

**INVESTIGATING THE SYNERGISTIC IMPACT OF PRESS-
MUD, ZEOLITE, BIO-NEEMA, AND NANO-NPK ON THE
GROWTH, PRODUCTIVITY, AND QUALITY OF SWEET
SORGHUM (*SORGHUM BICOLOR* (L.) MOENCH)**

Thesis Submitted for the Award of the Degree of

DOCTOR OF PHILOSOPHY

in

Agronomy

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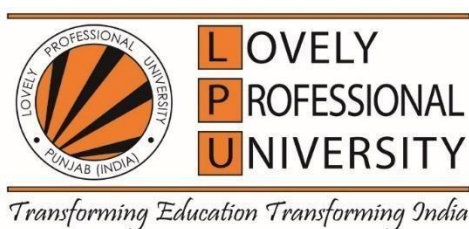
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2026

DECLARATION

I, hereby declared that the presented work in the thesis entitled "**Investigating the synergistic impact on press mud, zeolite, bio-neema, and Nano NPK on the growth, productivity, and quality of Sweet Sorghum (*Sorghum bicolor* (L.) Moench**" in fulfilment of degree of **Doctor of Philosophy (Ph. D.)** is outcome of research work carried out by me under the supervision of **Dr. Prasann Kumar**, working as **Associate Professor** in the **Department of Agronomy, School of Agriculture** of **Lovely Professional University, Punjab, India**. In keeping with general practice of reporting scientific observations, due acknowledgements have been made whenever work described here has been based on findings of other investigator. 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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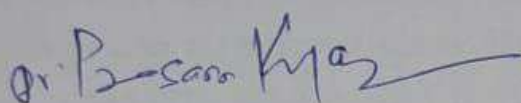
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CERTIFICATE

This is to certify that the work reported in the Ph. D. thesis entitled "**Investigating the synergistic impact on press mud, zeolite, bio-neema, and Nano NPK on the growth, productivity, and quality of Sweet Sorghum (*Sorghum bicolor* (L.) Moench**" submitted in fulfillment of the requirement for the award of degree of **Doctor of Philosophy (Ph.D.)** in the **Department of Agronomy/School of Agriculture** is a research work carried out by **Mastu Patel (12215741)**, is bonafide record of his/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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ABSTRACT

The field experiment titled “Investigating the synergistic impact of press-mud, zeolite, bio-neema, and Nano NPK on the growth, productivity, and quality of Sweet Sorghum (*Sorghum bicolor* (L.) Moench)” was conducted over two seasons: 2023-24 and 2024-25. It was carried out at the Agricultural Research Farm, School of Agriculture, Lovely Professional University, Phagwara, Punjab 144411. The soil in the experimental field had the following characteristics: sandy loam texture; slightly alkaline pH of 7.90; and organic carbon content of 0.28%. The available nutrients included nitrogen (N) at 239.30 kg ha⁻¹, phosphorus (P) at 23.3 kg ha⁻¹, and potassium (K) at 249.70 kg ha⁻¹. The experiment employed a randomized block design with ten treatment combinations and three replicates. The treatments were: control absolute (T1), which received 100% of the recommended fertilizer dose; T2, with 75% of the recommended fertilizer dose plus Zeolite (1.5 t ha⁻¹); T3, with 75% of the recommended fertilizer dose plus Press-mud (15 t ha⁻¹); T4, with 75% of the recommended fertilizer dose plus Zeolite (1.5 t ha⁻¹) plus Press-mud (15 t ha⁻¹); T5, with 75% of the recommended fertilizer dose plus Zeolite (1.5 t ha⁻¹) plus Press-mud (15 t ha⁻¹) plus Bio-neema (5 kg ha⁻¹); T6, with Nano NPK (19:19:19) plus Zeolite (1.5 t ha⁻¹); T7, with Nano NPK (19:19:19) plus Press-mud (15 t ha⁻¹); T8, with Nano NPK (19:19:19) plus Zeolite (1.5 t ha⁻¹) plus Press-mud (15 t ha⁻¹); T9, with Nano NPK (19:19:19) plus Zeolite (1.5 t ha⁻¹) plus Press-mud (15 t ha⁻¹); and T10, with Nano NPK (19:19:19) plus Zeolite (1.5 t ha⁻¹) plus Press-mud (15 t ha⁻¹) plus Bio-neema (5 kg ha⁻¹). The experiment was repeated three times to ensure reliability. Results showed that sweet sorghum plants experienced significant improvements in growth, yield, quality, and soil health when treated with 75% of the recommended fertilizer combined with Zeolite (1.5 t ha⁻¹), Press-mud (15 t ha⁻¹), and Bio-neema (5 kg ha⁻¹) (T6). This treatment performed statistically similar to T5, which included 75% of the fertilizer with Zeolite and Press-mud. Interestingly, applying 100% of the recommended fertilizer without soil amendments produced results comparable to the combination of 75% fertilizer with Zeolite and Press-mud. Conversely, the combination of Press-mud, Zeolite, and Bio-neema, along with foliar application of Nano NPK but without RDF, showed minimal performance, likely due to limited macro-nutrient availability during crop growth compared to T2, T3, T4, T5, and T6, though still better than the absolute control. Additionally, treatments T7 to T10 significantly influenced the chlorophyll index (SPAD value), probably due to improved availability of macro-nutrients, especially nitrogen, which enhances photosynthesis. Notably, in the second year of the study, the experiment showed a

significant increase in system productivity, including growth, yield, quality, and nutrient profiles of the crop and soil, along with higher gross and net returns compared to the first year. Biological properties such as microbial count and urease activity were significantly higher with the application of 75% of the recommended fertilizer dose, Zeolite (1.5 t ha^{-1}), Press-mud (15 t ha^{-1}), and Bio-neema (5 kg ha^{-1}). In contrast, dehydrogenase activity was observed in T5. These findings suggest that an integrated nutrient management approach for sweet sorghum can be an effective strategy to increase crop yield and productivity. Furthermore, applying 75% of the recommended fertilizers along with Zeolite (1.5 t ha^{-1}), Press-mud (15 t ha^{-1}), and Bio-neema (5 kg ha^{-1}) can reduce fertilizer use while maintaining crop performance. The results indicate that adopting integrated nutrient management practices (75% of recommended fertilizer doses + Zeolite (1.5 t ha^{-1}) + Press-mud (15 t ha^{-1}) + Bio-neema (5 kg ha^{-1})) is sustainable. This method improves crop productivity and quality, enhances farm profitability, and promotes soil health. It also mitigates environmental vulnerabilities by improving energy and nutrient use efficiency (carbon use efficiency). Additionally, this approach helps minimize the environmental impact of farming by reducing chemical fertilizer application and encouraging organic and sustainable resource use.

Acknowledgement

I feel that this is a perfect day, to surrender all my success to the almighty, whose limitless kindness and enormous blessings made the present moment a successful endeavor. This is an extremely significant, pleasant moment and joyous opportunity to think about and express my gratitude to many known and unknown hands and learned souls who guided me to right path and enlightened it with their knowledge and experience. I shall ever remain grateful to them.

*First and foremost, I would like to take this opportunity to express my deep sense of gratitude to my guide, **Dr Prasann Kumar** Associate Professor, Agronomy, School of Agriculture, LPU Phagwara for his moral support, care, affection, constant guidance, valuable suggestions, encouragement, and constructive criticism during the research work and in preparation of manuscript. It is a matter of great pleasure and pride to get a unique and great opportunity of working with an able, efficient, dynamic, and benevolent scientist.*

*Every niche of this investigation is a beautiful conglomeration of ideas, appreciation and an amalgamation of rich concepts borrowed from the members of my Advisory Committee, **Dr. Sandeep Menon, Dr. Amandeep Kaur**. I express my deep sense of gratitude towards them for their constant guidance, moral support, and quick availability as and when I needed.*

*I wish to express my deep reverence to the Dean **Dr. Pardeep Kumar Chhuneja** for providing the necessary facilities throughout the tenure of this work. I also express my gratitude to this institute for keeping my financial worries at bay in the form of institutional fellowship during my doctoral programme and research work.*

*I wish to express my heartfelt thanks to **Dharmender Kumar and Dr. Manish Bakshi** for their cooperation and help in the field & laboratory works.*

*Thanks to my beloved friends and classmate **Umesh Kumar Singh, Amit Raj** whose company made me feel happy and proud.*

My vocabulary fails to accentuate my profound reverence and sincere regard to my parents and my family members whose love, affection, hard work, dreams, and constant encouragement made me to achieve all the things in life.

During the course of present study, I have received help from many persons in some way or the other. It is very difficult to acknowledge all of them individually by name. This shortcoming may be pardoned and I assure that I have offered a place in my heart for all of them who don't find their place in this acknowledgement.

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CHAPTER-I

Introduction

Sweet sorghum (*Sorghum bicolor* L. Moench), belonging to the genus *Sorghum*, is part of the tribe Andropogoneae within the family Poaceae. Its efficient C4 photosynthesis and superior nutrient and water use compared to other cereal crops are its most important features. (Teklewold *et al.* 2025). Therefore, this crop is ideally suited for semi-arid agro-climatic (SAT) regions, as well as in subtropical and temperate zones worldwide, including India, and is frequently referred to as the sugarcane of the temperate zone.

The crop is well adapted to SAT conditions and is among the most efficient dryland crops at converting atmospheric CO₂ into sugar. (Gatkal *et al.* 2024). It might be cultivated between a temperature range of 13 °C - 40 °C, requires 10-13 hours of daylight, and thrives with an optimal rainfall of 550-750 mm and relative humidity between 25-65%. As a quick-growing, photoperiod-sensitive crop, it produces reasonably good yields with low irrigation and fertilizer requirements. Additionally, sweet sorghum stalks are rich in sucrose and other sugars, resembling sugarcane in their juiciness and providing an advantage over sugarcane for alcohol production. (Singh *et al.* 2024).

India is the third-largest producer of sweet sorghum in the world, with a production of about 52.70 lakh tonnes from a total area of 50.24 lakh hectares, and an average productivity of 989.29 kg per hectare. It has an 8% share in global production, after the United States (14%) and Nigeria (11%) (according to IAPD 2023-24). In India, the western plateau and hill region, along with the west coast plains and ghat region, lead in production (69.10%) and in area (58%) (DES 2022-23)

The nutritional value of sweet sorghum:

The juice cane contributes to 50-75% of the total biomass production. It is becoming more popular as a health food due to its higher dietary fibre content (7.5-9.1). It contains 70-75% carbohydrate, 10-12% protein, 1.2 – 1.6% minerals, and 1.6% fat. It is rich in amino acids, including thiamine, lysine, riboflavin, and folic acid, as well as

B-complex vitamins, especially niacin (vitamin B6) (Tanwar *et al.* 2023). Furthermore, it provides macro- and micronutrients, including nitrogen (210-220 mg kg⁻¹), copper, and zinc. Grain flour is gluten-free and helps as a safe energy source for those with gluten allergies (Bhatla and Kathpalia, 2023). Sweet sorghum is not utilized as a sustainable substrate for ethanol production, but also as a supplement to sugarcane molasses. The average cost of ethanol production from Sweet.

Sorghum is much lower than that from other feedstocks, and it can be grown year-round, with at least two crops. Since petroleum resources are finite, the search for alternatives is ongoing worldwide, including India (Punia and Kumar, 2024). Meeting energy demand and reducing environmental pollution have been two significant challenges in recent years. The first involves developing an alternative, while the second focuses on renewable energy sources for transformation, which has become vital to the national effort for maximum self-reliance, a key part of the energy security strategy. Biofuels such as biodiesel and bioethanol, which are environmentally friendly, will help us meet more stringent emission regulations (Rial, 2024).

According to the Ministry of Petroleum and Natural Gas, to achieve 10% ethanol blending with petrol in 2021-22 and the target of 25% by 2030, bio-ethanol production needs significantly more feedstock to meet these goals and decrease harmful emissions. Sweet stalk extract is economically competitive with sugarcane molasses, emits less pollution during processing, and produces four times more energy than other cereal crops. Molasses, a byproduct of the sugar industry, is used to make over 90% of biofuels. It is the cheapest feedstock for producing ethanol through fermentation (Zhang *et al.* 2021).

Many factors influence the growth, yield, and quality of sweet sorghum. Among them, proper variety selection, appropriate spacing, balanced nutrient application, and optimal harvest stage are crucial for crop development, yield, and quality (Zahida *et al.* 2024). These factors ultimately affect juice yield, sugar production, and bioethanol output. The harvest stage is vital for biomass yield and stubble sprouting.

Nitrogen has been recognized as one of the most vital limiting nutrients, as a significant component of protein, hormones, chlorophyll, vitamins, and enzyme

activity for crop persistence, and as a significant factor limiting crop yield. Effective use of available resources, such as nitrogen, is required to maximise growth and yield throughout the growing season to generate economically viable returns (Zayed *et al.* 2023). At any point during the growing season, a minimum amount of nitrogen must be used to achieve the highest growth rate. Traditionally, field experiments using varying nitrogen fertilizer application rates have been used to determine the amount of nitrogen needed for crop production (Anas *et al.* 2020).

Nano NPK delivers nutrients to crops progressively and constantly, increasing yield, enhancing quality, and promoting the complete sustainability of the agricultural system (references). Nanoparticles smaller than 100 nm can serve as micro-fertilizers for effective nutrient management (Ghosh *et al.* 2023). Since they contain nutrients and growth promoters encapsulated in nanoscale polymers, these polymers ensure a slow, targeted, and efficient release of nutrients to the crop, thereby boosting nutrient use efficiency. In accordance with a crop's requirements, nano fertilizers gradually supply vital nutrients (Singh *et al.* 2024).

Nano NPK also plays an important role in soil health by building soil organic carbon, enhancing soil aggregation, and increasing water-holding capacity. Nano-NPK encapsulated in nanoparticles increases nutrient uptake. These fertilizers are produced through a biological process, are eco-friendly, and are designed to match inorganic fertilizers in terms of application rate and nutritional composition (Irewale *et al.* 2025). Nano-NPKs are synthesised and release nutrients more effectively than traditional fertilizers. Therefore, the use of nano fertilizers appears promising, as it may ensure the efficient translocation of nutrients to the desired parts of plants as required (Haydar *et al.* 2024).

However, applying nano-NPK to crop leaves starts a process that enables plants to receive and assimilate nitrogen. Consequently, foliar application of nano fertilizers increases nitrogen availability through gaseous uptake by leaf stomata, which may activate many enzymes present in biochemical pathways that maintain biological membranes (Kekeli *et al.* 2025)

Zeolites are hydrated aluminosilicate minerals made up of interlinked tetrahedra of alumina (AlO₄) and Silica (SiO₄). To put it another way, they are solids with a somewhat open three-dimensional crystal structure made up of silicon, aluminium,

oxygen, and alkali or alkaline-earth metals (Na, K, and Mg), as well as water molecules trapped in the spaces within them (Liu *et al.* 2021). Zeolite, which optimises nitrogen use efficiency and water use efficiency, can help decrease environmental degradation by supporting balanced fertilisation in agriculture. Slow-release nitrogen fertilizers can be created by incorporating urea with zeolite (Sarkar *et al.* 2025). The mechanism for the slow release of potassium may be similar to that of PO_4^{3-} and NH_4^+ , due to the zeolite exchanger's sequestering effects (Petrović-Oggiano *et al.* 2023).

Zeolite is capable of reversibly absorbing or releasing water and nutrients without altering its crystal structure, and it can be applied as a natural chelate, stabilizer, or fertilizer. It helps both inorganic and organic fertilizers releasing their nutrient slowly. Adding zeolite to sandy clay loam soil has been shown to reduce nitrogen leaching and increase soil moisture and nutrient levels, due to its larger surface area and cation-exchange capacity (Jarosz *et al.* 2025). This improves overall nutrient uptake, especially nitrogen, in sweet sorghum. It promotes plant growth by enhancing fertilizer efficiency through high adsorption rates, cation-exchange capacity, catalytic activity, and dehydration capacity. As a result, applying zeolite to the soil increases the soil cation-exchange capacity (CEC) by 2-3 times compared to other soils minerals. The combination of zeolite with inorganic and organic fertilizers has been studied to boost nutrient uptake and crop production (Singh *et al.* 2022).

It is produced as a byproduct of the sugarcane industry from the filtration of the cane juice and is characterised as a soft, spongy, amorphous, dark brown to brownish organic cake. Press-mud cake is one such source of organic matter and nutrients that can be profitably used for crop production (Singh *et al.* 2021). Press-mud, like other organic manures, has great potential to supply organic matter and micronutrients, as well as to affect soil physico-chemical and biological properties positively. Besides being a highly effective soil conditioner, press-mud is widely recognised as a valuable organic manure for agriculture because it contains important plant nutrients in an organic form (Lahori *et al.* 2024).

The plant nutrients in press mud and distillery effluents can be transformed into nutrient-rich organic manure. Besides addressing pollution and waste management, converting waste materials into rich organic manure also restores soil

health and reduces fertilizer costs (Umair *et al.* 2021). Because of its porous structure, press-mud can serve as an adsorbent to remove pollutants. It can also recycle plant nutrients through suitable biodegradation methods. Although considerable research has been conducted on the use of press-mud in sweet sorghum cultivation, the effects of composting and press-mud enrichment on nutrient availability, plant growth, yield, nutrient use efficiency, and quality remain underexplored (Poria *et al.* 2022).

Fourier transform infrared spectroscopy (FTIR) is an analytical technique used to identify chemical compounds based on their interaction with infrared radiation. However, FTIR is widely applied in chemistry, polymers, food, and environmental studies to analyse solids, liquids, and gases. At the same time, it provides both qualitative and semi-quantitative information. Furthermore, it is especially valuable for identifying unknown substances, verifying material purity, and studying chemical changes in reaction processes (Patel *et al.* 2025).

Thermogravimetric analysis (TGA) is an analytical technique that measures a material's mass as a function of temperature or time under a controlled atmosphere. However, TGA plays a crucial role in determining quality, composition, and processing characteristics. This is essential for evaluating the shelf life and storability of grain-based products. Excess moisture promotes microbial growth, caking, and spoilage; hence, knowing the precise water content via TGA helps optimise the drying and packaging processes. The subsequent stages of thermal degradation indicate the decomposition of organic matter, such as carbohydrates, proteins, and fats, providing the nutritional and structural components (Akash and Rehman, 2025). However, these analyses are vital for quality control and formulation in the food processing industry, as they help identify adulteration and contamination and set thermal limits for safe processing. While it is significantly contributing to product development, safety assurance, and standardization in agricultural and food material research

Enzymes play a vital role in maintaining soil health and fertility, directly influencing crop growth under different farming conditions. While these enzymes are produced by soil microorganisms, plant roots, and residual matter, they catalyse essential biochemical reactions that drive nutrient cycling (Daunoras *et al.* 2024). However, it is a function that supports nutrient balance, improves soil organic matter, and enhances root growth and microbial interactions. Thus, monitoring and

promoting these soil enzymes helps sustain productivity, improve nutrient efficiency, and ensure healthier crop growth under diverse agricultural practices (Xing *et al.* 2025).

Therefore, this study was conducted to address the importance of sweet sorghum cultivation in the region and the need for environmentally friendly applications of inorganic (RDF + Zeolite + Nano NPK) alongside organic sources (Press-mud and Bio-neema) in the Trans-Gangetic plain, especially in Punjab. The goal was to provide economically viable fertilizer options for sweet sorghum farmers in the region, promoting sustainable crop production and increasing resource-use efficiency.

It is important to note that minimal work has been initiated on these aspects in the Punjab region. Therefore, considering the above facts, the study titled **“Investigating the synergistic impact of press-mud, zeolite, bio-neema, and Nano NPK on the growth, productivity, and quality of Sweet Sorghum (*Sorghum bicolor* (L.) Moench)”** was planned with the following research objectives.

Research gap

A significant research gap exists in the synergistic use of press-mud, zeolite, and bio-neema, and Nano NPK, to enhance sweet sorghum growth and inorganic cultivation practices. Conventional farming relies heavily on chemical fertilizers, leading to soil degradation, nutrient imbalance, and environmental pollution. However, limited studies have explored how integrated organic-nano approaches can improve crop productivity and bioenergy yield. Since sweet sorghum is a promising bioenergy crop for renewable energy production, investigating eco-friendly nutrient management is crucial to reduce fertilizer dependence and restore soil health.

Objectives

1. To determine the growth yield parameters by the application of Zeolite, Pre-mud, and Bio-neema in Sweet Sorghum,
2. To evaluate the individual and combined effect of press-mud and zeolite on the productivity and quality of sweet sorghum,
3. To assess the soil properties and nutrient uptake by the application of press-mud and zeolite,
4. To work out the economics as influenced by various treatments,

CHAPTER-II

Review of literature

Sweet sorghum production has increased significantly following the Green Revolution. However, widespread use of fertilizers is a result of increased global demand for food. The commonly used chemical fertilizers may increase plant growth and output, but they have detrimental effects on the soil, the environment, and even human health. Therefore, the most promising alternatives to conventional fertilizers are nano fertilizers and any organic sources that are high in nutrients. These materials contain both macro and micronutrients that are delivered to the plant rhizosphere in a regulated manner.

The combined application of fertilizer sources, such as organic and inorganic, provides primary and secondary nutrients to increase the efficiency of both nutrients' use, which influences soil and overall crop development over the growth period, and is expected to improve crop yield. It would be a great use to “Investigating the synergistic impact on press-mud, zeolite, bio-neema and Nano NPK on the growth, productivity, and quality of Sweet Sorghum (*Sorghum bicolor* (L.) Moench)” which is scientifically well recognized.

Therefore, an effort is made to provide an overview of research related to the present investigation that has been conducted at various locations, both domestically and overseas. The review of the research problem is presented under the following heading.

2.1 Effect of inorganic fertilizers on the growth and yield of the crop

2.2. Effect of inorganic fertilizers on quality, soil properties, and economics of crops

2.3. Effect of zeolite on the growth and yield of crops

2.4. Effect of zeolite on quality, soil properties, and economic crops

2.5 Effect of press-mud on the growth and yield of the crop

2.6 Effect of press-mud on quality, soil properties, and economic crops

2.7 Effect of bio-neema on the growth and yield of the crop

2.8 Effect of bio-neema on quality, soil properties, and economics of crop

[A] SYSTEMATIC REVIEW

2.1 Effect of inorganic fertilizers on growth, yield, quality, soil properties, and economic crops

Samijan *et al.* (2024) to determine the optimization of sorghum productivity using balanced fertilizers on dryland. The improved sorghum yield (21.38-36.06%) with combined fertilizers (organic 1600 kg ha⁻¹ + NPK 300 kg ha⁻¹ + urea 200 kg ha⁻¹) was greater than the existing fertilizers. This study indicated that balanced fertilizers could provide sufficient nutrients to the crop.

Desalegn *et al.* (2023) studied the sugarcane productivity and sugar yield improvement: variety, nitrogen fertilizer rate, and bioregulators with two sugarcane varieties (D42/58 and NCo-334), three nitrogen (N) fertilizer ratio (0, 100, and 150 kg ha⁻¹), and two bioregulators (Agrostemin and Crops). Sugarcane variety D42/58 resulted in higher performance in cane yield (153.34 tons/ha), Pol% (15.81%), and sugar yield (10.25 tons ha⁻¹). High-performance cultivar, suitable nitrogen rates, and plant bioregulators could increase sugarcane productivity and sugar output because most of the sugarcane yield, juice, quality, and sugar yield traits showed positive correlations.

Reddy and Umesha (2023) to determine the efficacy of inorganic fertilizers and biofertilizers consortium for enhanced growth of sweet sorghum. The nutrient was applied in different ratios of inorganic fertilizers, such as 50, 75, 100, and 125% of % recommended dose, with or without a biofertilizer consortium, compared with an absolute control. The experimental results show that using 125%% of the recommended dose of fertilizers with a biofertilizer consortium resulted in maximum yield attributes, such as the number of ear heads, ear head length (cm), filled grains per ear head, grain yield, stover yield, and biological yield. The application of 125% RDF + BFC has the most significant effect for improving yield traits and overall crop yield, thus promoting soil health in crop cultivation.

Desalegn *et al.* (2023) studied the sugarcane productivity and sugar yield improvement: variety, nitrogen fertilizer rate, and bioregulators with two sugarcane varieties (D42/58 and NCo-334), three nitrogen (N) fertilizer rates (0, 100, and 150 kg ha⁻¹), and two bioregulators (Agrostemin and Crops). Sugarcane

variety D42/58, in terms of sprouting, number of tillers, plant height, and number of millable canes, increased by 7.49%, 9.50%, 12.80%, and 10.50% respectively. Overall, the selection and combination of sugarcane variety D42/58 with 100 kg N ha⁻¹ or Agrostemin bioregulator could maximize sugarcane growth.

Reddy and Umesha (2023) to determine the efficacy of inorganic fertilizers and biofertilizers consortium for enhanced growth of sweet sorghum. The nutrient was applied in different ratios of inorganic fertilizers, such as 50, 75, 100, and 125% of % recommended dose, with or without a biofertilizer consortium, compared with an absolute control. The experimental results show that using 125% of % recommended dose of fertilizers with a biofertilizer consortium resulted in maximum plant growth, and dry matter accumulation was recorded. The application of 125% RDF + BFC has the most significant effect for improving growth traits and microbial growth, thus promoting soil health in crop cultivation.

