26	44,873.85
46I2	T0	2,050 + 3,433.68 = 5,483.68	26,389.00	5,106.70	4,274.81	41,254.19
	T1	2,050 + 4,055.68 = 6,105.68	26,389.00	5,341.96	4,470.36	42,306.00
	T2	2,050 + 6,399.68 = 8,449.68	26,389.00	6,437.48	5,383.76	46,659.92
	T3	2,050 + 4,025.19 = 6,075.19	26,389.00	5,337.89	4,463.71	42,265.79
	T4	2,050 + 6,522.32 = 8,572.32	26,389.00	6,477.36	5,410.55	46,849.23
	T5	2,050 + 4,806.68 = 6,856.68	26,389.00	5,852.04	4,888.00	43,985.72
	T6	2,050 + 6,491.84 = 8,541.84	26,389.00	6,461.82	5,405.31	46,797.97