Olugbemi *et al.* (2018) evaluated the growth and ethanol yield response of sweet sorghum (*Sorghum bicolor* Moench) varieties to nitrogen fertilizer rates. The main plots were assigned to the cultivar (NTJ-2, 64 DTN, SW Makarfi 2006, and SW Dansadau 2007), while the sub-plots of a split-plot design were given nitrogen fertiliser (0, 40, 80, 120, and 160 kg N ha⁻¹) in three replicates. The maximum yield parameters, including stalk yield, juice yield, and ethanol production, were significantly influenced by the application of 80 kg N ha⁻¹. Based on the investigation, sweet sorghum yields the highest when 80 kg N ha⁻¹ is applied.

Olugbemi *et al.* (2018) evaluated the growth and ethanol yield response of sweet sorghum (*Sorghum bicolor* Moench) varieties to nitrogen fertilizer rates. The main plots were assigned to the varieties (NTJ-2, 64 DTN, SW Makarfi 2006, and SW Dansadau 2007), while the sub-plots of a split-plot design were given nitrogen fertilizer (0, 40, 80, 120, and 160 kg N ha⁻¹) in three replicates. The maximum growth parameters, such as plant height, leaf area, leaf area index, crop growth rate, net assimilation rate, and leaf area ratio, were recorded under the application of 80 kg N ha⁻¹.

Mishra *et al.* (2017) investigated the performance of sweet sorghum

cultivars as a source of green fodder under varying nitrogen levels in the semi-arid tropics. Application of 120 kg N ha⁻¹ recorded significantly higher plant height, a maximum number of leaves, larger leaf length and width, and higher leaf area than 80 kg N ha⁻¹. When nitrogen rates increased from 80 to 120 kg nitrogen ha⁻¹, the production of fresh and dry feed showed a considerable variance. Green and dry fodder yield rose by 8.86 and 12.1 over 80 kg nitrogen ha⁻¹, respectively, when 120 kg N ha⁻¹ was applied.

Mekdad and El-Sherif (2016) evaluated two sweet sorghum varieties under the effect of three nitrogen levels and three potassium levels on yield and its attributes. Honey (V1) and Brandes (V2) were the sweet sorghum varieties assigned to the main plots of the experiment, which was set up using a three-factorial (split-split plot) block design in three replications. Three nitrogen levels were present in the subplots, with levels of 80 (N1), 100 (N2), and three equal doses of 120 (N3) Kg N/fed (fed = 4200 m² = 0.405 ha). Three equal doses of potassium sulphate (48% K₂O) were applied to the soil at levels of 25 (K1), 50 (K2), and 75 (K3) kg K₂SO₄-fed, which were arranged in the sub-subplot treatments. The results showed significantly improved stem height, stem diameter, leaf length, leaf area, and leaf weight in the interaction between the Brandes (V2) variety and the application of 120 kg N/fed (N3) and 75 kg K/fed (K3).

Sawargaonkar and Wani (2016) evaluated the nitrogen response of sweet sorghum cultivars during the rainy season under three cultivars (CSH 22SS, NTJ-2, and ICSV-93046) with two row spacing (60 and 45 cm) and six nitrogen levels (0, 30, 60, 90, 120, and 150 kg ha⁻¹). The results revealed that applying 150 kg N ha⁻¹ to sweet sorghum cultivar CSH 22SS produced the maximum green stalk yield (46.90 t ha⁻¹) and ethanol yield (1940 l ha⁻¹) compared to the other cultivars.

Singh *et al.* (2015) to determine the effect of inorganic and organic nutrients on the yield of sweet sorghum. The nutrients, comprising 75% inorganic and 25% organic components, significantly improved yield parameters. The outcome highlighted the following yields: fodder yield (52.8 t ha⁻¹), dry matter yield (13.5 t ha⁻¹), juice yield (9,910 kl ha⁻¹), sugar yield (0.91 t ha⁻¹), and

ethanol yield (2,762 kl ha⁻¹) for the combination of these treatments. An increase in yield attributes, combined with the use of nutrient fertilizers, may be attributed to the availability of plant nutrients throughout the growth period, which directly impacts yield parameters.

Kurai *et al.* (2015) investigated the effective rate of nitrogenous fertilizers for irrigated sweet sorghum production in the semi-arid tropic during the post-rainy season. Two varieties of sweet sorghum were used in field tests with four different nitrogen fertilizer rate was used (0, 63, 90, and 150 kg ha⁻¹). Results showed the grain and stalk yield increased with N fertilizers, but significantly only up to 90 kg N ha⁻¹. The observed increases in grain yield were attributed to the rise in kernel numbers. Corresponding to the differences in biomass, both the relative growth rate and crop growth rate increased with the N fertilization rate up to 90 kg N ha⁻¹. Furthermore, studies of NUE indices showed that agronomic N use efficiency (ANUE, indicating yield production per unit of fertilizer N) responded comparably up to 90 kg N ha⁻¹, and decreased significantly thereafter. These results collectively suggest that 90 kg N ha⁻¹ is an efficient amount for biomass and yield production, and is among the tested treatments recommended for sustainable sweet sorghum cultivation during the post-rainy season in the semi-arid tropics.

Kurai *et al.* (2015) studied the efficient rate of nitrogenous fertilizers for irrigated sweet sorghum cultivation during the post-rainy season in the semi-arid tropics. Field experiments were conducted on two sweet sorghum cultivars with four different N fertilization rates (0, 63, 90, and 150 kg ha⁻¹). Results showed significantly increased plant height, dry matter accumulation, crop growth rate, relative growth rate, net assimilation rate, and leaf area index with N fertilizer rates up to 90 kg ha⁻¹. These results collectively suggest that 90 kg N ha⁻¹ is an efficient amount for biomass and yield production, and is among the tested treatments recommended for sustainable sweet sorghum cultivation during the post-rainy season in the semi-arid tropics.

Uchino *et al.* (2013) determined the optimal nitrogen (N) rate for maximizing grain and sugar yields of sweet sorghum during the rainy season in India. In Andhra Pradesh, India, the application of six nitrogen fertilizers rate 0,

30, 60, 90, 120, and 150 kg ha⁻¹ was assessed. Based on results, an input of 90-120 kg N ha⁻¹ could be recommended for maximizing sweet sorghum growth and productivity.

Uchino *et al.* (2013) determined the optimal nitrogen (N) rate for maximizing grain and sugar yields of sweet sorghum during the rainy season in India. The application of six N rates (0, 30, 60, 90, 120, and 150 kg N ha⁻¹) was evaluated in Andhra Pradesh, India. The fresh cane weight and grain dry weight increased significantly in line with higher N rates. The value of extract yield and sugar percentage also considerably increased. Based on results, an input of 90-120 kg N ha⁻¹ could be recommended for maximizing sweet sorghum productivity.

Sawargaonkar *et al.* (2013) evaluated the nitrogen response and water use efficiency of sweet sorghum under three cultivars (CSH 22SS, NTJ-2, and ICSV-93046) with two row spacing (60 and 45 cm) and six nitrogen levels (0, 30, 60, 90, 120, and 150 kg ha⁻¹). In comparison to NTJ 2 (32.66 Mg ha⁻¹ and 1.70 Mg ha⁻¹) and ICSV 93046 (38.44 Mg ha⁻¹ and 2.03 Mg ha⁻¹), the sweet sorghum variety CSH 22 SS had the highest green stalk yield (45.4 Mg ha⁻¹) and grain yield (2.33 Mg ha⁻¹). Up to 150 kg ha⁻¹ applied nitrogen, all cultivars responded; after that the yield increase was negligible. These findings lead to the conclusion that the most profitable combination for optimizing production in sweet sorghum cultivar CSH 22 SS at 150 kg ha⁻¹.

Almodares *et al.* (2009) investigated the impact of nitrogen fertilizer on the chemical composition of corn and sweet sorghum. This study was carried out to evaluate the effect of four nitrogen levels (50, 100, 150, and 200 kg urea ha⁻¹) on biomass, crude protein, soluble carbohydrates, and crude fibre contents in three fodders (corn and sweet sorghum). The findings showed that nitrogen treatments and feeds had a significant impact on the measurements. The biomass of sweet sorghum and corn (64.80 t ha⁻¹ and 66.50 t ha⁻¹) was produced through the application of 200 kg N ha⁻¹, and the lowest total biomass was obtained in 50 kg N ha⁻¹ in both crops.

Almodares *et al.* (2008) determined the effect of inorganic fertilizers on the growth parameters of sweet sorghum cultivars with three nitrogen doses (0,

90, and 180 kg ha⁻¹), and two rates of potassium (0 and 50 kg ha⁻¹). Results showed that the application of 180 kg N ha⁻¹ and the addition of potassium in the subplots at 50 kg ha⁻¹ significantly increased growth traits, including stem height (12.65%), stem diameter (11.36%), and stem fresh weight (24.57%). The best output was obtained with the application of combined fertilizers

2.2 Effect of inorganic fertilizers on quality, soil properties, and economics of crops

Samijan *et al.* (2024) to determine the optimization of sorghum productivity using balanced fertilizers on dryland. The fertilizers were applied in four ratios: organic fertilizers at 1600 kg ha⁻¹, NPK at 300 and 150 kg ha⁻¹, Urea at 200 and 100 kg ha⁻¹, and biofertilizers at 4.1 kg ha⁻¹. This research indicated that balanced fertilizers could provide sufficient nutrients to the soil, increase nutrient availability for sorghum, and promote the uptake of N, P, and K nutrients, as well as improve the organic carbon and water-holding capacity of the soil.

Reddy and Umesha (2023) to determine the efficacy of inorganic fertilizers and biofertilizers consortium for enhanced growth of sweet sorghum. The nutrient was applied in different ratios of inorganic fertilizers, such as 50, 75, 100, and 125% of % recommended dose, with or without a biofertilizer consortium, compared with an absolute control. The nitrogen content in grain and stover was significantly increased by the various levels of recommended fertilizers combined with biofertilizers. The superior treatments showed a 125% RDF + biofertilizers consortium with the maximum nitrogen content in grain (1.55%) and stover (0.63%), followed by a 100% RDF + biofertilizers consortium with 1.51% in grain and 0.51% in straw. Based on the investigation, 125% RDF + BFC has the most significant effect on the crop nutrient content of sweet sorghum.

Kubsad (2018) reported on the response of rabi sorghum with different fertility levels under rainfed conditions. The treatment consisted of eight genotypes in main plots and three rates of fertilizers in sub-subplots. The findings showed that application of 100% RDF recorded significantly higher gross returns (Rs. 1,11,468 ha⁻¹), net returns (Rs. 76,413 ha⁻¹), and B: C ratio

(3.18) over the rest of the treatments.

Mishra *et al.* (2017) investigated the influence of economics through various nutrient rates of inorganic fertilizer in different cultivars. Results revealed that the application of 120 kg N ha⁻¹ improved the net return (₹ 26,138 ha⁻¹) over the application of 80 kg N ha⁻¹. Amongst cultivars, 'SSV 74' (₹ 30,145 ha⁻¹), being on a par with 'SSV 84' (₹ 30,145 ha⁻¹), 'CSH 22SS' (₹ 25,920 ha⁻¹), and 'RSSV 167' (₹ 30,145 ha⁻¹) recorded significantly higher net returns as compared to the rest of the cultivars.

Mekdad and El-Sherif (2016) evaluated two sweet sorghum varieties under the effect of three nitrogen levels and three potassium levels on yield and its attributes. Honey (V1) and Brandes (V2) were the sweet sorghum varieties assigned to the main plots of the experiment, which was set up using a three-factorial (split-split plot) block design in three replications. Three nitrogen levels were present in the subplots, with levels of 80 (N1), 100 (N2), and three equal doses of 120 (N3) Kg N/fed (fed = 4200 m² = 0.405 ha). Three equal doses of potassium sulphate (48% K₂O) were applied to the soil at levels of 25 (K1), 50 (K2), and 75 (K3) kg K₂SO₄-fed, which were arranged in the sub-subplot treatments. Interaction between the Brandes (V2) variety and 120 kg N/fed (N3) and 75 kg K/fed (K3) produced the highest values of seed index in both seasons, as well as Brix, juice extraction, juice yield, sugar yield, sucrose percentage, and purity (%).

Sawargaonkar and Wani (2016) observed the nitrogen response and water use efficiency of sweet sorghum under three cultivars (CSH 22SS, NTJ-2, and ICSV-93046) with two rows spacing (60 and 45 cm) and six nitrogen levels (0, 30, 60, 90, 120, and 150 kg ha⁻¹). The result, related to economics, showed a net return of CSH 22 SS (US\$684 ha⁻¹) to be significantly higher than that from NTJ 2 (US\$415 ha⁻¹) and ICSV 93046 (US\$539 ha⁻¹). Up to 150 kg ha⁻¹ of applied nitrogen, all cultivar responded; after that the yield increase was negligible. Based on the investigation nitrogen uses efficiency (NEU) value, the ideal nitrogen level of the sweet sorghum crop was 90 kg N ha⁻¹.

Uchino *et al.* (2013) determined the optimal nitrogen (N) rate for maximizing grain and sugar yields of sweet sorghum during the rainy season in

India. The application of six N rates (0, 30, 60, 90, 120, and 150 kg N ha⁻¹) was evaluated in Andhra Pradesh, India. Net income, as estimated from cane fresh weight and grain dry weight, increased at rates up to 90 kg N ha⁻¹, and higher N rates did not significantly affect productivity or income, but instead caused severe lodging in 150 kg N ha⁻¹ at the harvest stage. Based on the results, an input of 90-120 kg N ha⁻¹ could be recommended for maximizing sweet sorghum productivity and farmers' income in the semi-arid tropics of India.

Sawargaonkar *et al.* (2013) investigated the nitrogen response and water use efficiency of sweet sorghum under three cultivars (CSH 22SS, NTJ-2, and ICSV-93046) with two row spacings (60 and 45 cm) and six nitrogen levels (0, 30, 60, 90, 120, and 150 kg ha⁻¹). The result related to economics, with a net return of CSH 22 SS (US\$681 ha⁻¹), was also significantly higher than that from NTJ 2 (US\$415 ha⁻¹) and ICSV 93046 (US\$539 ha⁻¹). All cultivars responded to applied N up to 150 kg ha⁻¹; however, beyond 90 kg ha⁻¹ N rate, the increase in yield was insignificant. Estimated N use efficiency (NEU) values indicated that 90 kg N ha⁻¹ was an optimum N level for the sweet sorghum crop. Based on these results, it is concluded that sweet sorghum cultivar CSH 22 SS at 150 kg ha⁻¹ is the best remunerative combination for economic returns and resource use efficiency.

Singh *et al.* (2012) reported the effect of inorganic fertilizers on the productivity and economics of sorghum. The results revealed that the application of the 100% recommended dose (80:40 kg N and P ha⁻¹) yielded significantly higher biological yield, gross return, net return, and B: C ratio than that of 50% RDF.

Holou and Stevens (2012) determined the production of sweet sorghum juice, sugar, and bagasse on different soils with seven nitrogen fertilization rates applied, ranging from 0 to 134 kg N ha⁻¹. The results showed that the juice content increased in sweet sorghum stalks, averaging 68.8% by weight, and the juice yield ranged from 15.2 to 71.1 m³ ha⁻¹, as well as an increased Brix ratio in the juice, varying from 10.7 to 18.9%. The dry bagasse yield fluctuated between 3.2 and 13.8 Mg ha⁻¹, with a significant difference observed in relation to the N rate. Based on the investigation, a minimum of 67 kg N ha⁻¹ was required to

optimize juice, sugar, and bagasse yield in sweet sorghum.

Almodares *et al.* (2009) investigated the impact of nitrogen fertilizer on the chemical composition of corn and sweet sorghum. This study was carried out to evaluate the effect of four nitrogen levels (50, 100, 150, and 200 kg urea ha⁻¹) on the amount of biomass, crude protein, soluble carbs, and crude fibr in three types of fodder (corn, sweet sorghum, and sweet sorghum bagasse). The findings showed that nitrogen treatments and feeds had a significant impact on the measurements. The sweet sorghum and corn had the highest recorded protein content (8% and 7.10%). Corn was performing better than sweet sorghum with the application of 200 kg N ha⁻¹. Compared to corn and sweet sorghum, sweet sorghum bagasse exhibited a higher crude fiber content and a lower crude protein and carbohydrate content. In fodders, the amount of crude protein increased while the amount of crude fibre reduced as the amount of nitrogen fertilizer increased. Based on the results could improve both species portability and digestibility. Therefore, 200 kg ha⁻¹ of urea should be supplied for corn and sweet sorghum-based cropping system.

Alomdares *et al.* (2008) determined the effect of inorganic fertilizers on growth parameters of sweet sorghum cultivars with three nitrogen doses (0, 90, and 180 kg ha⁻¹), and two rates of potassium (0 and 50 kg ha⁻¹). Results showed the application of 180 kg N ha⁻¹ significantly increased total sugar (10.50%), sucrose content (9%), and juice extraction (34.96%). The subplot of potassium at 50 kg ha⁻¹ passively increased total sugar (10.50%) and juice extraction (9%) at physiological maturity. The maximum quality traits, including sucrose content, juice extraction, and sugar content, were achieved with the application of 180 kg N ha⁻¹ and 50 kg K ha⁻¹. The best results were obtained with the application of both combined nutrients

2.3 Effect of zeolite on the growth and yield of crops

Khaliq *et al.* (2024) to determine the synergistic effect of urea, poultry manure, and zeolite on wheat growth and yield. The treatments included a control (T1); urea nitrogen at 120 kg N ha⁻¹ (UN120) (T2); poultry manure (PM) at 120 kg N ha⁻¹ (T3); zeolite⁻¹ (Z1) at 5 t ha⁻¹ (T4); zeolite-2 (Z2) at 5 t ha⁻¹ (T5); UN120 + Z1 (T6); PM + Z1 (T7); UN120 + Z2 (T8); PM+Z2(T9); ½ UN + ½

PM+Z1(T10); $\frac{1}{2}$ UN + $\frac{1}{2}$ PM+Z2(T11); and $\frac{1}{2}$ UN + $\frac{1}{2}$ PM+ $\frac{1}{2}$ Z1+ $\frac{1}{2}$ Z2(T12). The UN120 treatments revealed significant enhancements in the growth of wheat, including a notable increase in the length of the shoot (76.7%), fresh shoot weight (50.8%), length of root (50.6%), chlorophyll content (53.6%), and leaf area (72.5%) compared to the control. This nutrient composition positively increases the growth and growth attributes of wheat crops.

Hassan *et al.* (2024) investigated the effect of tillage practices and zeolite treatments on soil carbon retention and wheat crop growth and productivity. Tillage practices including three levels vis: T1 (6 practices by the cultivator (control), T2 (minimum tillage), and T3 (cultivation with cultivator and Mold-bord plough), with four level of zeolite including; Z1 (0 ha⁻¹), Z2 (5 t ha⁻¹), Z3 (10 t ha⁻¹), and Z4 (15 t ha⁻¹). The resulted showed the maximum plant height (92.14 and 92.97 cm), number of leaves (32.88 and 38.11 cm), dry weight (420.11 and 530.98 m-2), and number of tillers (278.65 and 283 per unit area), was recorded in zeolite applied at 10 t ha⁻¹ and zero/minimal tillage practices (T2 X Z3) comparted to control and other treatments combination in the both years respectively. Thus, to improve yield and soil carbon retention in rain-fed wheat crops, minimum tillage should be used in conjunction with zeolite application at a rate of 10 t ha⁻¹.

Mohammadnaseri and Tadayon, (2024) studies the effect of different levels of zeolite on some physiological parameters, oil, and protein yield of linseed under deficit irrigation conditions as a primary factor including four levels 50 (control), 80, 130 and 180 mm and zeolite was used as secondary factor with three levels; control (no application), 5 and 10 t ha⁻¹ was applied. The experiment's findings demonstrated that applying zeolite at a 5% probability level significantly impacted the growth and yield, and quality traits of linseed. The maximum oil yield and protein yield were recorded with the application of 10 t Z ha⁻¹, and 180 mm of evaporation from the evaporation pan. Based on the investigation, the application of zeolite has significantly enhanced the performance of the linseed crop in moderate drought stress conditions.

Hassan *et al.* (2024) investigated the effect of tillage practices and zeolite treatments on soil carbon retention and wheat crop productivity. Tillage practices

including three levels viz: T1 (6 practices by the cultivator (control), T2 (minimum tillage), and t3 (cultivation with cultivator and Mold-bord plough), with four level of zeolite including; Z1 (0 ha⁻¹), Z2 (5 t ha⁻¹), Z3 (10 t ha⁻¹), and Z4 (15 t ha⁻¹). The impact that zeolite and tillage techniques have on several soil and crop-related traits, including carbon dioxide (CO₂) emissions, dissolved organic carbon, soil organic carbon, and growth and productivity of the wheat crop. When combined with minimum tillage, zeolite applied at 10 t ha⁻¹ resulted in a notable wheat yield. The resulted showed the highest length of spike (11.88 and 12.11 cm), total number of spikelet's (20.11 and 20.98), total number of tillers (278.65 and 283 m⁻²), 1000 weight of grain (50.74 and 52.54 g), biological yield (8134.87 and 8187.38 kg ha⁻¹), and yield of grain (2984.28 and 3028.96 kg ha⁻¹) as well as harvest index (36.96 and 37.04%) of wheat was recorded in zeolite applied at 10 t ha⁻¹ with minimum tillage practices (T2 X Z3) comparted to control and other treatments combination in the both year respectively. Thus, to improve yield and soil carbon retention in rain-fed wheat crops, minimum tillage should be used in conjunction with zeolite application at a rate of 10 t ha⁻¹.

Rahmani *et al.* (2023) to determine the effect of vermicompost and zeolite on improving the yield of black cumin (*Nigella sativa* L). The experimental treatments included four vermicompost levels (0, 2, 4, and 6 t ha⁻¹) and four doses of zeolite (0, 3, 6, and 9 t ha⁻¹). The results revealed by application of 6 t ha⁻¹ vermicompost and 9 t ha⁻¹ zeolite were recorded as maximum seed and biological yield (466.2 and 3716.7 kg ha⁻¹), respectively.

Ali *et al.* (2020) revealed zeolite is a naturally occurring hydrated crystalline aluminosilicate mineral composed mainly of silicon (Si), aluminum (Al), and oxygen arranged in a three-dimensional framework. This study used a randomized block design method with two factors, namely zeolite concentration factor with three level of inorganic fertilizers It possesses a unique porous structure, high cation exchange capacity (CEC), large internal surface area, and remarkable water adsorption and ion exchange properties. These physicochemical characteristics make zeolite an effective soil amendment capable of improving nutrient retention, water availability, and overall plant

physiological performance.

Wu *et al.* (2019) demonstrated increased nitrogen use efficiency with reduced nitrogen application frequencies by using zeolite in rice. In this study, nitrogen was applied through urea (157.5 kg ha^{-1}), and it was applied at the same rate as either a one-time application or a three-way split application with and without 10 t ha^{-1} zeolite. The data revealed 1000-grain weight (g), unfilled grain percentage, and rice yield. The maximum yield parameters were significantly different, with grain yields of 8.5% and 10.7% under Z3N10. The treatment also led to a higher weight of 1000 grains and the lowest unfilled grain percentage compared with N1Z0. It is suggested that the Zeolite amendment could enhance rice grain yield.

Akhzari and Alipoor, (2019) reported that the maximum root dry weight was obtained in vetiver grass when zeolite and compost were applied, compared to the control.

Bybordi *et al.* (2018) to determine the result of zeolite, selenium, and silicon on quality and quantitative traits of onion growth under salinity conditions. An experiment was performed at three three-factorial design and three replications, including: zeolite at three rates ($0, 4, \text{ and } 8 \text{ t ha}^{-1}$), selenium at three rates ($0, 0.5, \text{ and } 1 \text{ kg ha}^{-1}$), and silicon at three rates ($0, 200, \text{ and } 400 \text{ kg ha}^{-1}$). The findings showed a decrease in small-sized bulbs with increasing application of zeolite, selenium (Se), and silicon (Si). Total dry matter and yield of onion were increased due to the application of Zeolite, Se, and Si. Moreover, 8 t ha^{-1} , along with 1 kg ha^{-1} Se and 400 kg ha^{-1} Si, resulted in the highest onion yield and qualitative traits, including physiological ones.

Hazrati *et al.* (2017) studied the effect of zeolite and water stress on growth, yield, and chemical composition of Aloe vera L. Therefore, to study the impact of water stress (20, 40, 60, and 80%) of the field capacity and zeolite ($0, 4, \text{ and } 8 \text{ g kg}^{-1}$) on growth, yield, and chemical compositions of aloe vera. The plants produced a superior number of new leaves and pupae irrigated with 20% and 40% FC, respectively, with 8 g of zeolite. The maximum fresh weight of the leaf and gel fresh weight were recorded 270 days after imposing the treatment, when plants were irrigated after depleting 40% of the F and treated with 8 g of

zeolite. Furthermore, the findings showed that the plants that were irrigated 90 days after the treatments were implemented accumulated the most aloin and proline when 80% and 60% of the FC were depleted, respectively, without the use of zeolite. Based on the investigation, zeolite application can alleviate the adverse effects of water stress and improve plant growth and yield.

Chen *et al.* (2017) evaluated the influences of irrigation, nitrogen, and zeolite management on the yield properties of rice. This study investigated an integrated irrigation, nitrogen (N), and zeolite rice production system. It investigated its impact on yield performance in comparison to wetting and drying irrigation (AWD) and traditional flooding irrigation. The highest yields in AWD (9.8 t ha^{-1}) and conventional flood irrigation (8.9 ha^{-1}) were obtained with 105 kg N and $10 \text{ t zeolite ha}^{-1}$ and 10 kg N and $5 \text{ t zeolite ha}^{-1}$, respectively. Without significantly lowering rice grain quality, these two treatments plan enhanced yield by 10.6% and 0.6% respectively, while requiring 27.8% and 8.1% less water and 33.3% fewer N fertilizers.

Cairo *et al.* (2017) investigated the impact of zeolite and organic fertilizers on soil quality and sugarcane yield. Organic fertilizers (sugarcane filter cake-SFC) and natural minerals (zeolite), along with chemical fertilization (N, P_2O_5 , and K_2O), were applied. The yield of sugarcane traits, like as cane yield (t ha^{-1}) and yield of sucrose (t ha^{-1}), were noted. The results revealed in the cane yield. The maximum cane yield was achieved with the application of 7.5 t Z ha^{-1} + SFC 22.5 t ha^{-1} , representing a 200% relative increase compared to the control (no application of mineral fertilizers).

Sembiring *et al.* (2017) investigated the impact of zeolite and urea fertilizers on maize growth. The treatment was applied including five level of zeolite; Z0 0 g/plot, Z1 105 g/plot, Z2 210 g/plot, Z3 315 g/plot. Z4 420 g/plot and five rate of urea; U0 0 g/ plot, U1 21 g/ plot, U2 42 g/plot, U3 63 g/ plot, U4 84 g/plot. The results revealed that the 100-seed weight, number of cobs per plant, cob line, and corn yield were significantly influenced by zeolite application at a rate of 420 g per plot, and these parameters were positively improved by urea at a rate of 84 g per plot.

Hazrati *et al.* (2017) studied the effect of zeolite and water stress on

growth, yield, and chemical composition of Aloe vera L. Therefore, to study the impact of water stress (20, 40, 60, and 80%) of the field capacity and zeolite (0, 4, and 8 g kg⁻¹) on growth, yield, and chemical compositions of aloe vera. The plants produced a superior number of new leaves and pupae irrigated with 20% and 40% FC, respectively, with 8 g of zeolite. The maximum fresh weight of the leaf and gel fresh weight were recorded 270 days after imposing the treatment, when plants were irrigated after depleting 40% of the F and treated with 8 g of zeolite. Furthermore, the findings showed that the plants that were irrigated 90 days after the treatments were implemented accumulated the most aloin and proline when 80% and 60% of the FC were depleted, respectively, without the use of zeolite.

Sembiring *et al.* (2017) investigated the impact of zeolite and urea fertilizers on maize growth. The treatment was applied including five level of zeolite; Z0 0 g/plot, Z1 105 g/plot, Z2 210 g/plot, Z3 315 g/plot, Z4 420 g/plot and five rate of urea; U0 0 g/ plot, U1 21 g/ plot, U2 42 g/plot, U3 63 g/plot, U4 84 g/plot. The results revealed that plant height (cm), leaf area, stem diameter (mm), and number of leaves were significantly influenced by zeolite application at a rate of 420 g per plot. These parameters were positively improved by urea at 84 g per plot and by the interaction Z3U3.

Wu *et al.* (2016) investigated the effects of nitrogen and zeolite on rice grain yield, water and nitrogen use efficiency, and soil total nitrogen content. This article aims to examine the impact of varying zeolite levels (0, 7500, and 15000 kg ha⁻¹) and nitrogen rates (0, 78.75, and 157.5 kg ha⁻¹) on rice growth and grain yield. Based on the investigation, the maximum dry weight, plant height, leaf dry weight, and water consumption were observed when applying N3Z2 (7500 kg ha⁻¹ and 157.5 kg ha⁻¹) compared with conventional fertilization (N3Z1). Z may reduce the amount of water needed for the milky ripening, heading-flowering, and jointing-booting stages, which helps growth under water-deficient conditions.

Bybordi, (2016) to determine the influence of zeolite, selenium, and silicon upon some agronomic and physiologic characteristics of canola grown under salinity. The treatment combination included zeolite (0.5 and 10 t ha⁻¹),

selenium (0, 2, and 4 g liter⁻¹), and silicon (0, 2, and 4 g liter⁻¹), which were applied. The findings showed that zeolite-enhanced canola growth components, such as plant height (cm), fresh and dry weight, and the number of branches per plant, were significantly increased with the combination of zeolite at 10 t ha⁻¹, along with 4 g l⁻¹ of silicon. Zeolite and silicon had a significant effect on growth and agronomic traits, and increased them. The interaction between zeolite and selenium was substantial in terms of leaf relative water content, photosynthesis, chlorophyll content, and activity of antioxidant enzymes.

Zaghlou et al. (2016) examined the impact of zeolite and PGPR cooperation on thyme essential oil output and antibacterial activity. There are two foliar spray treatments in the main plot (without and *Saccharomyces cerevisiae* extract) and five treatments in the subplot (control, full doses of NPK, half dose of NPK + PGPR, full dose of zeolite, half dose of zeolite + PGPR). PGPR, namely *Azotobacter chroococcum* ML1, *Bacillus circulans* ML2, and *Bacillus megaterium* ML3. The results showed that the maximum plant height, number of branches, and fresh and dry weight were observed when the rhizosphere of thyme was supplemented with a half-dose of zeolite, PGPR, and *Saccharomyces* extract, yielding the highest significant values. These outcomes hold for both growing seasons and two cuts.

Zaghlou et al. (2016) evaluated the influential cooperation between zeolite and PGPR on the yield and antimicrobial activity of thyme essential oil. The current study comprises five treatments in the subplot (control, full dose of NPK, half dose of NPK + PGPR, full dose of zeolite, half dose of zeolite + PGPR), and two foliar spraying treatments in the main plot (without and with *Saccharomyces cerevisiae* extract). PGPR, namely *Azotobacter chroococcum* ML1, *Bacillus circulans* ML2, and *Bacillus megaterium* ML3. The results showed that the maximum essential oil yield was observed when the rhizosphere of thyme was supplemented with a half-dose of zeolite, PGPR, and *Saccharomyces* extract, which had the highest significant values. These outcomes hold for both growing seasons and two cuts. However, a chemical analysis of thyme grown under various conditions revealed that the highest significant values of macronutrients and carbohydrate content were obtained from chemical

fertilizer treatments.

Wu *et al.* (2016) investigated the effects of nitrogen and zeolite on rice grain yield, water and nitrogen use efficiency, and soil total nitrogen content. This article aims to examine the influences of different levels of zeolite (0, 7500, and 15000 kg ha⁻¹) and nitrogen (0, 78.75, and 157.5 kg ha⁻¹) on rice grain yield, total soil nitrogen (TSN), water productivity (WP), and nitrogen recovery efficiency (NER). The findings showed that as N rates increased, grain yield, water consumption, nutrient accumulation, and WP correspondingly increased. However, zeolite input could result in a higher spike and weight of root, grain yield, 1000-grain weight, nitrogen accumulation, TSN, and NRE. Z may reduce the amount of water needed for the milky ripening, heading-flowering, and jointing-booting stages. Based on the investigation, Z and N led to a reduction in NRE. N3Z@ increased grain yield by 10.4%, WP by 7.3% and NRE by 63% compared with conventional fertilization (N3Z1). The N3Z2 approach is suggested to promote yield, WP, NRE, and TSN comprehensively.

Bybordi *et al.* (2016) to determine the influence of zeolite, selenium, and silicon upon some agronomic and physiologic characteristics of canola grown under salinity. The experiment was a randomized complete block design, arranged in a factorial with 27 treatment combinations, including zeolite (0, 0.5, and 10 t ha⁻¹), selenium (0, 2, and 4 g liter⁻¹), and silicon (0, 2, and 4 g liter⁻¹), with three replications. The findings showed that zeolite enhanced canola yield and yield components. The highest number of siliques, number of seeds per silique, biological yield, harvest index, and oil percentage were recorded with a combination of zeolite at 10 t ha⁻¹, along with Selenium at 4 g l⁻¹ and silicon at 4 g l⁻¹. Positive Interaction with zeolite, selenium, and Silicon on leaf water content, photosynthesis, chlorophyll content, and activity of antioxidant enzymes.

Villarreal-Nunez *et al.* (2015) to determine the effect of zeolite on the nitrogen efficiency in rice crop. The rice cultivar used was IDIAP FL 106 1, with a seedling density of 110 kg ha⁻¹, in moderately fertile soil. The nutrient using N rate of 80 kg ha⁻¹ mixed with different % of zeolite (0, 15, 25, 35, and 45%). The isotopic technique, using ¹⁵N with a 3% excess, is employed to determine

nitrogen fertilizer use efficiency. The maximum grain yield was obtained with 80 kg nitrogen ha⁻¹ + 45% zeolite ha⁻¹ and 80 kg N + 15% zeolite ha⁻¹. A 7% increase in nitrogen fertilizer use efficiency was achieved with the addition of natural zeolite. Minor doses of 12 kg ha⁻¹ (15%) of zeolite can improve nitrogen fertilizer use efficiency; after subsequent experiments, it is recommended to reduce the amount of N applied in soils with similar soil and climatic conditions suitable for growing rice.

Ozbahce *et al.* (2015) investigated the impact of zeolite application on the yield components and nutrient uptake of common bean under water stress. These studies evaluated the effects of six zeolite levels (Z:0, Z3:30, Z6:60, Z9:90, and Z12:120 t ha⁻¹) and three water levels (I50: 0.50, I75: 0.75, and I100: 1.00) on the yield, quality, and nutrient absorption of common beans under arid conditions. The findings showed that varying zeolite dosages and variations in irrigation rate had an impact on yield and yield components in each treatment, as well as affected water use efficiency by the application of zeolite and irrigation. The superior yield of 4777 and 4114 kg ha⁻¹ was recorded through Z9I100 application. During the investigation, water consumption at the same treatment was determined to be 451 and 468 mm, respectively.

Shahsavari *et al.* (2014) investigated the effect of zeolite and zinc on the qualitative characteristics of a canola variety at varying moisture levels. The treatments were with factor 1) irrigation (I): complete (regular irrigation) (I1), and restricted irrigation (I2) applied at the pod formation stage, 2) zeolite (Z): 0 (Z1), and 15 t ha⁻¹ (Z2), and 3) Zn: zinc sulfate concentrations of 0%, 0.1%, and 0.2% (Zn1, Zn2, and Zn3) on Opera, Licord, and RGS003 cultivars. The maximum rate of all study parameters was obtained by applying Z2Zn2 (15 t ha⁻¹) zeolite and 0.1% zinc sulphate in both irrigation regimes. The Opera variety in regular irrigation and the RGS003 variety in stress conditions exhibited the highest yields and yield components, including oil yield and oil content.

Li *et al.* (2013) determined that zeolite, as a slow-release fertilizer, enhances spinach yields and quality in a greenhouse test. Zeolite suggested for usage as a carrier to regulate the release of potassium and ammonium due to its large cation exchange capacity and high surface area. The growth and quality of

spinach were assessed in a greenhouse test following the application of zeolite pre-load with ammonium (NH_4^+) and potassium (Eco-zeolite). A promotion in spinach yield with comparable vitamin content was achieved using Eco-zeolite. Furthermore, elevated oxalate content was unexpected, possibly due to the presence of NH_4^+ as the exchange cations after modification.

Bybordi and Ebrahimian (2013) investigated morphological, yield, and quality attributes of canola fertilized with urea and zeolite. The four levels of zeolite (0, 4, 8, and 12 t ha^{-1}) and five levels of nitrogen (0, 150, 200, 250, and 300 kg ha^{-1}) were added and thoroughly mixed with the soil. The combined analysis of variance revealed that they had a significant impact on the iron (Fe) content, respiration rate, and silique number per plant. Additionally, results showed that N fertilizer increased 1000-seed weight, seed yield, silique number per plant, seed number per silique, and plant height. Zeolite also improved the yield and yield components. Additionally, photosynthesis and respiration were enhanced by N and zeolite treatments. Nitrate reductase activity was significantly influenced by N and zeolite. Additionally, the application of N or zeolite influenced the micro- and macronutrients, increasing N, K, Fe, and zinc, while decreasing the P content. Overall, our findings showed that applying zeolite can enhance canola production and growth, possibly by improving soil physical properties and Nitrogen Use efficiency.

Bybordi and Ebrahimian (2013) investigated growth, yield, and quality components of canola fertilized with Urea and Zeolite. The four levels of zeolite (0, 4, 8, and 12 t ha^{-1}) and five levels of nitrogen (0, 150, 200, 250, and 300 kg ha^{-1}) were added and thoroughly mixed with the soil. The combined analysis of variance revealed that the combined use of 300 kg N ha^{-1} and 12 t Z ha^{-1} had a significant impact on plant height (cm), number of branches, and number of siliques. Additionally, the application of N or zeolite reduced nutrient leaching and improved nutrient use efficiency. Overall, our findings showed that applying zeolite can enhance canola production and growth, possibly by improving soil physical properties and Nitrogen Use efficiency.

Gholamhoseini *et al.* (2012) investigated the effect of nitrogen (N) and natural zeolite rates on canola seed yield. The nitrogen levels (90, 180, and 270

kg N ha⁻¹) and four zeolite rates (0, 3, 6, and 9 t zeolite ha⁻¹) were combined in a factorial combination to create the experimental treatments. The results revealed that the N270Z9 treatments determined the maximum seed yield (2452.3 kg ha⁻¹), whereas the control (N0Z0) produced the minimal seed yield (1038.3 kg ha⁻¹). Furthermore, the use of 270 kg N ha⁻¹ without zeolite (N270Z0) resulted in a significantly higher amount of N leaching loss (144.23 kg ha⁻¹). The application of zeolite reduced N leaching loss across all N rates. This indicated whether high N applications had low N-use efficiency. More N use efficiency and high seed yield are attributed to zeolite application.

Sibi *et al.* (2011) evaluated the effect of water stress, taking zeolite and salicylic acid, on the yield and yield components of spring safflower. Water stress was selected as primary factor with three levels (I0: irrigation water requirement plants as control, I1: 85% and I2: 70% of the amount of irrigation water requirements) in the main plots and different rate of zeolite with three levels (Z0: no application of Z, Z1: zeolite applied 4 t ha⁻¹ and Z2: zeolite applied 8 t ha⁻¹) along with two levels of salicylic acid SA0 (no application), SA1 (spray of SA) as minor factor in a factorial combination of sub-plots were considered. The findings revealed that, at the sub-percent probability level, the impact of varying water stress levels on characteristics like plant height, boll number per plant, and fresh and dry weight was significant. Additionally, the effects of varying zeolite consumption levels on the following characteristics were important at a 5% level of statistical significance: plant height. Based on the findings, the zeolite had a substantial effect on the growth and yield performance of sunflowers.

Malekian *et al.* (2011) examined the influence of clinoptilolite and zeolite on nitrate leaching and plant growth, finding that the maximum dry matter yield (10389.27 kg ha⁻¹) was recorded at 27 t ha⁻¹, compared to the control (9393.97 kg ha⁻¹).

Ippolito *et al.* (2011) investigated the impact of zeolite soil application on inorganic nitrogen, moisture, and corn growth. The nutrient was applied through single urea fertilizers (224 kg N ha⁻¹) along with either band-applied or thoroughly mixed zeolite (at 90 Mg ha⁻¹). The results showed a significant

growth of corn. The maximum plant height, stem diameter, number of leaves, and dry matter accumulation were positively recorded after 6 weeks of amendment with urea and zeolite compared to the control. However, thoroughly mixing zeolite into the soil reduced the rate of nitrification, likely due to the adsorption of NH_4^+ in the zeolite mineral lattice. Thus, mixing zeolite into soil may reduce the leaching of inorganic nitrogen. Mixing may also improve soil water status, although initial leaching of zeolite-borne sodium may be necessary before growing crops.

Sibi *et al.* (2011) evaluated the effect of water stress, taking zeolite and salicylic acid, on the yield and yield components of spring safflower. The experiment was conducted as a split-plot factorial design based on RCBD with four replications. Water stress was selected as primary factor with three levels (I0: irrigation water requirement plants as control, I1: 85% and I2: 70% of the amount of irrigation water requirements) in the main plots and different rate of zeolite with three levels (Z0: no application of Z, Z1: zeolite applied 4 t ha^{-1} and Z2: zeolite applied 8 t ha^{-1}) and two levels of salicylic acid SA0 (no application), SA1 (spray of SA) as minor factor in a factorial combination of sub-plots were considered. The findings revealed that, at the sub-percent probability level, the impact of varying water stress levels on yield characteristics, such as grain per boll, boll grain yield, and biological yield, was significant. Additionally, the effects of varying zeolite consumption levels on the following factors were important at a 5% level: grain yield and biological yield at the sub-attribute level, number of bolls per plant, and seeds per boll. Salicylic acid also exhibited characteristics, such as the number of grains per bushel and yield levels, which were statistically significant in percentage terms. The highest and lowest average grain yields among the various water stress levels were 954.75 and $455.29 \text{ kg ha}^{-1}$, respectively. Moreover, 8 tonnes of treated zeolite and untreated zeolite were used, resulting in varying levels of maximum and minimum zeolite consumption with average grain yields of 823.58 and $589.33 \text{ kg ha}^{-1}$, respectively.

Valadabadi *et al.* (2010) To determine the eco-physiological effects of selenium and zeolite on the ability of various rapeseed cultivars to withstand water deficiency stress. Three cultivars of winter rapeseed (Opera, SLM 046, and

Modena) made up the sub-plot factor. The main-plot factor were irrigation regimes (control and irrigation interrupted during the flowering stage), zeolite (non-application and 10 t ha^{-1}), and selenium (non-application and 30 g l^{-1}). The findings demonstrated that while drought stress had practically significant effects on TDW (total dry weight), LAI (leaf area index), RGR (relative growth rate), and CGR (crop growth rate), and that zeolite and selenium applications decreased the water deficit stress damages, total dry weight (TDW), life area index (LAI), and crop growth rate (CGR) were all highly significantly different among the rapeseed cultivars. The results also revealed that the highest TDW, LAI, RGR, and CGR were obtained from the opera cultivar when treated with zeolite and selenium under no-drought conditions. The results demonstrated that the physiological growth indices of winter rapeseed variety are severely reduced by drought stress. In contrast, the damage caused by water deficit stress was mitigated by zeolite and selenium treatments.

Mahmoodabad (2010) conducted an experimental study on the effect of natural zeolite on the toxicity of lead, growth, nodulation, and chemical composition of soybeans (*Glycine max* L. var. Williams). Was evaluated. Treatment combination with zeolite three levels (0, 2, and 5 g kg^{-1}) and three levels of Pb (0, 10, and 25 mg kg ha^{-1}) was applied. Through the application of Pb, a decrease in shoot and root dry weights was observed. The addition of zeolite increased the concentrations of iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu), as well as the shoot dry weight, without the use of Pb. It also increased the number and dry weight of root nodules. Furthermore, the highest level of zeolite application ($5 \text{ g zeolite kg}^{-1} \text{ soil}$) produced the highest value for these parameters. Zeolite is considered to enhance soybean growth and improve its chemical composition while reducing lead toxicity in plant parts.

Kavoosi (2007) evaluated the effect of zeolite application on rice yield, nitrogen recovery, and nitrogen use efficiency, with three levels of 8, 16, and 24 tons of zeolite ha^{-1} combined into the soil with and without $60 \text{ kg nitrogen ha}^{-1}$ as urea. Their effects on the grain and straw yields, available K, apparent N recovery, N use efficiency, and some soil properties were determined. Results showed a significant positive effect of the treatment on the grain yield, straw

yield, and number of tillers of rice. Grain yield increased significantly at all levels of zeolite with N levels when compared to the 60 kg N ha⁻¹ treatment and the control. Additionally, soil available potassium and its uptake by rice straw were also significantly increased. The minimum apparent N recovery (40%) was obtained from application of 60 kg N ha⁻¹, whereas application of 8- or 16-ton zeolite ha⁻¹ augmented deceptive nitrogen retrieval up to 65%. NUE (nitrogen use efficiency) was also improved.

Polat *et al.* (2004) reported that zeolite significantly improved nitrogen and potassium availability, resulting in increased chlorophyll synthesis, higher photosynthetic activity, and improved biomass accumulation in maize. The primary mechanism through which zeolite influences plant physiology is by improving nutrient availability in the rhizosphere. Due to its high cation exchange capacity, zeolite adsorbs positively charged nutrients such as ammonium (NH₄⁺), potassium (K⁺), calcium (Ca²⁺), and magnesium (Mg²⁺), preventing their leaching and gradually releasing them according to plant demand. This slow-release characteristic ensures a continuous supply of nutrients throughout crop growth, thereby enhancing nutrient uptake and maintaining metabolic activities.

2.4 Effect of zeolite on quality, soil properties, and economic crops

Khaliq *et al.* (2024) to determine the synergistic effect of urea, poultry manure, and zeolite on the nutrient content of wheat. The treatments included a control (T1); urea nitrogen at 120 kg N ha⁻¹ (UN120) (T2); poultry manure (PM) at 120 kg N ha⁻¹ (T3); zeolite⁻¹ (Z1) at 5 t ha⁻¹ (T4); zeolite-2 (Z2) at 5 t ha⁻¹ (T5); UN120 + Z1 (T6); PM + Z1 (T7); UN120 + Z2 (T8); PM+Z2(T9); ½ UN + ½PM+Z1(T10); ½ UN +½PM+Z2(T11); and ½ UN +½PM+½Z1+ ½ (T12). The UN120 treatments revealed a significant increase in nutrient content analysis, demonstrating substantial enhancements in shoot nitrogen (70.6%), phosphorus (33.3%), and potassium (15.6%) compared to the control. The combination of UN and PM with zeolites further raised nutrient levels. Wheat productivity in degraded mountainous soils was successfully increased by combining organic amendments, zeolites, and mineral nitrogen sources.

Mohammadnaseri and Tadayon (2024) investigated the impact of

varying zeolite levels on several physiological parameters, including oil and protein yields, of linseed under deficit irrigation. Deficit irrigation as the primary factor in four rates, including 50 (control), 80, 130, and 180 mm of evaporation through the class A evaporation pan, and use of zeolite as a secondary factor in three levels, with: no application (control), 5, and 10 t ha⁻¹ was applied. The experiment's findings demonstrated that applying zeolite at a 1% probability level significantly impacted the amounts of chlorophyll a, chlorophyll b, total chlorophyll, and carotenoids in leaves, as well as oil yield, nitrogen percentage, and protein percentage. Additionally, different levels of irrigation were significant for all the revealed attributes at the 1% level. The maximum quality attributes were obtained from the control treatment (regular irrigation) and the application of 10 t ha⁻¹ of zeolite; however, the minimal amount of these traits was obtained through the treatment of 180 mm of evaporation by the evaporation pan and no application of zeolite. Based on the investigation, the application of zeolite has significantly improved the performance of the linseed crop in non-stress conditions and moderate drought stress conditions.

Kavvadias *et al.* (2023) evaluated the short-term effect of chemical fertilizers, compost, and zeolite on soil properties. The experiment consisted of two levels of olive compost (0% and 10% v/v), three rates of zeolite (0, 2, and 5% w/w), and two levels of chemical fertilizers (no application and NPK fertilization). The results revealed that the compost treatment significantly affected soil pH, EC, soil organic matter (SOM), total N, and available P. In contrast, similar results have been documented regarding the availability of P, K, and Na in soil and plants.

Rahmani *et al.* (2023) to determine the effect of vermicompost and zeolite on improving nutrient uptake, essential oil production, and composition of black cumin (*Nigella sativa* L). The experimental treatments included four vermicompost levels (0, 2, 4, and 6 t ha⁻¹) and four zeolite rates (0, 3, 6, and 9 t ha⁻¹). The results, obtained by applying 6 t ha⁻¹ vermicompost and 9 t ha⁻¹ zeolite, showed a recorded maximum amount of N, P, and K in the seed increased by 13.5%, 10.8% and 14.10% in the oil, along with unsaturated fatty acids including linoleic (53.3%), oleic (25.36), and linolenic acid (0.6%, with a 24.1% increase

in the essential oil content over the control plot. This highlighted the agronomic potential of both amendments in promising and environmentally friendly agricultural systems.

Cataldo *et al.* (2021) reported that zeolites are Natural crystalline aluminosilicates to use as a soil conditioner to enhance the chemical and physical characteristics of soil, such as water-holding capacity (WHC), cation exchange capacity (CEC), infiltration rate, and saturated hydraulic conductivity (Ks). Owing to their characteristics. These elements may reduce the volatilisation of ammonia and nitrate leaching. The ability of zeolites to carry fertilisers, micronutrients, and slow-release macronutrients is another well-known feature. However, these materials have potential applications in the agricultural sector, and as a sustainable product, zeolites have the potential to directly enhance the farm ecosystem.

According to Mondal *et al.* (2021) the unique properties of zeolite enhance fertilizers and water use efficiency, subsequently reducing environmental pollution by decreasing nitrate leaching and the emission of nitrous oxide, as well as ammonia. By using these minerals as soil ameliorants, heavy metal toxicity is reduced, and the physical and chemical characteristics of the soil are improved.

Palanivell *et al.* (2019) to determine the economic viability of including crude humic substance, chicken litter biochar, and clinoptilolite zeolite in rice cultivation. Results showed that long-term cultivation of rice with zeolite is the most economical practice, followed by biochar and chicken litter or clinoptilolite zeolite.

Ryan *et al.* (2018) reported that the use of zeolite at 7.5 t ha^{-1} in soyabean showed the maximum return (Rs 94759 ha^{-1}), net return (Rs 68255 ha^{-1}), and benefit-cost ratio (3.58), respectively.

Cairo *et al.* (2017) studied the effect of zeolite and organic fertilizers on soil properties. The nutrient was applied to sugarcane filter cake and zeolite, along with inorganic fertilizers (N, P_2O_5 , and K_2O). While the soil sample were collected at a depth of 0-20 cm. the results showed that applying 7.5 t ha^{-1} of zeolite and sugarcane filter cake at 22.5 t ha^{-1} improved soil properties after crop

harvest, including degree of soil aggregation, water-stable aggregates, permeability, lower plastic limit, pH, organic matter, and electrical conductivity. The relationships between soil properties and principal components validated the positive effects of zeolite application on soil quality and sugarcane yield.

Bybordi, (2016) to determine the effect of zeolite, selenium, and silicon on qualitative and quantitative traits of onion growth under salinity conditions. Nutrients were applied, including zeolite at three levels (0, 4, and 8 t ha⁻¹), selenium at three levels (0, 0.5, and 1 kg ha⁻¹), and silicon at three levels (0, 200, and 400 kg ha⁻¹). The data revealed that soluble solids, bulb nitrogen, leaf sodium and potassium, chlorophyll content, and peroxidase activity had a significant impact on all traits. Increase bulb size due to the application of zeolite, Se, and Si. The application of zeolite, Se, and Si resulted in a significant increase in dry matter, soluble solids, nitrogen content, nitrate concentration, and protein content, as well as a decrease in sodium content in leaves and enzyme activity. Overall, qualitative characteristics, such as soluble solids, potassium, protein, chlorophyll, and photosynthesis, were produced by 8 t of zeolite per hectare, 1 kg ha⁻¹ of Se, and 400 kg ha⁻¹ of Si per hectare.

Ozbahce *et al.* (2015) investigated the impact of zeolite application on the nutrient uptake of common beans under water stress. These studies evaluated the effects of six levels of zeolite (Z:0, Z3:30, Z6:60, Z9:90, and Z12:120 t ha⁻¹) and three levels of water (I50: 0.50, I75: 0.75, and I100: 1.00) on the quality and nutrient absorption of common bean under arid conditions. The findings showed that varying zeolite dosages and variations in irrigation rate had an impact on N, K, Zn, Mn, and Cu in the leaves. The increase in the amount of zeolite further increases these nutrients.

Villarreal-Nunez *et al.* (2015) to determine the effect of zeolite on the nitrogen efficiency in soil characteristics. The N rate of 80 kg ha⁻¹ was associated with different ratio of zeolite (0%, 15%, 25%, 35%, and 45%). The isotopic technique, using ¹⁵N with a 3% excess, was employed to determine nitrogen fertilizer use efficiency. Zeolite at 12 kg ha⁻¹ (15%) can improve nitrogen fertilizer use efficiency. Following subsequent experiments, it is recommended that the amount of N applied in soils with similar soil and climatic conditions

suitable for growing rice be reduced.

Ramesh *et al.* (2015) evaluated the impact of zeolite on soil quality, plant development, and nutrient performance in sweet potato. Results revealed that 1% commercial zeolite 4A (CZ) had slightly higher electrical conductivity (0.45 dSm^{-1}) than the control (0.17 dSm^{-1}).

Shahsavari *et al.* (2014) the research was performed to investigate the effect of zeolite and zinc on the qualitative characteristics of a canola variety at different moisture levels. The treatments were with factor 1) irrigation (I): complete (regular irrigation) (I1), and restricted irrigation (I2) applied at the pod formation stage, 2) zeolite (Z): 0 (Z1), and 15 t ha^{-1} (Z2), and 3) Zn: zinc sulfate concentrations of 0%, 0.1%, & 0.2% (Zn1, Zn2, and Zn3) on Opera, Licord, and RGS003 cultivars. The maximum rate of all study parameters was obtained by applying Z2Zn2 (15 t ha^{-1}) and 0.1% zinc sulphate in both irrigation regimes. The Opera variety in regular irrigation and the RGS003 variety in stress conditions had the maximum oil content, oil yield, and Glucosinolate in canola.

Bybordi and Ebrahimian (2013) reported that the physical properties of the soil were significantly improved through the application of zeolite, along with five levels of nitrogen, resulting in improved nitrogen use efficiency.

Gholamhoseini *et al.* (2013) to figure out how zeolite-amended cattle dung effects nutrient leaching, water use efficiency, on sunflower production and seed quality. The treatment arrangement including; irrigation regime (I1: full irrigation and I2: limited irrigation) provided the whole-plot treatments with five fertilization strategies (F1: urea, F2: urea + composted manure (CM) with 0% (w/w) zeolite, F3: urea + CM with 7% zeolite, F4: urea + CM with 14% zeolite and F5: urea + CM with 21% zeolite) providing in the sub-plots. The maximum protein content was achieved with the F5 treatments, while the minimum seed protein content was observed in F1 and F2, respectively. We concluded that amending soil with manure and zeolite can be a beneficial approach for decreasing chemical fertilizer application rate and improving the nutritional value and sustainability of the agricultural system.

Li *et al.* (2013) determined that zeolite, as a slow-release fertilizer, affects spinach yields and quality in a greenhouse test. With a high surface area and

large cation exchange capacity, zeolite is proposed for use as a carrier to control the release of ammonium and potassium. The growth and quality of spinach were assessed in a greenhouse test following the application of zeolite pre-load with ammonium (NH_4^+) and potassium (Eco-zeolite). A promotion in spinach yield with comparable vitamin content was achieved using Eco-zeolite. Furthermore, elevated oxalate content was unexpected, possibly due to the presence of NH_4^+ as the exchange cations after modification.

Ippolito *et al.* (2011) reported the impact of zeolite application on inorganic nitrogen, moisture, corn growth, and soil properties. The finding showed that zeolite application with concentrations of 6.7 t ha^{-1} , 13.4 t ha^{-1} , and 20.2 t ha^{-1} , respectively, improved the improvement of soil CEC from $12.8 \text{ cmol (+) kg}^{-1}$ to $13.3 \text{ cmol (+) kg}^{-1}$, $13.7 \text{ cmol (+) kg}^{-1}$, and $14.2 \text{ cmol (+) kg}^{-1}$.

Mahmoodabad (2010) conducted an experimental study on the effect of natural zeolite on the toxicity of lead, growth, nodulation, and chemical composition of soybeans (*Glycine max* L. var. Williams). Treatments consisted of a factorial combination with three levels of zeolite (0, 2, and 5 g kg^{-1}) and three levels of Pb (0, 10, and 25 mg kg ha^{-1}). The addition of zeolite raised the concentrations of iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu), and increased the total number of nodules and dry weight of nodules without the use of Pb. Furthermore, the highest level of zeolite application ($5 \text{ g zeolite kg}^{-1} \text{ soil}$) produced the highest value for these parameters. Zeolite is considered to enhance soybean growth and improve its chemical composition while reducing lead toxicity in plant parts.

2.5 Effect of press-mud on the growth and yield of the crop

Ram *et al.* (2024) evaluated the optimization of sugarcane productivity and soil nutrient uptake using sulphitated press-mud, phosphorus-solubilizing bacteria, and *Trichoderma viride* in calcareous soil. The highest germination percentage (43.5%), number of tillers, plant height (272 cm), number of millable cane ($125.67 \times 10^{-1} \text{ ha}^{-1}$), cane girth (2.20 cm), and single cane weight (0.831 kg) were recorded with applied sugarcane press-mud cake @ 12.5 t ha^{-1} along with *T. viride* + PSB. The addition of sulphated press mud cake, either alone with *T. viride* or in combination with PSB, resulted in profitable growth of the sugarcane

crop.

Ram *et al.* (2024) evaluated the optimization of sugarcane productivity and soil nutrient uptake using sulphitated press-mud, phosphorus-solubilizing bacteria, and *Trichoderma viride* in calcareous soil. The highest cane yield (71.98 t ha⁻¹), brix (18.2%), pol (17.15%), purity (88.10%), commercial cane sugar (12.47 %), and sugar yield (8.37 t ha⁻¹) were registered with applied sugarcane press-mud cake @ 12.5 t ha⁻¹ along with *T. viride* + PSB. The addition of sulphitated press mud cake, either by itself or in conjunction with PSB and *T. viride*, produced a profitable sugarcane crop yield.

Sasy and Abu-Ellail (2021) studied the effect of nitrogen, potassium as inorganic fertilizers, and press-mud as an organic fertilizer on the yield and quality of the G.2003-47 variety of sugarcane. The results showed that the application of press-mud at 4 tonnes per hectare had a positive influence on plant height, cane diameter, the number of millable canes, and stalk weight, when combined with the application of inorganic fertilizers at 150 to 210 tonnes per hectare. Correlation with inorganic fertilizers, such as potassium 48 kg along with press-mud and nitrogen 210 kg N, was recorded in significant growth parameters.

Prabhavathi *et al.* (2019) to determine the combined application of press-mud and bio-compost on the growth and yield of finger millet. The finding revealed that the maximum grain yield (3625 kg ha⁻¹) and straw yield (6363 kg ha⁻¹) were obtained by the application of RDF + bio-compost @ 10 t ha⁻¹, compared to the control, which was on par with the application of RDF + press-mud @ 10 t ha⁻¹ compared to the control. Based on the investigation, it can be concluded that the application of bio-compost, sugarcane press-mud, along with the recommended dose of fertilizers, is best for the yield of finger millets.

Rahmad *et al.* (2019) investigated the impact of sugarcane bagasse and filter compost fertilizers, as well as manure application, on the growth and production of sugarcane. The organic sources of fertilizers, such as sugarcane bagasse, compost, and manure, were applied at a rate of 15 t ha⁻¹, along with NPK fertilizers at 350 kg ha⁻¹. The results showed that the maximum plant height (163 cm), segment length (18.33 cm), stem diameter (2.62 cm), and

cane weight (158.36 kg per plot) were recorded with the application of compost from a mixture of bagasse and manure (1:1) along with 350 kg NPK per hectare.

Prabhavathi *et al.* (2019) to determine the combined application of press-mud and bio-compost on the growth and yield of finger millet. The finding revealed that the maximum plant height, number of tillers plant⁻¹, and dry matter accumulation were recorded at different plant growth stages @ 30, 60, and at harvest through the application of RDF + bio-compost @ 10 t ha⁻¹ compared to control, which was on par with the application of RDF + press-mud @ 10 t ha⁻¹ compared to control. Based on the investigation, it can be concluded that the application of bio-compost, sugarcane press-mud, along with the recommended dose of fertilizers, is best for the growth of finger millets.

Lucena *et al.* (2018) to determine ethanol production potential from sweet sorghum fertilized with filter cake and vinasse for the sugarcane industry. The treatments were applied with two independent factors: five rates of vinasse application (0, 19.42, 77.68, 155.36, and 310.72 m³ ha⁻¹) and five rate of filter cake (0, 2.75, 11.0, 22.0, and 44.0 Mg ha⁻¹). The data recorded included total recoverable sugars, wet cane weight, reducing sugars, fibre, stem yield, and ethanol potential in sweet sorghum: Vinasse and filter cake promote sorghum stem growth, sugar production, and potential yield. Therefore, the use of vinasse and filter cake enables the production of sweet sorghum for ethanol production, complementary to sugarcane.

Kalaivanan and Omar Hattab (2016) investigated the effect of enriched press-mud compost from sugarcane industrial byproduct on soil properties, growth, yield attributes, and yield of rice. The treatment consisted of five levels of press-mud compost (0.00, 1.25, 2.50, 3.75, and 5.00 t ha⁻¹), applied to three cultivars: ADT 36 and ADT 43, and the hybrid ADTRH1. The results showed that the maximum number of effective tillers, grain yield, and straw yield was registered in hybrid ADTRH 1 when 5 tons of press-mud compost enrichment was applied, compared with 2.5 tons ha⁻¹ of enriched press-mud compost.

Kalaivanan and Omar Hattab (2016) investigated the effect of enriched press-mud compost from sugarcane industrial byproduct on soil properties, growth, yield attributes, and yield of rice. The treatment consisted of five levels

of press-mud compost (0.00, 1.25, 2.50, 3.75, and 5.00 t ha⁻¹), applied to three cultivars: ADT 36 and ADT 43, and the hybrid ADTRH1. The results showed that the maximum plant height, number of tillers, and dry matter accumulation were recorded in hybrid ADTRH 1 when 5 tons of press-mud compost enrichment was applied, compared with 2.5 tons ha⁻¹ of enriched press-mud compost.

Sharma *et al.* (2014) evaluated the effect of press-mud and FYM, combined with zinc sulfate application, on rice yield. T1 (Control). T2 (FYM 5 t ha⁻¹ + 0 kg ZnSO₄), T3 (FYM 5 t ha⁻¹ + 2.5 kg ZnSO₄), T4 (FYM 5 t ha⁻¹ + 5 kg ZnSO₄), T5 (FYM 5 t ha⁻¹ + 7.5 kg ZnSO₄) T6 (FYM 10 t ha⁻¹ + 0 kg ZnSO₄), T7 (FYM 10 t ha⁻¹ + 2.5 kg ZnSO₄), T8 (FYM 10 t ha⁻¹ + 5 kg ZnSO₄), T9 (FYM 10 t ha⁻¹ + 7.5 kg ZnSO₄), T10 (Press mud 5 t ha⁻¹ + 0 kg ZnSO₄), T11 (Press mud 5 t ha⁻¹) + 2.5 kg ZnSO₄), T12 (Press mud 5 t ha⁻¹ + 5 kg ZnSO₄), T13 (Press mud 5 t ha⁻¹ + 7.5 kg ZnSO₄). Results showed that the maximum number of effective tillers, number of grains per spike, spike length (cm), and grain yield (4.85 t ha⁻¹) were noted with application of FYM 10 t ha⁻¹ + 7.5 kg ZnSO₄, which was at par with 5 t ha⁻¹ press-mud + 7.5 kg ZnSO₄ ha⁻¹. Based on the study, it can be concluded that proper zinc application, along with organic combination plant nutrient sources, can be used to achieve maximum output.

Sharma *et al.* (2014) evaluated the effect of press-mud and FYM, combined with zinc sulfate application, on rice yield. T1 (Control). T2 (FYM 5 t ha⁻¹ + 0 kg ZnSO₄), T3 (FYM 5 t ha⁻¹ + 2.5 kg ZnSO₄), T4 (FYM 5 t ha⁻¹ + 5 kg ZnSO₄), T5 (FYM 5 t ha⁻¹ + 7.5 kg ZnSO₄) T6 (FYM 10 t ha⁻¹ + 0 kg ZnSO₄), T7 (FYM 10 t ha⁻¹ + 2.5 kg ZnSO₄), T8 (FYM 10 t ha⁻¹ + 5 kg ZnSO₄), T9 (FYM 10 t ha⁻¹ + 7.5 kg ZnSO₄), T10 (Press mud 5 t ha⁻¹ + 0 kg ZnSO₄), T11 (Press mud 5 t ha⁻¹) + 2.5 kg ZnSO₄), T12 (Press mud 5 t ha⁻¹ + 5 kg ZnSO₄), T13 (Press mud 5 t ha⁻¹ + 7.5 kg ZnSO₄). Results showed that the maximum plant height, dry matter accumulation, and number of tillers were recorded with the application of press-mud 5 t ha⁻¹ + 7.5 kg ZnSO₄.

Shukla and Yadav (2011) observed that the application of PSB + press-mud cake improved the ratoon cane yield (67.86 t ha⁻¹), and commercial sugar yield (8.01 t ha⁻¹) was obtained.

Shankaraiah and Murthy (2005) studied the effect of enriched press-mud cake on the growth, yield, and quality of sugarcane. The treatment was applied through inorganic fertilizers, including (50:75:100% RDF), with two levels of press-mud cake (10 t and 15 t ha⁻¹) compared to raw press-mud 15 t ha⁻¹. The finding showed that plant height (255 cm), weight of cane (1.80 kg⁻¹), and cane diameter (2.75 cm) were recorded with 100% RDF, and (252 cm), 1.76 kg⁻¹, and 2.77 cm) through the application of 15 t ha⁻¹ enriched press-mud cake compared with control.

Shankaraiah and Murthy (2005) studied the effect of enriched press-mud cake on the growth, yield, and quality of sugarcane. The treatment was applied through inorganic fertilizers, including (50:75:100% RDF), with two levels of press-mud cake (10 t and 15 t ha⁻¹) compared to raw press-mud 15 t ha⁻¹. The finding showed that the highest cane yield (198.00 t ha⁻¹) and sugar yield (29.32 t ha⁻¹) were recorded with the application of enriched press-mud cake along with 100% recommended dose of fertilizers.

2.6 Effect of press-mud on quality, soil properties, and economic crops

Dotaniya *et al.* (2025) to determine the application of FYM and press-mud to improve soil health properties. The treatments applied include: FYM in four levels (0, 2.5, 5, and 10 t ha⁻¹), and four levels of press-mud (0, 2.5, 5, and 10 t ha⁻¹), screening the nutrient pattern of farm yard manure, and press-mud and its effect on soil properties and enzyme activities. The findings revealed that electrical conductivity and soil pH were reduced after one year through the application of these nutrient sources, and the maximum nitrogen, phosphorus, potassium, and sulfur uptake, as well as soil enzymatic activities, were observed with farmyard manure and press-mud (10 t ha⁻¹) applied over the control. Based on the study, it can be concluded that organic input sources, such as fertilizers, may enhance soil fertility, mitigate salt ion toxicity, and improve the potential for food production.

Ram *et al.* (2024) evaluated the optimization of sugarcane productivity and soil nutrient uptake using sulphitated press-mud, phosphorus-solubilizing bacteria, and *Trichoderma viride* in calcareous soil. The nutrient uptake by the sugarcane crop was significantly improved through the application of sugarcane

press-mud + *T. viride* or sugarcane press-mud + *T. viride* + PSB. Moreover, the nutrient influenced by sugarcane including; N, P, and K (292.54, 32.64, 278.55 kg ha⁻¹) and micronutrient viz., Fe, Mn, Zn, and Cu (530.53, 434.25, 454.12, and 109.86 g ha⁻¹), was positively influenced through the application of sugarcane press-mud cake @ 12.5 t ha⁻¹ along with *T. viride* + PSB. Based on the investigation, a promising strategy for improving sugarcane productivity and nutrient uptake is presented in an integrated manner.

Sasy and Abu-Ellail (2021) studied the effect of nitrogen, potassium as inorganic fertilizers, and press-mud as an organic fertilizer on the yield and quality of the G.2003-47 variety of sugarcane. The results showed that the maximum Brix, sucrose percentage, and sugar recovery percentage were recorded with the application of press-mud at 4 tonnes per hectare, along with the application of inorganic fertilizers, at 150 to 210 kg ha⁻¹. Correlation with inorganic fertilizers, such as potassium at 48 kg along with press-mud and nitrogen at 210 kg N, was recorded as significantly improving quality attributes.

Rahmad *et al.* (2019) investigated the impact of sugarcane bagasse and filter compost fertilizers, as well as manure application, on the growth and production of sugarcane. The organic sources of fertilizers, such as sugarcane bagasse, compost, and manure, were applied at a rate of 15 t ha⁻¹, along with NPK fertilizers at 350 kg ha⁻¹. The results showed the highest pol value (31.32%), and the Brix value (23.43%) was recorded with the application of press-mud (15 t ha⁻¹) without the addition of manure, at a rate of 350 kg NPK per hectare.

Prabhavathi and Ramakrishna Parama (2019) reported the effect of sugar industry solid waste, press-mud, and bio-compost on soil properties at different intervals in the finger millet crop. The results showed that indicated significantly lower bulk density and an increase in MWHC was recorded by the application of RDF + 10 t ha⁻¹ press-mud (1.39, 2.61, and 37.46% respectively). Soil pH varied from 7.50 to 8.07 at 30 DAT to harvest and later decreased, and EC ranged from 0.33 to 0.51 dS m⁻¹. The maximum organic carbon content and higher CEC were recorded in RDF + bio-compost (10 t ha⁻¹), respectively.

Jha *et al.* (2017) reported that the uptake of nutrients was significantly

enhanced compared to the control due to the combined application of press-mud (10 t ha^{-1}) and sugarcane trash (10 t ha^{-1}) along with inorganic fertilizers. They additionally noted that press-mud, either alone or in combination with sugarcane trash, resulted in the highest uptake of nitrogen, phosphorus, and potassium as well as micronutrients (Fe, Zn, Cu, and Mn)

Ghulam *et al.* (2012) reported that the application of press-mud reduced the soil pH from 8.1 to 7.9 as a result of increased press-mud treatment levels. It can be concluded that the use of press-mud at $15\text{-}20 \text{ t ha}^{-1}$ would be satisfactory for improving the physical and chemical properties of the soil.

Sarangi *et al.* (2008) reported that composting sugar mill press-mud had a positive effect on soil characteristics and crop growth. The results showed that the soil's physical and chemical properties were enhanced, and a substantial amount of organic matter was added to the soil. During growth, provide essential plant nutrients.

Shankaraiah and Murthy (2005) studied the effect of enriched press-mud cake on the growth, yield, and quality of sugarcane. The treatment was applied through inorganic fertilizers, including (50:75:100% RDF), with two levels of press-mud cake (10 t and 15 t ha^{-1}) compared to raw press-mud 15 t ha^{-1} . The findings showed that the maximum net return and benefit-cost ratio were registered (Rs 82,300 t ha^{-1} and 1.19), which was comparable to 10 t ha^{-1} applied enrichment press-mud cake along with 100% RDF.

2.7 Effect of bio-neema on the growth and yield of the crop

Silva *et al.* (2024) studied the use of neem vegetable cake to increase corn productivity. The study aimed to investigate the effect of neem vegetable cake on the yield attributes of corn at four consistent levels of neem vegetable cake (3, 6, 9, and 12 kg ha^{-1}), and it was compared with the control (no application of organic fertilizers). It was found that the maximum grain productivity was recorded with the application of 12 kg ha^{-1} of neem cake. It was concluded that grain productivity increased proportionally to 38 kg ha^{-1} of corn for each kilogram of neem cake applied, compared to the control.

Reddy and Umesha (2023) observed the effect of organic nutrients and neem cake on the growth and yield of wheat (*Triticum aestivum* L.). The

treatments is consisted; T1 (FYM 10 t ha⁻¹ + Neem Cake 300 kg ha⁻¹), T2 (FYM 10 t ha⁻¹ + Neem Cake 400 kg ha⁻¹), T3 (FYM 10 t ha⁻¹ + Neem Cake 500 kg ha⁻¹), T4 (Vermicompost 1 t ha⁻¹ + Neem Cake 300 kg ha⁻¹), T5 (Vermicompost 1 t ha⁻¹ + Neem Cake 400 kg ha⁻¹), T6 (Vermicompost 1 t ha⁻¹ + Neem Cake 500 kg ha⁻¹), T7 (Poultry manure 0.5 t ha⁻¹ + Neem Cake 300 kg ha⁻¹), T8 (Poultry manure 0.5 t ha⁻¹ + Neem Cake 400 kg ha⁻¹), T9 (Poultry manure 0.5 t ha⁻¹ + Neem Cake 500 kg ha⁻¹) and T10 (Control (150:60:40 NPK kg ha⁻¹) was applied. The findings that the maximum plant height (101.32 cm), number of tillers hills⁻¹ (13.45), and dry weight of plant (29.24 g plant⁻¹) were registered with the combined application of poultry manure (4 t ha⁻¹) + neem seed cake 500 kg ha⁻¹.

Suman *et al.*, (2023) reported the effect of vermicompost and neem cake with inorganic fertilizers on growth and yield of maize (*Zea mays* L.). it is showed from the three level of Vermicompost (0, 5, and 10 t ha⁻¹), and three level of RDF (0, 50, and 100% ha⁻¹) with three level of neem cake (0, 250, and 500 kg ha⁻¹). The results showed that the maximum cob length (17.93 cm), test weight (28.68 g), and grain yield (45.67 q ha⁻¹) were noted at 30, 60, and 90 days after sowing, through the application of 100% recommended dose of fertilizers + 10 t vermicompost + 500 kg neem cake per hectare. It was concluded to be the best for enhancing the yield and yield attributes of maize.

Reddy and Umesha (2023) observed the effect of organic nutrients and neem cake on the growth and yield of wheat (*Triticum aestivum* L.). The treatments is consisted; T1 (FYM 10 t ha⁻¹ + Neem Cake 300 kg ha⁻¹), T2 (FYM 10 t ha⁻¹ + Neem Cake 400 kg ha⁻¹), T3 (FYM 10 t ha⁻¹ + Neem Cake 500 kg ha⁻¹), T4 (Vermicompost 1 t ha⁻¹ + Neem Cake 300 kg ha⁻¹), T5 (Vermicompost 1 t ha⁻¹ + Neem Cake 400 kg ha⁻¹), T6 (Vermicompost 1 t ha⁻¹ + Neem Cake 500 kg ha⁻¹), T7 (Poultry manure 0.5 t ha⁻¹ + Neem Cake 300 kg ha⁻¹), T8 (Poultry manure 0.5 t ha⁻¹ + Neem Cake 400 kg ha⁻¹), T9 (Poultry manure 0.5 t ha⁻¹ + Neem Cake 500 kg ha⁻¹) and T10 (Control (150:60:40 NPK kg ha⁻¹) was applied. The findings that the highest effective tiller (11.86), grains per spike (54.17), test weight (43.41 g), grain yield (55.78 q ha⁻¹), and straw yield (116.41 q ha⁻¹) were recorded with the combined application of poultry manure (4 t ha⁻¹) + neem seed cake 500 kg ha⁻¹.

Suman *et al.*, (2023) reported the effect of vermicompost and neem cake with inorganic fertilizers on growth and yield of maize (*Zea mays* L.). it is showed from the three level of Vermicompost (0, 5, and 10 t ha⁻¹), and three level of RDF (0, 50, and 100% ha⁻¹) with three level of neem cake (0, 250, and 500 kg ha⁻¹). The resulted revealed the maximum plant height (60.26, 83.96, and 170.33 cm), number of leaves (7.13, 12.23 and 14.85), and stem diameter (1.45, 2.24 and 2.46 cm) was registered at 30, 60, and 90 days after sowing, through the application of 100% recommended dose of fertilizers + 10 t vermicompost + 500 kg neem cake per hectare. It was concluded to be best for the enhanced growth of maize.

Shenoy (2020) reported the effect of neem cake urea mixed application on the growth and yield of rice under submerged conditions. The treatments consisted of control, 100% nitrogen with five levels of urea and neem cake mixed with different proportions, including 100% (60:30:60 kg NPK ha⁻¹), 75% (45:30:60 kg NPK ha⁻¹), and 50% (30:30:60 kg NPK ha⁻¹), along with neem cake (50, 75, and 100%). The findings showed that the highest plant height (107.30 cm) and number of tillers (472 m⁻²) were reported with the application of 75% RDN (45:30:60) + 100% neem cake compared to the control (0:30:60 + no neem cake applied).

Shenoy (2020) reported the effect of neem cake urea mixed application on the growth and yield of rice under submerged conditions. The treatments consisted of control, 100% nitrogen with five levels of urea and neem cake mixed with different proportions, including 100% (60:30:60 kg NPK ha⁻¹), 75% (45:30:60 kg NPK ha⁻¹), and 50% (30:30:60 kg NPK ha⁻¹) along with neem cake (50, 75, and 100%). The finding showed that maximum panicles (445 m⁻²), grain yield (55 q ha⁻¹), and straw yield (4.35 q ha⁻¹) were recorded with application of 75% RDN (45:30:60) + 100% neem cake compared to control (0:30:60 + no applied neem cake).

Eifediyi *et al.*, (2017) to determine the impact of neem-based cake and nano NPK fertilizers in growth and yield of sesame (*Sesamum indicum* L.). treatments involved of three rates of NPK fertilizers (0, 100, 200 kg ha⁻¹) and neem seed cake (NSC) with four level (0, 1, 2, 3, and 4 t ha⁻¹). The data were

recorded on soil parameters, growth attributes, and yield components. The results showed that the maximum indicated plant height (cm), number of leaves, and leaf area were recorded during the study duration through the application of 100 kg NPK ha⁻¹ and 3 tons of neem seed cake.

Eifediyi *et al.*, (2017) to study the effect of neem seed cake and NPK fertilizers in growth and yield of sesame (*Sesamum indicum* L.). treatments involved of three rates of NPK fertilizers (0, 100, 200 kg ha⁻¹) and neem seed cake (NSC) with four level (0, 1, 2, 3, and 4 t ha⁻¹). The data were recorded on soil parameters, growth attributes, and yield components. The results of the investigation reflected the highest number of capsules per plant, seed weight per plant, and total seed yield achieved through the application of a high level of NPK, combined with 3 tons per hectare of neem seed cake.

Saha *et al.* (2012) observed the response of neem cake and N on wheat yield and uptake. The dry matter yield of wheat improved significantly with the application of neem cake at up to 0.125% and nitrogen at up to 60 mg kg⁻¹.

2.8 Effect of bio-neema on quality, soil properties, and economics of crop

Silva *et al.* (2024) studied the use of neem vegetable cake to increase corn productivity. The study aimed to investigate the effect of neem vegetable cake on the yield attributes of corn at four consistent levels of neem vegetable cake (3, 6, 9, and 12 kg ha⁻¹), and it was compared with a control (no application of organic fertilizers). It was concluded that the application of 12 kg ha⁻¹ of neem cake is economically viable. The results showed that the maximum experimental dose was applied (12 kg ha⁻¹) to get a profit of around R\$119.92 per hectare, compared to the control.

Roshan and Verma (2015) reported that neem-based inputs, including fertilizers, manure, urea coating agents, fumigants, pesticides, and soil conditioners, are highly beneficial for effective pest management and contribute organic matter to the soil.

Saha *et al.* (2012) observed the response of neem cake and N on wheat yield and uptake. The nutrient uptake, such as NPK, through wheat was significantly improved with an N level of up to 60 mg kg⁻¹ neem cake, corresponding to 0.125%. The percentage of available nitrogen, phosphorus, and

organic carbon increased after harvest, particularly with increased nitrogen and neem cake application.

Joseph *et al.* (2010) to determine the safety of neem products to the tetragnathid spider in the rice ecosystem. The mortality of *Tetragnatha mandibulata* and *Tetragnatha maxillosa* when treated with synthetic insecticides, such as triazophos 0.05% and quinalphos 0.05%, was extremely high (56.73% and 35.56%, respectively, for *T. Mandibulata*, and 64.78% and 46.79%, respectively, for *T. maxillosa*). At the same time, imidacloprid 0.005% was found to be safer than the other chemical compounds. The lowest mortality rate was 5% for NSKE. It was discovered that spiders died more when the compounds were applied typically when they come into indirect contact.

Prasad *et al.* (2006) investigated the impact of varying bio-neema rates, combined with inorganic fertilizers, on the chlorophyll, phenol, ascorbic acid, acidity, total soluble sugar, reducing sugar, lycopene, and carotene components in tomatoes. The treatments were set as bio-neema with three levels (2, 4, and 6 g plot⁻¹) and two levels of nitrogen (10.86 and 22.17 g plot⁻¹). The maximum chlorophyll content was recorded at B2N1 (225.76 mg L⁻¹), while the total phenol content was reported to be 280 mg per 100 g of sample. The ascorbic acid, acidity, and total soluble sugar levels were enhanced at B1N2 to the extent of 32.78 mg/100 g, 1.96, 6.2, and 7%, respectively. The lycopene and carotene content were the highest in B2N2 compared to the control.

Saha *et al.* (2012) observed the response of neem cake and N on wheat yield and uptake. The nutrient uptake, such as NPK, through wheat was significantly improved with an N level of up to 60 mg kg⁻¹ neem cake, corresponding to 0.125%. The percentage of available nitrogen, phosphorus, and organic carbon increased after harvest, particularly with increased nitrogen and neem cake application.

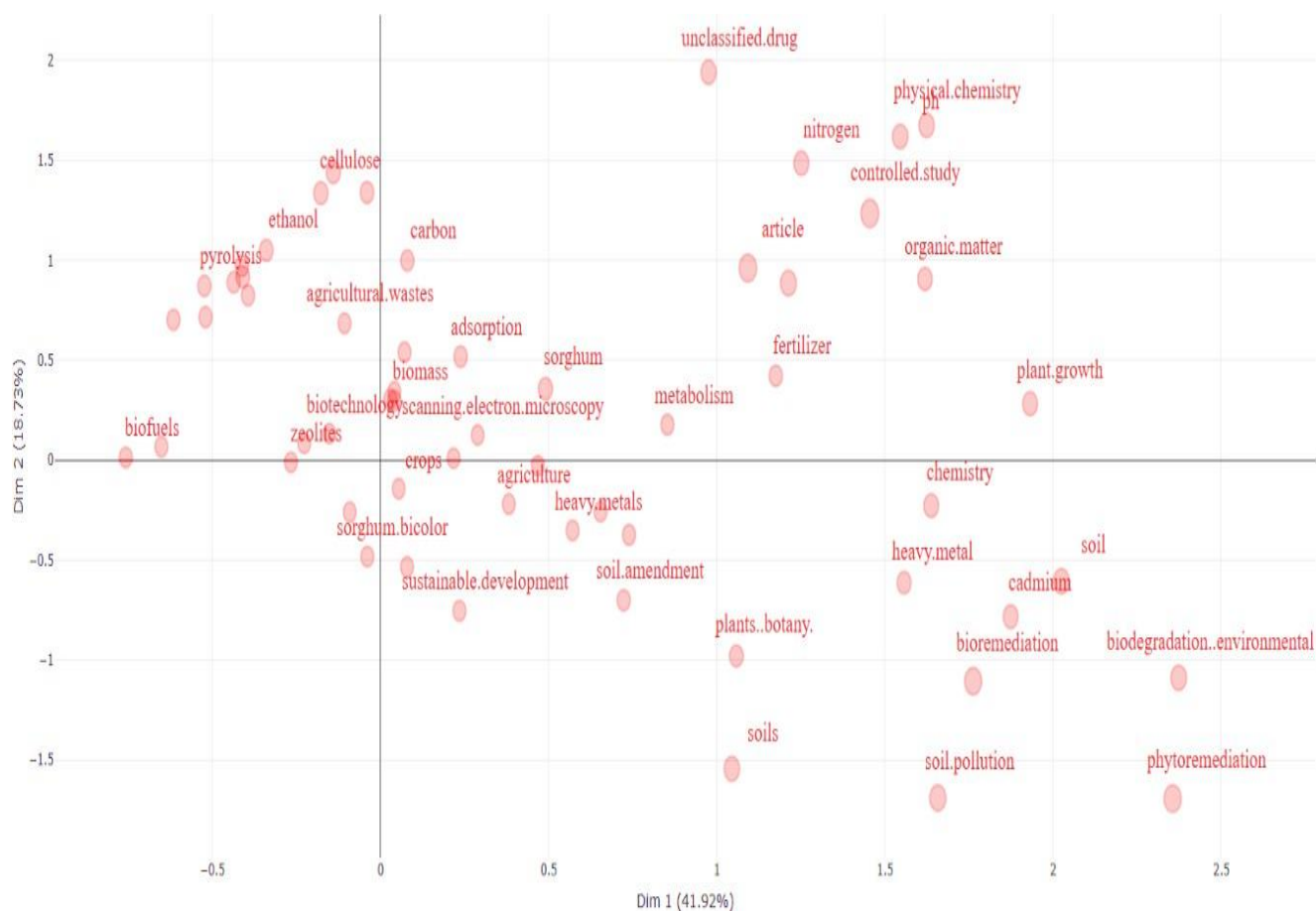
[B] BIBLIOMETRIC

1 Factorial analysis

The bibliometric thematic map from the Scopus dataset shows the conceptual structure of global research trends related to zeolites in agricultural and environmental applications. The two-dimensional visualization, which

explains 41.92% of the variance on Dimension 1 and 16.73% on Dimension 2, displays clear thematic clusters of keywords representing different but connected research areas. The central cluster features the interdisciplinary core concepts of “zeolites,” “biotechnology,” “biomass,” and “agriculture,” indicating how zeolitic materials are integrated into bio-based and sustainable farming systems. The close grouping of terms like “scanning electron microscopy,” “adsorption,” and “biomass” suggests a methodological focus where surface characterization and adsorption studies support experimental research on zeolite performance. On the left side of the map, keywords such as “biofuels,” “ethanol,” “carbon,” and “pyrolysis” cluster together, highlighting a strong link between zeolite research and renewable energy production as well as biomass valorization. These terms point to the use of zeolite catalysts in thermochemical conversion and carbon recycling, promoting circular bioeconomy models. Conversely, the lower right quadrant groups “phytoremediation,” “bioremediation,” “soil pollution,” and “biodegradation,” reflecting a primary research area centered on zeolite-assisted remediation of contaminated soils. This cluster underscores the growing significance of zeolites as environmentally friendly amendments for immobilizing heavy metals, mitigating soil toxicity, and enhancing microbial degradation. The close association among “cadmium,” “heavy metals,” and “soil amendment” underscores the importance of zeolite-based strategies in reducing trace metal contamination, a key issue in sustainable agriculture and environmental management. In the upper right region, keywords like “nitrogen,” “fertilizer,” and “organic matter” co-occur, indicating ongoing interest in nutrient management and improving soil fertility with zeolitic formulations. The inclusion of “plant development” between this cluster highlights the role of zeolites in improvement nutrient retention, water-holding capacity, and complete plant strength. The shift to the right for keywords like as “chemistry,” “physical chemistry,” and “controlled study” showed a focus on fundamental research into ion exchange, adsorption mechanisms, and zeolite modification, which underpin their practical applications. Peripheral themes such as “sorghum,” “crops,” and “agricultural wastes” signify the application of agricultural studies that utilize zeolites as soil incorporation or carriers for

fertilizers, thus supportive sustainable crop management. The co-occurrence of “sustainable development” near “agriculture” and “heavy metals” additional supports the linking between zeolite research and the United Nations Sustainable Development Goals (SDGs), specifically those intensive on clean soil, food security, and environmental recovery. Completely, the thematic map highlights how zeolite research is shifting from material characterization to integrated applications in soil remediation, nutrient management, and biomass utilization. The multidisciplinary linkage within physical chemistry, plant sciences, and environmental biotechnology demonstrate a strong and growing field determined by global sustainability achievement. The interconnected keywords reveal an active research network where innovations based on zeolites support farming that is sustainable, ecological restoration, and the development of clean energy. This inclusive investigation showed that zeolites, with their permeable (porous) structure, high cation exchange capacity, and eco-friendly nature, remain a key material in supporting ecofriendly resilience and agricultural productivity in a variety of scientific field.



2 Trends Topics

A bibliometric dataset from Scopus, visualized through trend-topic mapping, offers a long-term perspective on the evolution of zeolite research from 2000 to 2025, especially its links to bioresource management, environmental science, and agriculture. The thickness and frequency of keywords over time in this visualization demonstrate changes in the focus of the research as well as the rising or falling significance of particular subjects. This analysis highlights a dynamic path: zeolite research has moved from early studies on material combination and physicochemical characterization in the early 2000s to application-focused, interdisciplinary methods that tackle urgent sustainability issues in agriculture and the environment.

Phase 1: Foundations (2000–2010)

During the first decade, research focused on core material properties, and key terms including synthesis, controlled study, and soil.

Furthermore, these highlight an emphasis on understanding zeolite structures, the effect of structure on performance, & the investigation validation of this considerate. On the same time, frequent mentions of cadmium, heavy metals, and adsorption indicate an early focus on zeolites' ability for ion exchange and pollutant immobilization. Their high surface area, cation exchange capacity, and microporous structure made them suitable for soil remediation with eliminating poisonous or toxic metals from water and land systems. Early references to phosphorus, biochar, and soils also suggest initial explorations into nutrient retention—laying the foundation for agricultural applications.

Phase 2: Diversification into Bioeconomy (2010–2015)

Between 2010 and 2015, the thematic scope expanded considerably to include circular bioeconomy principles.

Keywords like as agricultural waste, biofuels, bagasse, pyrolysis, charcoal, and biotechnology became prominent in dendrogram visualizations, indicating a approach shift to waste valorisation and renewable energy. Zeolites have been used as catalytic or support materials in thermochemical conversion processes (e.g., pyrolysis and gasification) to enhance the yield of bio-oils, syngas, and biochar from lignocellulosic biomass. Increased interest in lignin, cellulose, and fermentation signaled a move toward bioconversion technologies for energy and biochemical production. At the same time, progressive investigative methods, particularly scanning electron microscopy and adsorption techniques, gained prominence, displayed advances in nanostructure engineering and surface modification of zeolite composites. This period thus marked a materials science-driven expansion into environmental biotechnology/bioengineering and renewable energy systems.

Phase 3: Integration into Agro-Environmental Systems (2015–2020)

From 2015 to 2020, research increasingly focused on agro-environmental sustainability and bioremediation.

Keywords such as biodegradation, industrial waste, bentonite, soil

pollution, toxic metals, and bioremediation highlight an integrated emphasis on crop and soil health. Simultaneous references to fertilizers, nitrogen, and phosphorus indicate innovation in zeolite-mediated nutrient managing, mostly from controlled-release fertilizers (CRFs) and soil amendments that enhance nutrient retention and break leaching channel through targeted sorption. This period aligns closely along with universal sustainability initiatives, especially the UN Sustainable Development Goals (SDGs), notably SDG 2 (Zero Hunger) and SDG 15 (Life on Land). Zeolites were increasingly used in multifunctional systems that combine waste recycling, soil restoration, and yield improvement. Furthermore, the regular mention of biotechnology recommends a rising attention in microbial immobilization, such as biofilm formation on zeolite surfaces, as a mechanism for nutrient cycling and contaminant degradation.

Phase 4: Consolidation and Climate-Adaptive Solutions (2020–2025)

The most recent period (2020–2025) sees the consolidation of zeolite research into climate-resilient and integrated environmental management frameworks.

Emerging keywords like as waste management, phytoremediation, degradation, biodegradation, and carbon sequestration highlight a systems-oriented approach. Notably, synergistic combinations of zeolites with biochar are being actively explored to rejuvenate degraded soils and remediate pollutants. These hybrid composites demonstrate increased effectiveness in immobilizing heavy metals (e.g., Cd, Pb, Zn), however positively influencing nutrient cycles of soil and microbial diversity. The specifically mention of *Sorghum bicolor* as a model crop suggests that experimental validation of zeolite-based soil treatments in energy and fodder crops may yield promising results, boosting yields, and reducing contaminant uptake.

Post-2020 keyword maps reveal notably larger and denser nodes for terms such as soil, fertilizer, bioremediation, and waste management, indicating intensified research activity driven by urgent global environmental challenges. Biochemical terms such as hydrolysis and degradation now reflect the complex transformation mechanisms at zeolite interfaces, which are mediated by enzymes, microorganisms, or catalytic sites. The continued use of controlled studies and articles (e.g., iTMP-tagged publications) underscores the ongoing

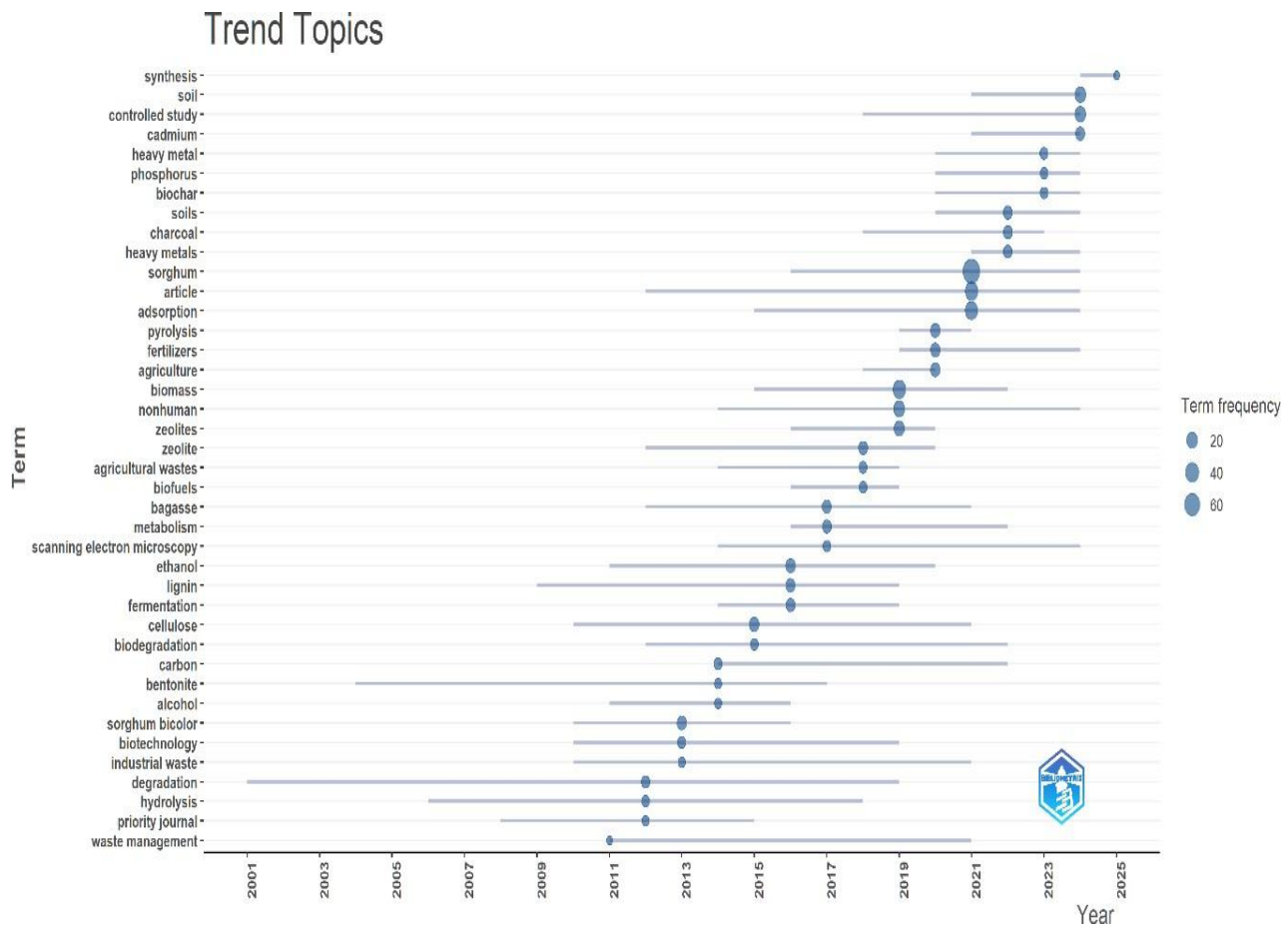
importance of

experimental rigor and scholarly dissemination in translating lab-scale innovations into field applications. Collectively, this temporal analysis shows a clear progression: from material-centric investigations to multidisciplinary, sustainability-driven applications. Zeolites have transitioned from being valued mainly for their adsorption and ion-exchange properties to serving as multifunctional platforms in integrated solutions for soil remediation, waste valorization, renewable energy, and biofertilizer development. Persistent themes—biodegradation, industrial waste, and biofuels highlight their lasting relevance in advancing molecular sustainability across industrial and agricultural sectors.

The increase in post-2020 research coincides with international initiatives to minimize pollution, adopt circular economy concepts and become carbon neutral. Zeolite-based composites, often combined with biochar, bentonite, or nanomaterials, utilize natural abundance, chemical stability, and excellent adsorption capacity to achieve these goals. Future research is expected to focus on zeolite-mediated microbe–mineral interactions, carbon capture processes, and the development of hybrid nanostructures for various environmental applications. The merging of biotechnology, degradation, and waste management further indicates a shift toward bio-catalytic and bio-integrated materials that use zeolite frameworks to improve bioremediation efficiency.

In conclusion, zeolite research has shifted from presence mainly intensive on synthesis to becoming a lively, interdisciplinary field that links materials science, environmental engineering, and agricultural biotechnology. The growing diversity of keywords and increasing term frequencies reflect a rapidly changing and highly active area. Zeolites now help as a critical connection between environmental restoration and sustainable agriculture, by applications spreading beyond adsorption to include catalysis, nutrient management, and microbial support. Looking forward, the integration of advanced zeolitic materials driven by digital monitoring (such as IoT-based soil sensors) and advanced biotechnological modifications offers excellent potential. The next frontier will probably be shaped by advancements in circular agricultural systems and zeolite-

biochar composites, which will position zeolite science as catalyst for global sustainability and climate conscious resources management in addition to being a symbol of scientific advancement



CHAPTER-III

Methods and materials

The investigation entitled “Investigating the synergistic impact on press-mud, zeolite, bio-neema and Nano NPK on the growth, productivity, and quality of Sweet Sorghum (*Sorghum bicolor* (L.) Moench)” was conducted during the *Kharif* seasons of 2023-24 and 2024-25 at the “Agriculture farm, School of Agriculture, Lovely Professional University, Phagwara, Punjab”. This chapter provides a concise description of the experimental materials and techniques used in the course of the investigation.

3.1. Location of experimental site

The experimental site was located at a latitude of 31°22'31.81" N and a longitude of 75°23'03.02" E with an average elevation of 252 m above mean sea level. The location falls under the central plain zone of Punjab's agro-climatic zones (Fig. 3.1).

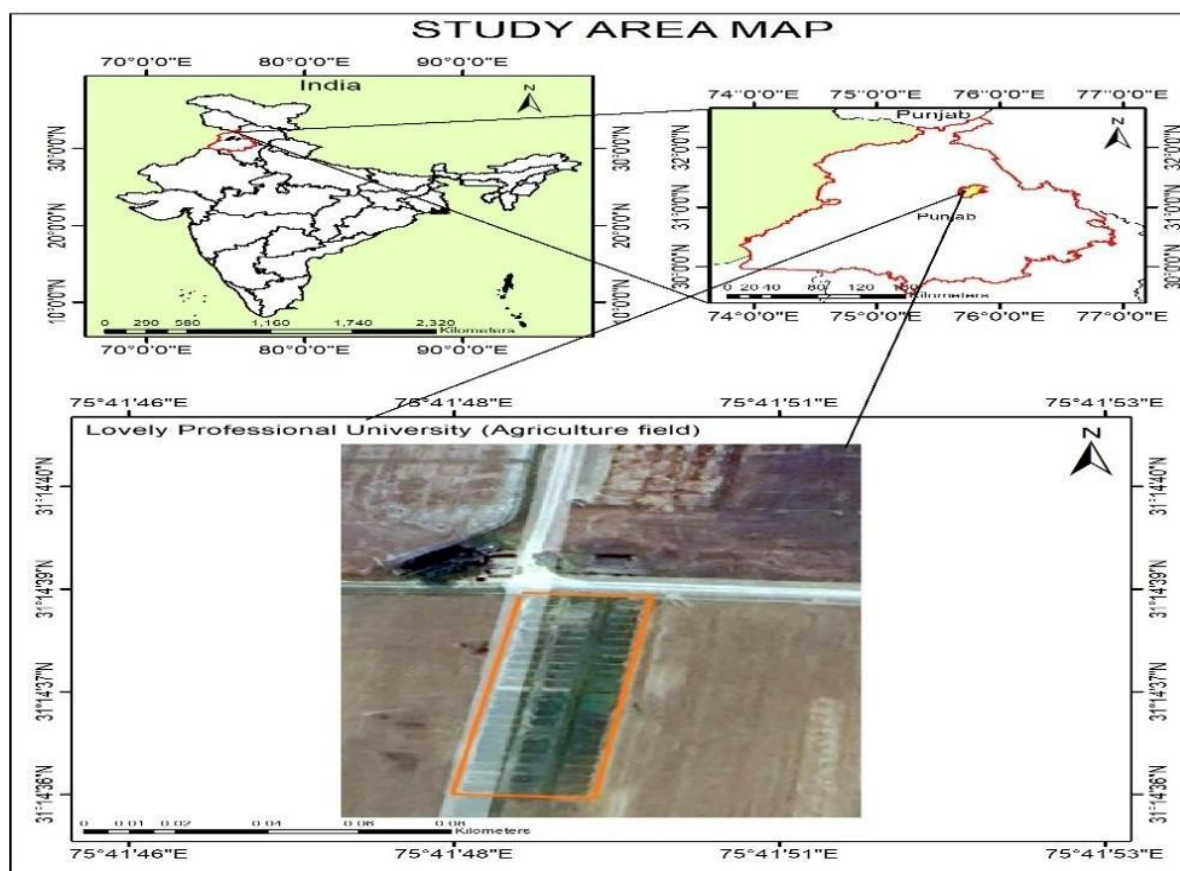


Fig-3.1. Location of the field and real-time view.

3.2 Weather observation at the experimental site

The climate in Phagwara is classified as sub-tropical with low rainfall and cold winters. In this region, the monsoon season typically begins in the first fortnight of July, continues through to September, and then subsides in the second week of October. From September onwards, there is a decline in rainfall, and temperatures in November to January are very cool in this region.

The average weekly weather data on total rainfall (mm), average maximum, minimum temperature (C), average maximum and minimum relative humidity (%), and weekly total pan evaporation (mm week) for the period during the cropping season were recorded at automated weather station of LPU (Phagwara), Jalandhar, Punjab are presented in Appendices I and II.

In *Kharif*, the mean weekly maximum temperature during the *Kharif* season was 34.03°C, while the minimum temperature was 23.93°C in 2023. The maximum temperature reached 35.56°C, and the minimum temperature was 24.82°C, both recorded during the *Kharif* season of 2024. In *Kharif* 2023, the mean weekly maximum relative humidity was 89.24%, while the minimum humidity was 60.66%. In *Kharif* 2024, the maximum relative humidity was 89.53%, while the minimum was 61.02%. The average wind speed was 4.64 km h⁻¹ in 2023, while the minimum wind speed was 5.79 km/h, recorded during the *Kharif* season of 2024. In *Kharif* 2023, the 27th standard week recorded the maximum rainfall of 153.20 mm, followed by the 30th and 31st weeks. In *Kharif* 2024, the maximum rainfall for the 33rd standard week was 33 mm, followed by the 32nd and 34th weeks. In *Kharif* 2023, the total rainfall was 466.5mm, and the total evaporation was 479.53mm. In the *Kharif* 2024 season, the total rainfall was 133.90 mm, and the total evaporation was 846.30 mm. Accordingly, the standard metrological week, during *Kharif* 2023, showed the highest evaporation in the 25th meteorological week and the lowest in the 32nd meteorological week. During 2024, the maximum evaporation was 25 meteorological weeks, followed by 24 meteorological weeks, and the lowest was recorded in the 33rd meteorological week, followed by the 43rd meteorological week. The average number of sunshine hours was 6.38 hours per day in 2023 and 6.81 hours in 2024 (Fig. 3.3).

Appendix I: Meteorological data during crop growth period (4 June 2023 - 30 October 2023)

Standard weeks	T. Max (°C)	T. Min (°C)	RH Max (%)	RH Min (%)	Wind speed (km hr ⁻¹)	Rain (mm)	Evaporation (mm)	Sunshine (hrs)
<i>Kharif season 2023</i>								
23	37.57	22.14	81.86	34.57	5.29	22.8	40.4	11.34
24	36.29	23.71	82.43	45.86	3.57	41.2	34.6	9.56
25	37.86	27.57	82	51.57	2.57	16.2	43.4	5.86
26	35.71	27	82.86	56.14	2.57	2.2	33.2	4.71
27	33.57	25.29	86.71	65.57	3	153.2	15.3	4.57
28	33.57	25.86	88.43	66.14	7	11.2	27.2	2.5
29	34.57	27.43	86.43	70	5.71	49.6	23.5	2.01
30	33.57	27	90.86	72.71	4.29	60	12.5	3.27
31	35.43	27.59	90.86	68.71	5.57	60.6	15.5	5.91
32	34.29	26.86	90.29	73	4.29	5.8	3.23	4.21
33	34.71	27.29	90.57	72.14	5.57	1.8	28.4	5.79
34	34.71	26.86	92	70	4.43	0	18.7	5.01
35	33.57	26.48	91.71	64.29	5.16	11	22.1	8.91
36	34.92	24.71	92	60.86	5.2	0	32.4	10.27
37	34.24	25.99	91	70	4.28	4	19.7	3.01
38	31.65	23.93	92	71.08	3.96	15.9	18.4	3.07
39	33.76	21.21	93	60.23	4.37	2.4	24.1	9.3
40	33.79	17.79	92.51	48.48	5.76	0	4.4	9.83
41	32.33	18.7	91.89	53.21	4.47	6.6	22.1	8.39
42	28.19	15.46	92.01	52.2	4.94	2	20.3	8.44
43	30.27	13.71	92.59	47.06	5.4	0	20.1	7.96

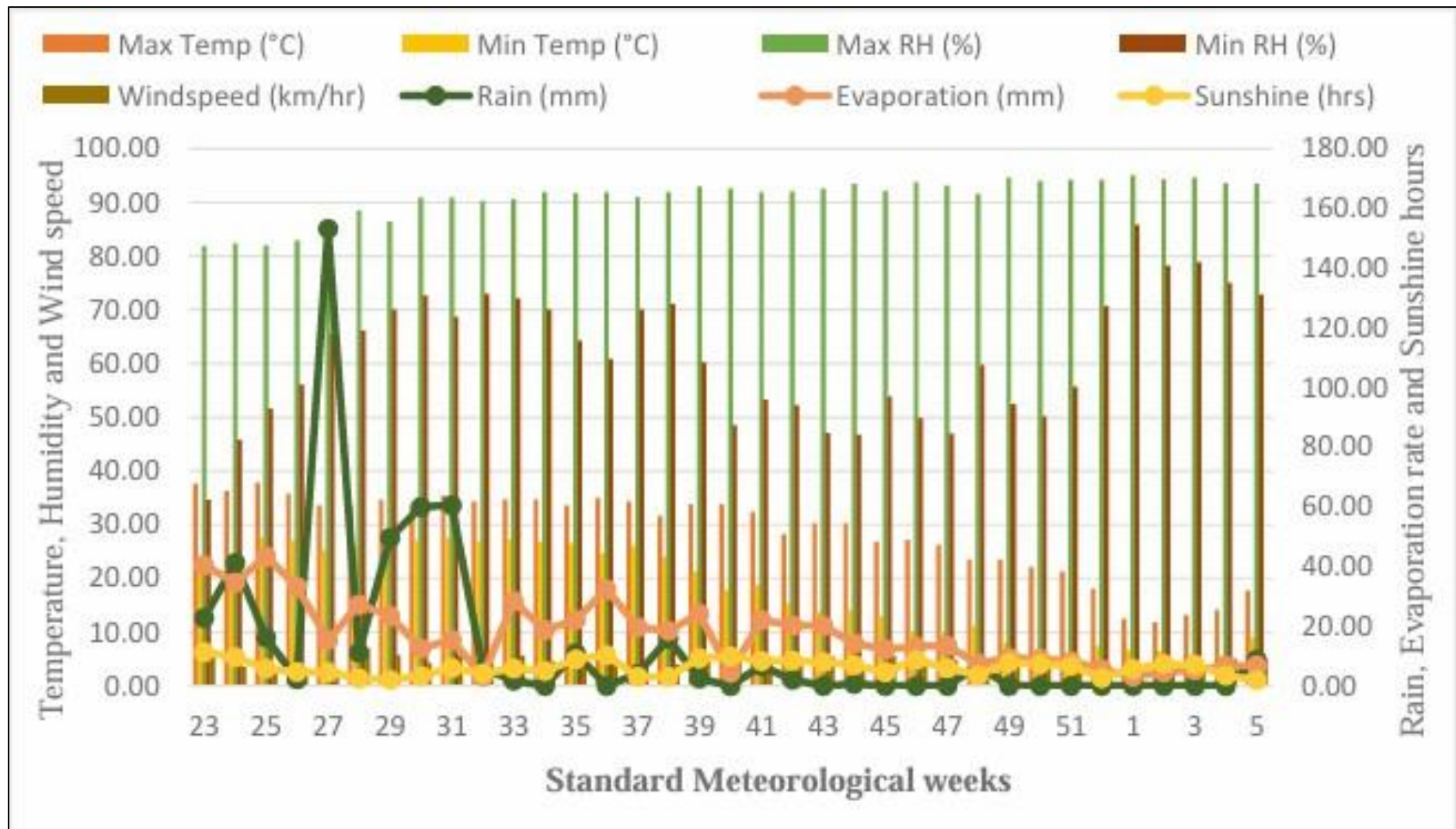


Fig. 3.2: Weekly meteorological data during the crop growth (4 June 2023 to 30 October 2023)

Appendix-II: Meteorological data during crop growth period (4 June 2024 to 30 October 2024)

Standard weeks	T. Max (°C)	T. Min (°C)	RH Max (%)	RH Min (%)	Wind speed (km hr ⁻¹)	Rain (mm)	Evaporation (mm)	Sunshine (hrs)
<i>Kharif season 2024</i>								
23	39.81	23.25	75.9	28.6	8.85	9.3	76.1	6.28
24	43.36	25.66	71.07	26.66	12.45	0	90.1	6.48
25	39.85	27.05	72.69	39.72	10.13	0	91.5	8.23
26	36.99	27.33	85.34	58.41	7.62	2.8	77.3	9.2
27	33.92	26.62	88.29	70.12	10.13	3.8	28.1	3.43
28	36.06	27.11	90.59	62.8	6.07	0	42.4	4.7
29	37.37	28.47	88.04	64.92	4.89	1.4	39.5	5.47
30	35.44	27.46	89.72	72.14	4.89	0	38.1	5.32
31	35.88	28.01	93.15	76.09	5.07	10.7	33	5.79
32	33.9	27.05	90.78	73.5	6.48	15.6	28	5.76
33	32.79	26.77	93.54	74.98	5.61	33.6	18	5.32
34	34.76	26.14	94.78	73.06	4.37	28.2	33.1	6
35	33.65	25.31	94.33	72.38	5.04	3.3	33.8	5.85
36	33.69	26.38	95.12	74.81	4.06	11.4	29.3	6.6
37	34.74	25.15	93.95	69.54	4.11	2.4	29.1	7.51
38	34.54	24.35	94.08	64.34	2.83	0	31.5	7.34
39	33.93	24.82	94.08	68.96	3.5	1.4	33	6.8
40	35.45	21.87	94.24	61.64	4.01	10	25.5	9.23
41	33.6	18.13	93.33	50.96	3.91	0	25.3	9.26
42	34.13	17.81	93.39	46.93	3.24	0	22.9	9.36
43	32.8	16.47	93.64	50.9	4.27	0	20.7	9.11

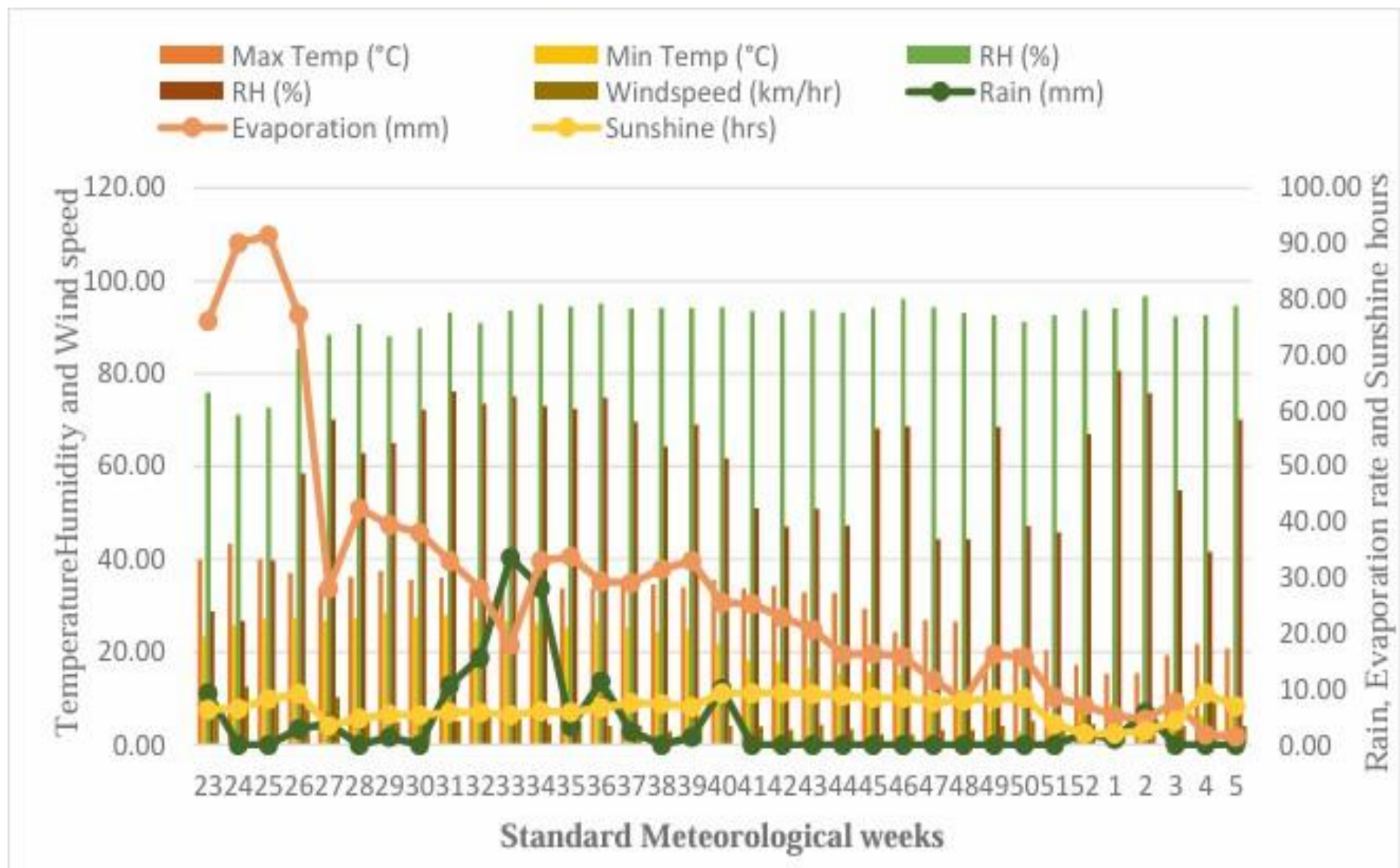


Fig. 3.3: Weekly meteorological data during the crop growth (4 June 2024 to 30 October 2024)

Table: 3.1 Soil physico-chemical properties of the experimental site (0-30 cm depth)

Properties	Analysis value	Methods	
A. Mechanical composition			
Sand (%)	74.0	International pipette method (Black & Evans, 1965)	
Silt (%)	9.3		
Clay (%)	15.7		
Texture	Sandy loam		
B. Chemical analysis			
pH	7.89	Slightly alkaline	pH meter (Jackson, 1967)
EC (dS m ⁻¹)	0.387	Normal	Conductivity bridge (Jackson, 1967)
Organic carbon (%)	0.28	Low	Walkley and Black’s rapid titration method (Jackson, 1967)
Available Nitrogen (kg ha ⁻¹)	239.30	Low	Alkaline permanganate method (Subbiah & Asija, 1965)
Available Phosphorus (kg ha ⁻¹)	23.3	Low	0.5 N Sodium bicarbonate extractant method Olsen’s method (1954)
Available Potash (kg ha ⁻¹)	249.70	Low	Flame photometer method (Jackson, 1973)

3.2 Cropping history of the experimental field

The cropping patterns followed in the experimental field for the previous five years and the year of experimentation are detailed in

Table 3.2 Cropping history of the experimental field

Year	<i>kharif</i>	<i>Rabi</i>
2020	Green gram	Wheat
2021	Fallow	Wheat
2022	Maize	Wheat
2023	Research experiment	Nill
2024	Research experiment	Nill

3.4 Details of Experimental

The study was conducted using a Randomized block design, with experiments carried out over two consecutive *kharif* seasons in 2023 and 2024. Each experiment had three replications and consisted of ten different treatment arrangements. For a visual depiction and further information on the experiments (Table 3.3)

3.4.1 Treatment Details

(A) *Kharif* season (2023-2024) T1: Control (absolute)

T2: 100% recommended dose of fertilizers

T3: 75% recommended dose of fertilizers + Zeolite (1.5 t ha^{-1}) T4: 75 recommended dose fertilizers + Press-mud (15 t ha^{-1})

T5: 75 recommended dose fertilizers + Zeolite (1.5 t ha^{-1}) + Press-mud (15 t ha^{-1})

T6: 75 recommended dose fertilizers + Zeolite (1.5 t ha^{-1}) + Press-mud (15 t ha^{-1}) + Bio-neema (5 kg ha^{-1})

T7: Nano NPK (19:19:19) + Zeolite (1.5 t ha^{-1}) T8: Nano NPK (19:19:19) + Press-mud (15 t ha^{-1})

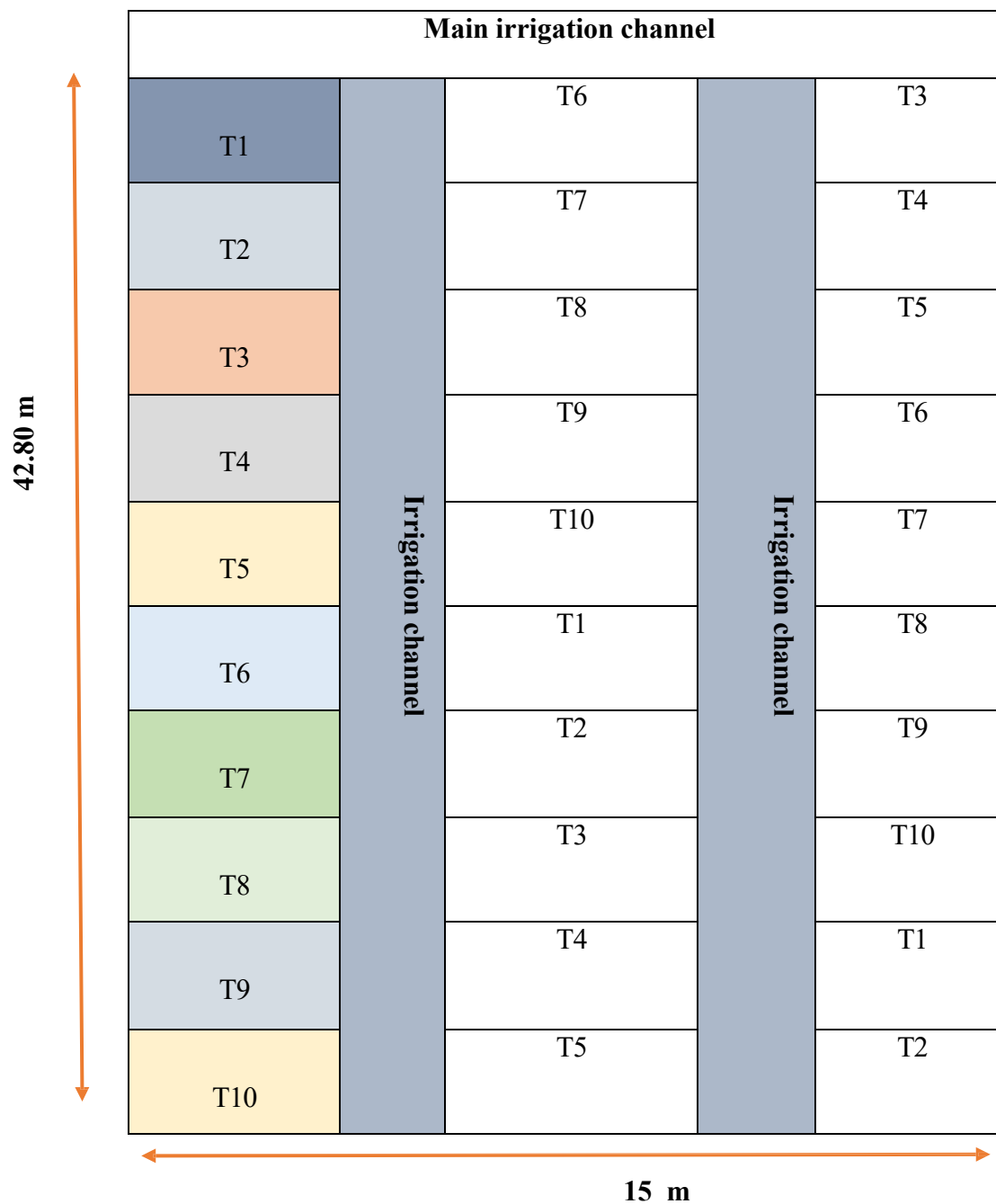
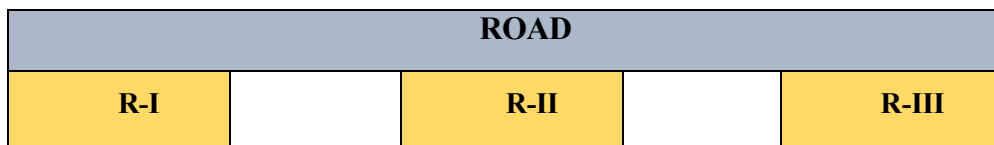
T9: Nano NPK (19:19:19) + Zeolite (1.5 t ha^{-1}) + Press-mud (15 t ha^{-1})

T10: Nano NPK (19:19:19) + Zeolite (1.5 t ha^{-1}) + Press-mud (15 t ha^{-1}) + Bio-neema (5 kg ha^{-1})

Table 3.3 Details of experimental field

Year and season	:	<i>Kharif</i> in 2023 and 2024
Design of experiment	:	Randomized block design
Number of replications	:	3
Number of treatments	:	10
Variety	:	SSV-84
Gross plot area	:	$4 \times 6.5 = 26\text{m}^2$,
Net plot area	:	$3 \times 4.05 \text{ m}^2 = 12.15\text{m}^2$
Crop	:	Sweet sorghum
Spacing of crops	:	$45 \times 15 \text{ cm}^2$
Seed rate	:	7.5 kg ha^{-1}

Field Layout



3.5 Cultural operations

The schedule of several cultural activities carried out during the investigation is provided below under different headings and their corresponding dates.

3.5.1 Field preparation

The field was prepared once the soil had reached a suitable working condition. The field was firstly ready using a tractor-drawn plough, followed by two passes with a cross harrow to achieve a well-pulverized seedbed. The weed and crop residues were eliminated to create a weed and stubble-free seedbed. The area was finally levelled using a tractor-driven leveller. The field was then laid out to accommodate 10 treatment combinations in each replication. The experimental plot was laid out in accordance with the specifications detailed in the layout plan. During the Kharif season, field preparation was conducted after harvesting the preceding crop. Two ploughing treatments were carried out, and then the land was planted.

Table 3.4 Cultural operation performed during the experimentation of field

Operations	2023	2024
One ploughing with a disc plough	14/07/2023	01/07/024
One ploughing with a harrow	16/07/2023	07/07/2024
Layout preparation	18/07/2023	12/07/2024
Date of sowing	20/07/2023	14/07/2024
30% germination	25/07/2023	20/07/2024
50% germination	27/07/2023	22/07/2024
100% germination	30/07/2023	24/07/2024
1 st Irrigation	05/08/2023	30/07/2024
Weeding	08/08/2023	03/08/2024
Spraying of insecticide	11/08/2023	07/08/2024
2 nd Irrigation	14/08/2023	08/09/2024
A single hoeing intercultural operation was performed	13/08/2023	17/08/2024
3 rd Irrigation	31/08/2023	18/08/2024
4 th Irrigation	23/09/2023	08/09/2024
One spray of Difenconazole and Azoxystrobin	26/09/2023	12/09/2024
Flower initiation	02/10/2023	12/10/2024

Fully panicle initiation	10/10/2023	19/10/2024
Day to maturity	05/11/2023	3/11/2024
Finally harvest	15/11/2023	9/11/2024

3.5.2 Characteristics of test crop variety

SSV-84

It is a selection through sorghum IS-23658. It was released in 1992 by the Agricultural Research Institute, Rahuri, Maharashtra. It can be cultivated throughout India with limited water and minimal input. The taller plant varied in height from 270 to 285 cm, with drooping leaves, a semi-compact ear head, and was freely threshable. It had relatively high rate of photosynthesis and was tolerant to charcoal rot and shoot fly, and was rich in fermentable sugars, with levels as high as 15-18 percent. The duration of the variety is 120-125 days. It can yield 40-60 tonnes of green stalk yield and 22-28 quintal grain per hectare

3.5.3 Seed treatment

The seeds of all three varieties were treated with Captan @ 2 g kg⁻¹ to overcome soil and seed-borne diseases.

3.5.4 Sowing method and Spacing

After field preparation, seeds were sown on 10 July 2023 and 13 July 2024, according to the respective crop spacing. Sowing was performed manually by planting seeds according to the recommendations on the packages and practices of IIMR. Sweet sorghum was sown manually at a spacing of 45 x 15 cm to a depth of 4-

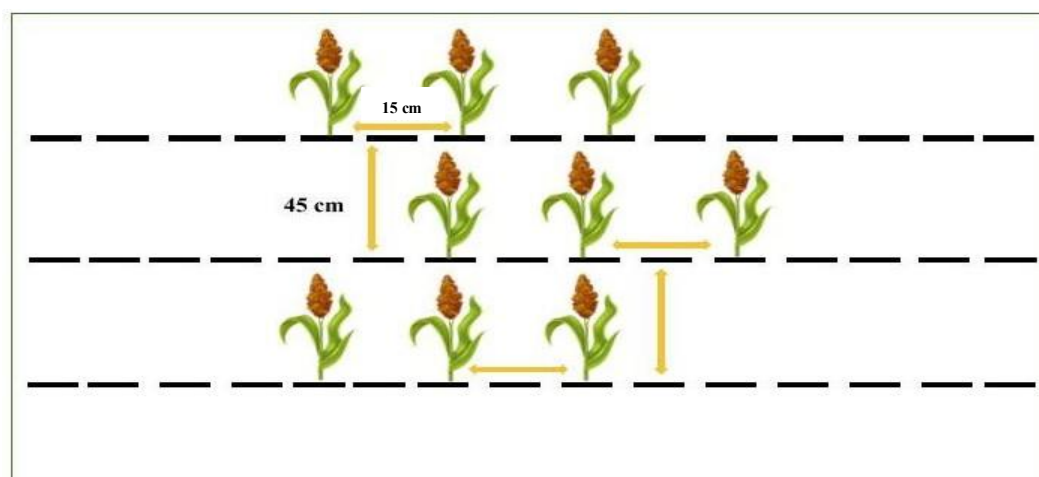


Plate 3.1: Geometry of plant

5 cm. A week after emergence, the seedlings were thinned to maintain two healthy seedlings per hill. Finally, thinning was done two weeks after crop emergence to maintain one seedling per hill (Plate 3.1)

3.5.5 Irrigation

The crop was grown in multiple rows in proportion, and irrigation was supplied at the critical stage of moisture.

3.5.6 Nutrient Management

The entire amounts of P_2O_5 and K_2O fertilizers were applied as a basal dressing at planting time in sweet sorghum. The nitrogen was split into three equal portions; the first one-third was applied at sowing time, and the remaining two portions were divided in half and applied at 30 and 60 days after sowing. Phosphorus (P_2O_5) was applied through single superphosphate; potash was applied through muriate of potash, and nitrogen through urea. Nano NPK (19:19:19) was applied at 30, 60, and 90 days after sowing @ 4 g l⁻¹ of water. Zeolites were correctly mixed into the soil at the time of crop sowing according to the respective treatments. Press-mud and Bio-neema were applied before 1.5 months of sowing of the crop on a dry basis according to the treatments (Table 3.5). The recommended dose of fertilizers for sweet sorghum was 90:40:40 kg N: P_2O_5 : K_2O , Nano NPK @ 4 g l⁻¹ of water, Zeolite (1.5 t ha⁻¹). Press-mud (15 t ha⁻¹) and Bio-neema (5 kg ha⁻¹). The quantity of fertilizers was dependent on the treatment arrangement and the respective fertilizer levels.

Table 3.5 Amount of Nutrient applied in the experimental field

Nutrient level	Sweet sorghum (N, P_2O_5 , K_2O) kg ha ⁻¹
Control	Absolute zero
100%RDF	90:40:40
75 % RDF	63:28:28
Zeolite (1.5 t ha ⁻¹)	1.5 t ha ⁻¹
Press-mud 15 t ha ⁻¹	15 t ha ⁻¹
Bio-neema	5 kg ha ⁻¹
Nano NPK	4 g l ⁻¹

3.5.7 Interculture Operations

The intercultural operations, including thinning, hoeing, weeding, top dressing, and earthing up, were completed on schedule. Crop thinning was performed 10 days after seed germination to prevent overcrowding of the plants. Hand weeding was conducted at 25 and 45 days after sowing (DAS). Earthing up in sweet sorghum was done at the knee height growth stage. Top dressing was applied at 30 and 60 days after sowing.

3.5.8 Plant Protection

Shoot fly is a major insect of sweet sorghum, which was controlled through the application of endosulfan 35 EC periodically, and for the stem borer control, carbofuran (3% granules) @ 3 kg ha⁻¹.

3.5.9 Harvesting

Harvesting was done at the physiological maturity of the crop. Samples from each plot of the plants were collected before the crop was harvested for post-harvest studies. The stalk was cut close to the ground level, and later, the ear heads were separated. The brix percentage was recorded before cutting the stalk. Labourers did the harvesting using a sickle.

3.5.10 Threshing

The selected plant was cut, and the separated ear head was manually removed from the stalk. The weight of that stalk was used for juice extraction. The separated seeds are completely sundried, weighed, and maintained at a consistent moisture level of 14%. The sweet sorghum seed yield was converted to quintal per hectare, and the fresh stalk was presented in tonne per hectare.

3.6 Collection of Experimental Data

3.6.1 Biometric observations

Biometrical observation was recorded at various growth stages, viz., 30, 60, 90, and at harvest of the crop. Five plants were randomly selected and tagged in each treatment across all replications for recording growth, yield, and quality traits. Quality parameters, such as Brix ratio, juice extraction percentage, bagasse content, and weight, were recorded at harvest and at subsequent harvests.

3.6.1. Pre-harvest observations of sweet sorghum

3.6.1.1 Plant height (cm)

The plant height (cm) was measured from the ground level to the base of the fully opened top leaf till panicle emergence. Later, plant height was recorded from the base of the plant to the base of the flag leaf and expressed in centimeters. The sum was then divided by five to determine the mean plant height.

3.6.1.2 Number of leaves p^{-1}

The total number of green leaves produced was counted in five plants and taken as the number of leaves per plant at 30, 60, 90, and at harvest. The average value was calculated, and the reported number of leaves per plant was stated.

3.6.1.3 Total dry matter (g plant⁻¹)

The plants were dug out from the experimental field and dried in the sun. The samples were then oven-dried at 60°C for 72 hours, after which the weight became constant. The dry matter accumulation per plant was calculated at 30, 60, and 90 DAS, as well as at the harvesting stage.

3.6.1.4 Leaf area (cm²)

The leaf area of plant-1 was measured from the five tagged plants in each plot at intervals of 30, 60, 90 days after sowing, and at harvest. The leaf area was measured in cm² with the help of a leaf area meter.

3.6.1.5 Chlorophyll index (SPAD)

Chlorophyll content, measured by a chlorophyll meter (SPAD502 plus), was recorded at 30, 60, and 90 days after sowing (DAS) for each of five plants per plot, and the mean of these values was calculated.

3.6.1.6 Stem diameter (mm)

Stem diameter will be recorded from the five tagged plants in each plot by using vernier callipers at 30, 60, 90 DAS, and at harvest, and expressed in millimetres (mm).

3.6.1.7 Number of internodes

The total number of internodes was counted randomly in five plants, and their average was taken as the number of internodes per plant

3.6.1.7 Internodes length (cm)

Internode length (cm) of the stem was measured from five selected plants in each treatment at the bottom, middle, and top, and the average was expressed as the length of the internode (cm)

3.6.2 Post-harvest observation

Five plants and ears were randomly selected from each plot, and all the post-harvest observations were recorded from these chosen ears.

3.6.2.1 Ear head length (cm)

Length of the ear head of sweet sorghum from randomly selected ear heads in each treatment was measured from the base of the lowest primary spikelet to the tip of the ear head, and the average was recorded as ear head length (cm).

3.6.2.2 Ear head girth (cm)

The circumference of the ear head from five randomly selected ear heads was measured at the bottom, middle, and top of the ear head, and the average was recorded as ear head girth/diameter in cm.

3.6.2.3 Number of grains ear head⁻¹

Grains per earhead⁻¹ was worked out by using the formula Number of grains earhead⁻¹ = Number of spikelet's × Number of seeds spikelet.

3.6.2.4 Grains weight ear head⁻¹ (g)

Grains were separated from the sun-dried ear head of five randomly selected plants and then weighed. The average weight was recorded in g earhead⁻¹.

3.6.2.5 1000 grains weight (g)

A thousand grains were randomly taken from each treatment and dried in the oven. The weight of the oven-dried sample was recorded using a sensitive measuring balance and expressed as the test weight in grams.

3.6.2.6 Grain yield (q ha⁻¹)

At physiological maturity, the ear heads were collected from each experimental plot. The harvested ear heads were dried in the air, shelled, cleaned, and weighed. Grain yield ha⁻¹ was calculated from kg plot⁻¹, which was converted to q ha⁻¹.

3.6.2.7 Stalk yield (t ha⁻¹)

At harvest, the fresh weight of stalk after separating leaves and ear head from the plant in each net plot was recorded and expressed in tonnes ha⁻¹

3.6.3 Estimation of quality parameters

3.6.3.1 Juice extraction (%) (Parvatikar & Manjunath, 1991)

The juice extraction percentage was calculated as an average by taking an average of five selected plants. Fresh stalks were crushed using a manual sugarcane juicer, and then the quantity of juice and the weight of the residual plant material, known as bagasse, were measured. Use this equation to determine the ultimate juice %.

$$\text{Juice extraction (\%)} = 100 \times \frac{\text{Stalk Yield (kg ha}^{-1}\text{)} - \text{Bagasses Yield (kg ha}^{-1}\text{)}}{\text{Stalk Yield (kg ha}^{-1}\text{)}}$$

3.6.3.2 Fresh bagasse's content (%)

After the juice extraction from the stalk's remaining portion, known as the bagasse's content, was measured in percentage by using this equation

$$\text{Bagasse's content (\%)} = 100 - \text{Juice extraction percentage}$$

3.6.3.3 Fresh bagasse's yield (t ha⁻¹)

Later, the remaining portion of the juice extraction is referred to as the fresh bagasse yield. It was calculated by using the formula and expressed in tonnes per hectare.

$$\text{Fresh Bagasse's Yield (t ha}^{-1}\text{)} = \frac{\text{Fresh Stalk (t ha}^{-1}\text{)} \times \text{Fresh Bagasses's Content (\%)}}{100}$$

3.6.3.4 Brix (%)

It indicates the total soluble solids in the sample. It was determined by using a hand refractometer and the room temperature (27.5 °C) at the time of observation, and values were expressed as a percentage

3.6.3.5 Juice pH

The juice pH was determined using a pH meter, following the procedure outlined by Mathur (1978).

3.6.3.6 Juice yield (l ha⁻¹)

It was calculated by using the following formula and expressed in liters per hectare

$$\text{Juice Yield (l ha}^{-1}\text{)} = \frac{\text{Fresh Stalk (kg ha}^{-1}\text{)} \times \text{Juice Extraction (\%)}}{100}$$

3.6.3.7 Sugar yield (t ha⁻¹) (Uchino et al., 2013)

The total sugar yield depended on juice yield and Brix ratio. It was calculated in tonnes per hectare by using the equation.

$$\text{Sugar yield (t ha}^{-1}\text{)} = (\text{brix (\%)} \times 0.8746) + 0.15166/100 \times \text{Juice yield (kl/ha)}$$

3.6.3.8 Estimated potential ethanol yield (kl ha⁻¹) (Spencer & Meade, 1963)

The following equation determined the potential ethanol yield, and it depended on juice yield and Brix ratio

$$\text{Potential ethanol yield} = \text{Juice yield (l ha}^{-1}\text{)} \times \text{brix (\%)} / 100 \times 0.85/1.76$$

Where: 0.85/1.76 is the factor of the coefficient used for calculating the potential ethanol yield

3.6.3.9 Total sugar Index (Mathur, 1978)

Total sugar includes both reducing sugars (glucose, fructose) and non-reducing sugars (sucrose)

Prepare solution

- Fehling A: Copper sulphate (34.639 g) in distilled water (500 ml)
- Fehling B: Sodium potassium tartrate (173 g Rochelle salt) + 53 g of NaOH in 500 ml distilled water

Standardization

- Titrate Fehling solution against standard glucose solution to determine the sugar factor (mg glucose per ml)

Titration of juice

- Take 100 ml of juice
- Add standard Fehling solution and heat
- Titrate with standard glucose until the blue colour disappears
- Calculate total reducing sugar

3.6.3.10 Reducing sugar

The reducing and non-reducing sugars in the juice sample were estimated using the procedures described by Lane and Eynon (1970), respectively, and expressed as a percentage.

$$\text{Reducing sugar (\%)} = \text{titrate value} \times 0.05 \times \text{Dilution factor} / \text{Weight of volume sample} \times 100$$

3.6.3.11 non-reducing sugar (%)

Non-reducing sugar (sucrose) is calculated by difference after acid hydrolysis

- Take the volume of juice
- Add dilute HCl (5 ml of 0.1 N HCl) and heat in a water bath (70 °C for 5-10 min)
- Neutralize with NaOH.

$$\text{Non-reducing sugar (\%)} = (\text{Total sugar after hydrolysis} - \text{initial reducing sugar}) * 0.95)$$

Where 0.95 is a factor that accounts for the water molecule added during the hydrolysis

3.6.4 Analysis of quality in the plant

3.6.4.1 Nitrogen content in grains (%)

The nitrogen content of oven-dried samples was determined using the Modified Kjeldahl method (Jackson, 1967).

$$\text{Nitrogen content (\%)} = \frac{N \times \text{Volume of 0.1N H, SO, used} \times \text{Dilution factor}}{1000 \times \text{weight of sample (g)}}$$

$$\text{Crude protein (\%)} = \text{Percent Nitrogen content} \times 6.25$$

3.6.4.2 Protein content in grains (%)

The protein content was calculated by multiplying by 6.25 and the nitrogen percentage of the grains

$$\text{Protein (\%)} = \text{nitrogen (\%)} \text{ in grains} * 6.25$$

3.6.4.3 Nitrogen content in plant (%)

The nitrogen content of oven-dried samples was determined using the Modified Kjeldahl method (Jackson, 1967).

3.6.4.4 Phosphorus content of seed and plant (%)

Analysis of phosphorus in the seed and plant, take one g of powder sample, was digested in triacid mixture ($\text{HNO}_3 + \text{H}_2\text{SO}_4 + \text{perchloric acid}$) and presented in percentage on a dry basis (Jackson, 1973)

3.6.4.5 Potassium content in seed and plant (%)

The potassium content in seeds and straw was determined using the flame photometer method, as described by Jackson (1967), and is expressed as a percentage on a dry weight basis.

3.6.4.6 Ash content (%)

The ash content was estimated using the AOAC methodology (1990). A 5g sample was initially incinerated on a hot plate until no further smoke was observed. The sample was placed in a crucible and then heated in a muffle furnace at 550°C for 5 hours. Afterward, the weight of the residue was measured, and the result was expressed as a percentage.

3.6.4.7 Hemicellulose percentage (%) Table 3.5: Material required

Sulfuric acid
Natural detergent solution (ADS)
Acetone
Muffle furnace
Oven
Desiccator
Balance equipment
Plant sample
Sieve

Procedure:

- Weight of sample and transfer into the glassware (W1)
- Boil the sample with a natural detergent solution for 1 hour,
- Wash with hot water and acetone (W2),
- then dry at 550° C to constant weight (W3)

$$\text{NDF (Natural detergent fibre \%)} = (W2-W3)/W1 * 100$$

3.6.4.8 Cellulose (%) (Ronney and Hans, 2007)

Procedure =

- Boil the natural detergent fibre (NDF) in the acid detergent solution (ADS) for one hour
- Filter, wash, dry at 550°C, and weight (W4)

$$\text{ADF (Acid detergent fibre \%)} = (W4-W2)/W1*100$$

3.6.4.9 Lignin (%)

- Treat ADF residue with 72% H₂SO₄ for 3 hours
- Wash, filter, dry at 550 °C, and weigh (W₅)

$$\text{ADL (Acid detergent lignin \%)} = (W_5 - W_2) / W_1 \times 100$$

Final calculation of Hemi-cellulose, cellulose, and lignin

$$\text{Hemi-cellulose\%} = \text{NDF (\%)} - \text{ADF (\%)}$$

$$\text{Cellulose} = \text{ADF (\%)} - \text{ADL (\%)}$$

$$\text{Lignin} = \text{ADL (after removal of ash from ADF)}$$

3.6.4.10 Chlorophyll content in leaves (mg g⁻¹) (Arnon, 1949)

The quantitative estimation of chlorophyll a and chlorophyll b was carried out using Arnon's method (1949). 1 g of fresh leaf material was taken, homogenized with 80% acetone, and centrifuged at 5000 rpm for 10 min. The Supernatant was adjusted to 25 ml in the volumetric flask. The absorbance of this extraction solution was measured at 663 and 665 nm. These readings of the concentrations of chlorophyll pigment were determined by using the following equation:

$$\text{Chlorophyll a mg g}^{-1} = \frac{12.7(A_{663}) - 2.69(A_{665}) \times V}{1000} \times W$$

$$\text{Chlorophyll b mg g}^{-1} = \frac{22.9(A_{665}) - 4.68(A_{663}) \times V}{1000} \times W$$

Where, A Absorbance at a specific wavelength, V Final volume of chlorophyll extraction, W Fresh weight of the sample

3.6.5 Analytical analysis

3.6.5.1 FTIR analysis of sorghum juice (Griffiths *et al.* 2012)

For sorghum juice, FTIR spectrum analysis was carried out.

Sample and Preparation:

Green stalks of *Sorghum bicolor* were harvested at physiological maturity and taken to the laboratory within one hour. The stalks were washed with distilled water to remove the surface pollutants and dried in the air at room temperature. Juice was obtained by crushing the stalks mechanically in a roll-type juice extractor. The juice was filtered with Whatman No. 1 filter paper to separate any suspended solids. The filtrate was collected and stored in an amber bottle at 4 °C ± 1 °C until assayed within

24 hours to prevent degradation of the composition.

Concentration and Drying:

Thereafter, for solid-state FTIR measurement, it was necessary to reduce the interference of water during spectral acquisition. Since a small amount of juice was diluted to achieve a specific volume, a portion of this juice was concentrated under reduced pressure at 40°C using a rotary evaporator. Some samples were freeze-dried (lyophilized) for solid-state FTIR analysis to obtain a dry powder, which provided superior spectral resolution.

Sample Preparation for FTIR: Two methods were used according to the state of the samples:

- Liquid Samples: ca. 2-3 μL of the juice was placed directly on the surface of the diamond ATR (attenuated total reflectance) of the FTIR spectrometer. The crystal was washed with ethanol and dried with lint-free tissue before each measurement.

FTIR Measurement and Apparatus:

FTIR spectra were measured with a (Model-Spectrum 2 PerkinElmer) outfitted with an ATR attachment. Spectra were acquired in the mid-infrared region of 4000–400 cm^{-1} at a spectral resolution of 4 cm^{-1} from 32 scans per sample. Background spectra were acquired before each producing run and automatically subtracted to compensate for atmospheric CO_2 and H_2O interference. The collected spectra were processed using (software name, e.g., OMNIC or OriginPro), and then baseline-corrected, normalized, and smoothed as necessary. Absorbance bands for critical functional groups, e.g., O–H stretching (3300 cm^{-1}), C–H stretching (2920 cm^{-1}), C=O stretching (1740 cm^{-1}), and C–O–C vibrations (1030 cm^{-1}) were determined for the sorghum juice, which in turn describes the biochemical behaviour of sorghum juice material. Evidence for the presence of sugars, amino acids, organic acids, and phenolic compounds was drawn from standard reference spectra.

3.6.5.2 TGA analysis of sweet sorghum seed powder

TGA analysis of sorghum seed powder was performed using the TGA 4000 PerkinElmer, as described earlier by Dhyan *et al.* (2017)

3.6.5.3 EDX analysis of sweet sorghum seed powder

EDX analysis and elemental mapping of sorghum extract were conducted using the OXFRD X-MaxN as the earlier described method outline by (Sutjaritvorakul *et al.* 2023). We put around 2–3 μL of the extract on the diamond ATR (attenuated total reflectance) of the FTIR spectrometer. Before each measurement, the crystal was washed with ethanol and dried with a tissue that didn't leave any lint.

3.6.6. Soil bio-chemical analysis

A composite sample was collected from a 0- to 15-cm soil depth in the experimental field at the initiation of the study to determine the soil fertility status. All the samples were oven-dried, ground, and sieved. (Table 3.6).

Table 3.6. Methods used for nutrient content analysis in soil

S.N.	Nutrient	Method
1.	Available N (kg ha^{-1})	Alkaline permanganate method (Subbiah and Asija, 1956)
2.	Available P_2O_5 (kg ha^{-1})	Olsen's method (Olsen et al., 1954)
3.	Available K_2O (kg ha^{-1})	Flame photometric method (Hanwy and Heiddle, 1952)

3.6.5.4 pH

A composite sample was collected from a 0- to 15-cm soil depth in the experimental field at the initiation of the study to determine the soil fertility status. All the samples were oven-dried, ground, and sieved (Jackson, 1973).

3.6.5.5 Electrical conductivity

The electrical conductivity of the soil samples will be measured in a 1:2.5 soil-to-water extract using a conductivity bridge, and the results will be expressed in terms of dS m^{-1} at 25°C (Jackson, 1973).

3.6.5.6 Organic carbon

The organic carbon content in the soil will be determined using the Walkley and Black wet oxidation method (Jackson, 1973) and expressed as a percentage (%).

3.6.5.7 Microbial count (cfu g⁻¹ 10⁴)

A more accurate and straightforward method for determining the microbial count is the plate method, where a food sample is placed on a culture medium plate. The number of colonies that have developed on the culture media plate can be counted after a suitable incubation period

3.6.5.8 Dehydrogenase activity ($\mu\text{g TPF g}^{-1} \text{ soil h}^{-1}$) (Casida et al., 1964)

Dehydrogenase activity can be measured using different tetrazolium salts, such as 2,3,5-triphenyltetrazolium chloride (TTC), as an artificial terminal hydrogen acceptor in the electron transport chain. This is reduced to red-coloured triphenyl formazan (TPF).

3.6.5.9 Ureases activity ($\mu\text{g NH}_4\text{-N g}^{-1} \text{ soil h}^{-1}$) (Tabatabai and Bremner 1972)

The ureases activity was determined adopting the procedure given by Tabatabai and Bremner (1972). It involves the determination of ammonia released by ureases activity when soil is incubated with tris (hydroxymethyl) amino methane (THAM) buffer, urea solution and toluene at 37 C for 2 hr, ammonia released being determined by a rapid procedure involving treatments of the incubated soil sample with 2.3M KCL containing a ureases inhibitor (Ag_2SO_4).

3.6.5.10 Available nitrogen (kg ha^{-1})

Available nitrogen in soil, determined after crop harvesting, was determined through the Alkaline Permanganate method (Subbiah & Asija, 1956)

3.6.5.11 Available Phosphorus (kg ha^{-1})

Available phosphorus in soil, determined after crop harvesting, was determined by using Olsen's method (Olsen *et al.* 1954)

3.6.5.12 Available Potassium (kg ha^{-1})

Available potassium in soil, determined after crop harvesting, was determined using the Flame photometer method (Hanway and Heidel 1952)

3.6.6 Various indices

3.6.6.1 Leaf Area Index (LAI)

The leaf area index (LAI) is calculated as the ratio of leaf area to ground area,

and the formula provided by Watson (1947) was used to determine this value at each stage.

$$\text{Leaf area Index} = \frac{\text{Total leaf area of Plant (cm}^2\text{)}}{\text{Total ground area of Plant (cm}^2\text{)}}$$

3.6.6.2 Crop growth rate (g m⁻² day⁻¹)

Crop growth rate (g plant⁻¹day⁻¹) is the rate of dry matter production per unit ground area per unit time and was computed between 0-30, 30-60, 60-90 DAS by the formula given by Watson (1952).

$$\text{CGR (g m}^{-2} \text{ d}^{-2}\text{)} = \frac{W_2 - W_1}{t_2 - t_1} \times \frac{1}{p}$$

Where W₁ and W₂ are the dry weights per unit area at times t₁ and t₂, and P area in cm, respectively.

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

Relative growth rate (g g⁻¹ day⁻¹) is the rate of increase in the dry weight per unit dry weight per unit of time and was calculated at 30-60, 60-90 DAS by the formula given by Watson (1952).

$$\text{CGR (g m}^{-2} \text{ d}^{-2}\text{)} = \frac{\log_n W_2 - \log_n W_1}{t_2 - t_1} \times \frac{1}{p}$$

Where, Loge = logarithm to the base e W₁ and W₂ = Dry matter production per plant (g) at time t₂ and t₁, respectively. t₁ and t₂ = time intervals.

3.6.7 Economics Observation

Economic studies of production were conducted by keeping a record of the operations carried out, the number of laborers engaged, and the power and inputs utilized. The standard cultivation expense was determined based on rates fixed by the government. The gross returns, net return per hectare, and benefit-to-cost ratio were calculated using the following formula.

3.6.7.1 Cost of cultivation

In computing the economics, different variable cost items will be considered treatment-wise, including the cost of land preparation, seeds, fertilizers, plant protection measures, and irrigation costs. Labour required for sowing, irrigation, weeding, top dressing, spraying, harvesting, threshing, juice extraction, making

bioethanol and sugar, etc., will be calculated based on prevailing market prices.

3.6.7.2 Gross return

Gross return will be calculated by multiplying grain and sugar yield, ethanol, and bagasse's yield of sweet sorghum (t ha^{-1}) with the prevailing market price and expressed in rupees per hectare (₹ ha^{-1}).

3.6.7.3 Net return

The net return will be calculated by deducting the cost of cultivation from the gross return and expressed in rupees per hectare (₹ ha^{-1}).

3.6.7.4 Benefit-cost ratio

The benefit-cost ratio will be calculated by dividing the gross return (₹ ha^{-1}) by the cultivation cost.

$$\text{Benefit Cost ratio } (\text{₹ ha}^{-1}) = \frac{\text{Gross Return } (\text{₹ ha}^{-1}) - 2.69 (\text{A665}) \times V}{\text{Cost of Cultivation } (\text{₹ ha}^{-1})}$$

Note: The methodological procedures are adequately described; however, the scientific justification for the selection of treatment doses and combinations is not sufficiently elaborated

✚ The treatment doses and combinations were selected based on published literature, recommended agronomic practices, and the complementary functions of each nutrient source. The 100% RDF served as the standard fertilizer practice, while 75% RDF was included to assess the potential for reducing chemical fertilizer use. Press-mud (15 t ha^{-1}), zeolite (1.5 t ha^{-1}), bio-neema (5 kg ha^{-1}), and Nano NPK (19:19:19) were selected for their roles in improving soil fertility, nutrient retention, microbial activity, nutrient use efficiency, and overall crop performance.

3.7 Statistically analysis

The data were analysed and interpreted using Fisher's analysis of variance methods as reported Gomez and Gomez (1984). The **least significant difference** (LSD) was determined at a significance level of $p \leq 0.05$ with **r-Studio software** used to compute the means of the treatment and graphical representation through **origin lab pro**.

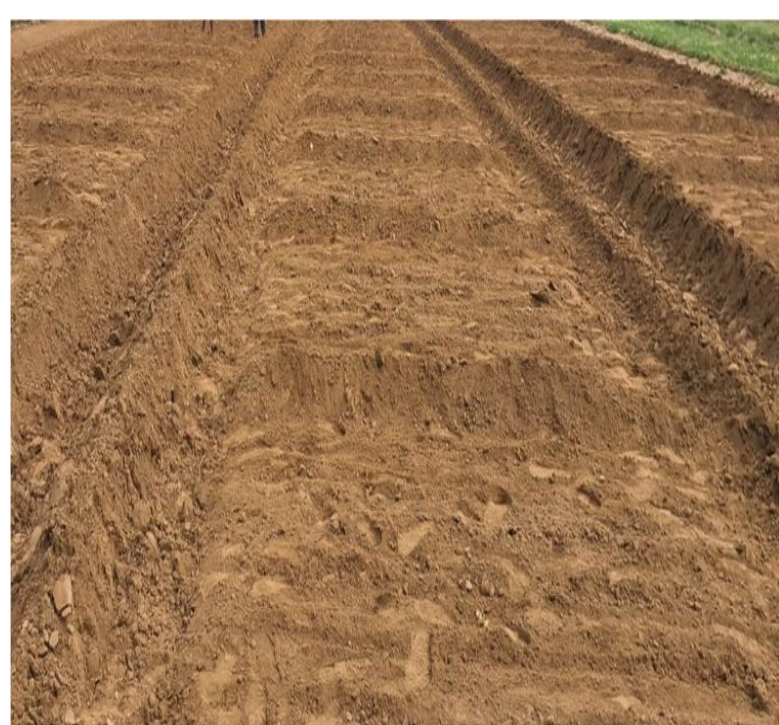


Plate 1: Layout Preparation



Plate 2: Application of Zeolite



Plate 3: Foliar Application of Nano NPK



Plate 4: Measured Chlorophyll Index (SPAD)



Plate 5: Measured plant height



Plate 6: Field Irrigation



Plate 7: Measured brix ratio



Plate 8: Measured stem diameter



Plate 9 : Plant sample after harvest



Plate 10: Juice extraction



Plate 11: Measured 1000 grains



Plate 12: Grains sample



Plate 13: Soil sample collection after harvest



Plate 14: Soil pH



Plate 15: Chemical preparation for analysis of phosphorus



Plate 16: Sample preparation for chlorophyll content analysis



Plate 17: Sample preparation for analysis of dehydrogenases activity

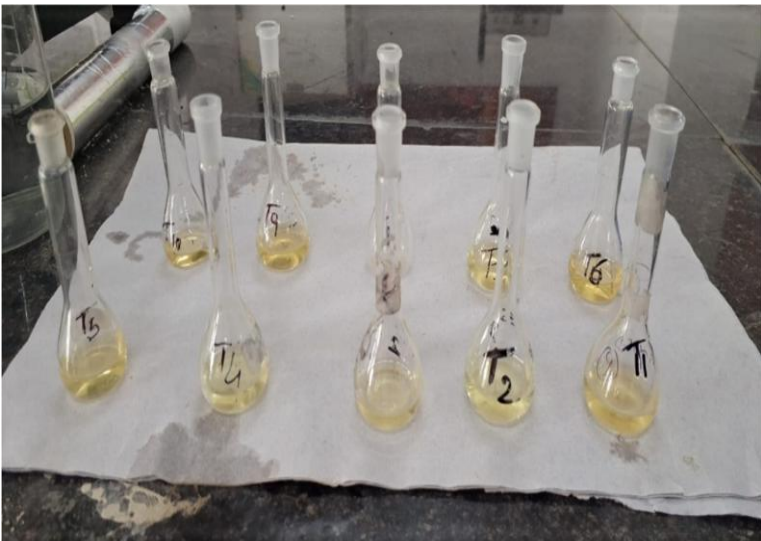


Plate 18: Sample preparation for analysis of urease activity



Plate 19: Measured titration reading



Plate 20: Doing titration

CHAPTER-IV

Result and discussion



The results obtained during investigation entitled “**Investigating the synergistic impact on press-mud, zeolite, bio-neema and Nano NPK on the growth, productivity, and quality of Sweet Sorghum (*Sorghum bicolor* (L.) Moench)**” was conducted during the *Kharif* season 2023 and 2024 at Agricultural research farm, School of Agriculture, Lovely Professional University, Phagwara, Punjab, have been described in this chapter and statistical edge. The biometric observation of different parameters, including on- and off-field assessment data related to various treatments, is verified for its significance using standard statistical methods, providing a rationale for the presented investigation. The mean weekly values of weather parameters and input-output constants are presented in the appendices. The findings of the appended study have been presented as follows

4.1. Morphological parameters

Key abiotic factors, including temperature, rainfall, sunlight, and soil, influence ecosystem productivity. Indicate that seasonal conditions during the growth period of the crop were normal. The 2024 season was more favorable than usual, with optimum temperatures ranging from 32.1 to 43.9 °C (highest) and 16.80 to 28 °C (lowest), along with suitable and distributed rainfall and solar radiation, which are ideal for sweet sorghum growth and development, resulting in a maximum grain yield and related traits. Both seasons experienced a minimum occurrence of severe pest and disease issues. The physical characteristics of the soil were conducive to the growth of sweet sorghum. The soil had a slightly acidic, low available nitrogen, medium phosphorus, and low available potassium. In this experiment, sweet sorghum showed positive responses to various levels of nutrients, along with bio-neema, in terms of growth, yield, and quality attributes.

4.1.1 Plant height (cm)

Plant height is a crucial indicator of plant growth, providing an immediate comparison of the different treatments (Table 1). The effect of varying nutrient management treatments on plant height was statistically significant across all growth stages.

At 30 DAS, treatment T₂ displayed the most significant plant height, measuring 42.63 cm in 2023 and 43.76 cm in 2024. This was significantly higher than the control (T₁), which recorded the lowest values (27.03 cm and 26.71 cm, respectively). Similarly, at 60 DAS, T₂ maintained the tallest plants (149.27 cm in 2023 and 150.52 cm in 2024), outperforming the control (117.17 cm and 119.82 cm, respectively), and was statistically comparable to T₂ (146.73 cm and 148.53 cm, respectively). Treatments T₇, T₈, T₉, and T₁₀ were found to be statistically similar to each other.

At 90 DAS, T₆ continued to show the highest plant height (222.16 cm in 2023 and 228.77 cm in 2024), followed closely by T₂ (218.17 cm and 222.02 cm), both significantly greater than the control (141.19 cm and 140.50 cm). At harvest, T₆ again recorded the maximum plant height (239.07 cm in 2023 and 242.88 cm in 2024), followed by T₂ (233.50 cm and 240.68 cm). The control (T₁) showed the lowest measurements (152.52 cm and 151.16 cm). These results indicate the superior performance of T₆, and to a lesser extent T₂, in promoting plant growth under the given agro-climatic conditions.

The application of inorganic fertilizers, along with press-mud, zeolite, and bio-neema, increased the plant height (cm) of sweet sorghum. Zeolite can promote plant growth by increasing the long-term availability of water and nutrients due to its porous structure, which stores water and raises humidity levels in the rhizosphere, thus aiding root development and boosting plant height (Samijan *et al.* 2024). Meanwhile, press mud and bio-neema help create a sustainable environment for plant growth, providing an adequate supply of macro- and micronutrients along with organic carbon (Khaliq *et al.* 2024; Ram *et al.* 2024).

Table 4.1 Effect of different nutrient management strategies on plant height (cm) of sweet sorghum.

Treatments	30 DAS		60 DAS		90 DAS		At harvest	
	2023	2024	2023	2024	2023	2024	2023	2024
T1	27.03	26.71	119.82	117.18	141.19	140.50	152.52	151.16
T2	42.63	43.76	149.27	150.52	218.17	222.02	233.50	240.68
T3	40.05	37.94	136.21	141.23	205.54	211.67	219.16	234.62
T4	39.76	37.01	134.63	138.06	200.52	204.85	211.81	217.18
T5	40.76	39.31	141.92	143.76	208.88	210.10	218.54	221.59
T6	41.29	41.18	146.73	148.53	222.16	228.77	239.07	242.88
T7	31.59	34.26	125.04	126.68	184.51	190.54	199.29	202.32
T8	28.91	34.60	131.23	132.13	187.00	189.52	198.55	202.40
T9	28.99	32.40	128.76	129.54	185.94	191.26	199.60	202.59
T10	31.16	37.92	129.35	134.14	191.50	195.93	205.49	206.59
SEm ($\pm$)	1.26	1.16	1.94	1.66	1.67	1.47	1.40	1.31
LSD (p=0.05)	3.74	3.46	5.76	4.94	4.97	4.36	4.17	3.89

T1-* Control (Absolute), T2-*100 % RDF (90:40:40 NPK), T3-*75 % RDF +Zeolite (1.5 t ha^{-1}), T4-*75 % RDF +Press-mud (15 t ha^{-1}), T5-*75 % RDF +Zeolite (1.5 t ha^{-1}) +Press-mud (15 t ha^{-1}), T6-*75 % RDF +Zeolite (1.5 t ha^{-1}) + Press-mud (15 t ha^{-1}) +Bio-neema (5 kg ha^{-1}), T7-*Nano NPK (19:19:19) +Zeolite (1.5 t ha^{-1}), T8-*Nano NPK (19:19:19) + Press-mud (15 t ha^{-1}), T9-*Nano NPK (19:19:19) + Zeolite (1.5 t ha^{-1}) + Press-mud (15 t ha^{-1}), T10-* Nano NPK (19:19:19) + Zeolite (1.5 t ha^{-1}) +Press-mud (1.5 t ha^{-1}) +Bio-neema (5 kg ha^{-1}). SEm-*Standard. Error of Mean, LSD (p=0.05) -* Least Significant Difference at 5 % significance level

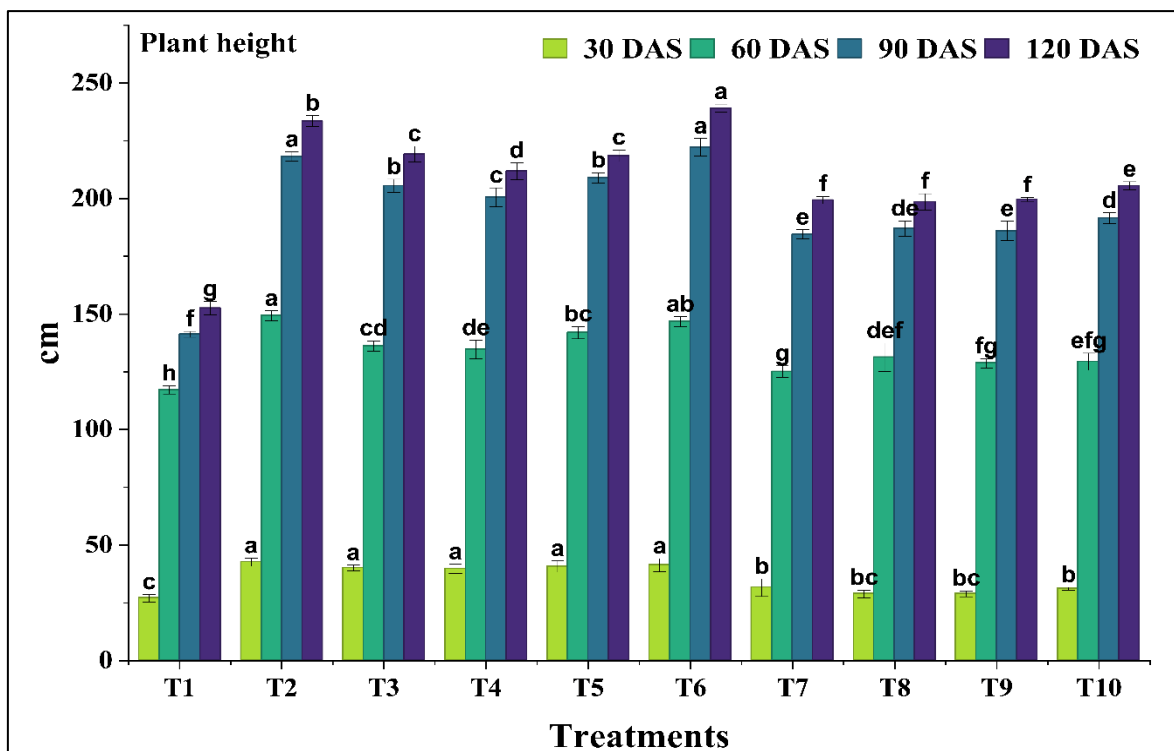


Fig 4.1: Effect of different nutrient management practices on plant height (cm) at 30, 60, 90, and at harvest of sweet sorghum in 2023

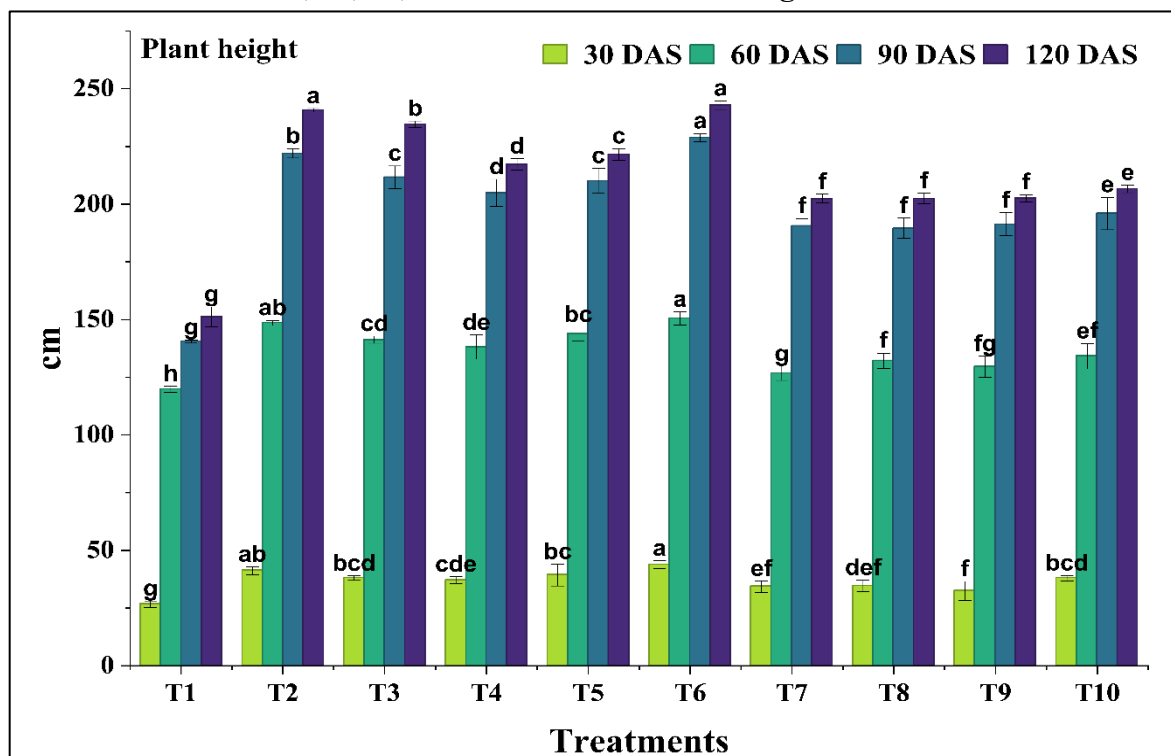


Fig 4.2: Effect of different nutrient management practices on plant height (cm) at 30, 60, 90, and at harvest of sweet sorghum in 2024

4.2. Stem diameter (mm)

Different nutrient management treatments affected the data on stem diameter of sweet sorghum at 30, 60, 90, and at harvest in 2023 and 2024 (Table 2).

The effect of different nutrient management treatments on stem diameter (mm) was statistically significant across all growth stages. At 30 DAS, treatment T₆ exhibited the greatest plant diameter, measuring 5.82 mm in 2023 and 5.72 mm in 2024. This was significantly higher than the control (T₁), which recorded the lowest values (3.36 mm and 3.20 mm, respectively). Similarly, at 60 DAS, T₆ maintained the maximum diameter (20.00 mm in 2023 and 21.75 mm in 2024), outperforming the control (12.29 mm and 11.75 mm, respectively), which was statistically comparable to T₅ (19.05 mm and 19.79 mm, respectively). Treatments T₇, T₈, T₉, and T₁₀ were found to be statistically similar to each other.

At 90 DAS, T₆ continued to exhibit the highest stem diameter (22.33 mm in 2023 and 22.96 mm in 2024), statistically on par with T₅ (21.25 mm and 22.05 mm), both of which were significantly greater than the control (16.30 mm and 15.73 mm). At harvest, T₆ again recorded the maximum plant diameter (23.00 mm in 2023 and 23.09 mm in 2024), which was statistically comparable to T₅ (22.91 mm and 22.49 mm), T₄ (21.14 mm and 21.30 mm), and T₂ (21.23 mm and 22.17 mm). T₁ showed the lowest measurements of stem diameter (16.39 mm and 15.98 mm). These results indicate the superior performance of T₆, and to a lesser extent, T₂, T₃, T₄, and T₅, in promoting plant growth under the given agro-climatic conditions.

Applying the recommended doses of fertilizers along with press-mud, zeolite, and bioneema ensures optimal nutrient supply for growth, promoting balanced uptake of nitrogen, phosphorus, and potassium essential for cell division, stem elongation, and width. Incorporating press-mud, zeolite, and bio-neema with RDF further boosts soil fertility and physiological efficiency (Shahsavari *et al.* 2014). Press-mud, rich in organic matter and micronutrients, improves soil structure, aeration, and microbial activity, leading to better root growth and nutrient absorption (Ram *et al.* 2024). Zeolite enhances cation exchange capacity and water retention, reducing nutrient leaching and providing steady nutrient availability throughout growth. These amendments work together to improve soil moisture and increase photosynthetic efficiency, resulting in higher assimilate translocation and thicker stems (Silva *et al.* 2024).

Table 4.2 Effect of different nutrient management strategies on stem diameter (mm) of sweet sorghum.

Treatments	30 DAS		60 DAS		90 DAS		At harvest	
	2023	2024	2023	2024	2023	2024	2023	2024
T1	3.36	3.20	12.29	11.75	16.30	15.73	16.39	15.98
T2	4.01	4.86	16.03	16.10	20.81	21.67	21.23	22.17
T3	4.27	4.62	16.60	16.48	20.50	20.20	20.94	21.18
T4	4.22	3.92	16.97	17.46	20.04	20.13	21.14	21.30
T5	5.45	5.11	19.05	19.79	21.25	22.05	22.91	22.49
T6	5.82	5.72	20.00	21.75	22.33	22.96	23.00	23.09
T7	3.81	3.83	14.41	14.73	18.31	18.66	18.94	19.36
T8	4.20	3.84	14.31	14.80	18.83	18.91	19.87	20.00
T9	4.06	4.12	14.66	14.83	19.00	19.00	19.95	20.35
T10	4.32	4.75	15.00	16.00	19.18	19.6	20.15	20.62
SEm ($\pm$)	0.27	0.33	0.59	0.69	0.54	0.66	0.57	0.63
LSD (p=0.05)	0.80	0.98	1.76	2.04	1.61	1.95	1.69	1.88

T1-* Control (Absolute), T2-*100 % RDF (90:40:40 NPK), T3-*75 % RDF +Zeolite (1.5 t ha⁻¹), T4*75 % RDF +Press-mud (15 t ha⁻¹), T5-*75 % RDF +Zeolite (1.5 t ha⁻¹) +Press-mud (15 t ha⁻¹), T6-*75 % RDF +Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹) +Bio-neema (5 kg ha⁻¹), T7-*Nano NPK (19:19:19) +Zeolite (1.5 t ha⁻¹), T8-*Nano NPK (19:19:19) + Press-mud (15 t ha⁻¹), T9-*Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹), T10-* Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) +Pressmud (1.5 t ha⁻¹) +Bio-neema (5 kg ha⁻¹). SEm-*Standard Error of Mean, LSD (p =0.05)-* Least Significant Difference at 5 % significance level.

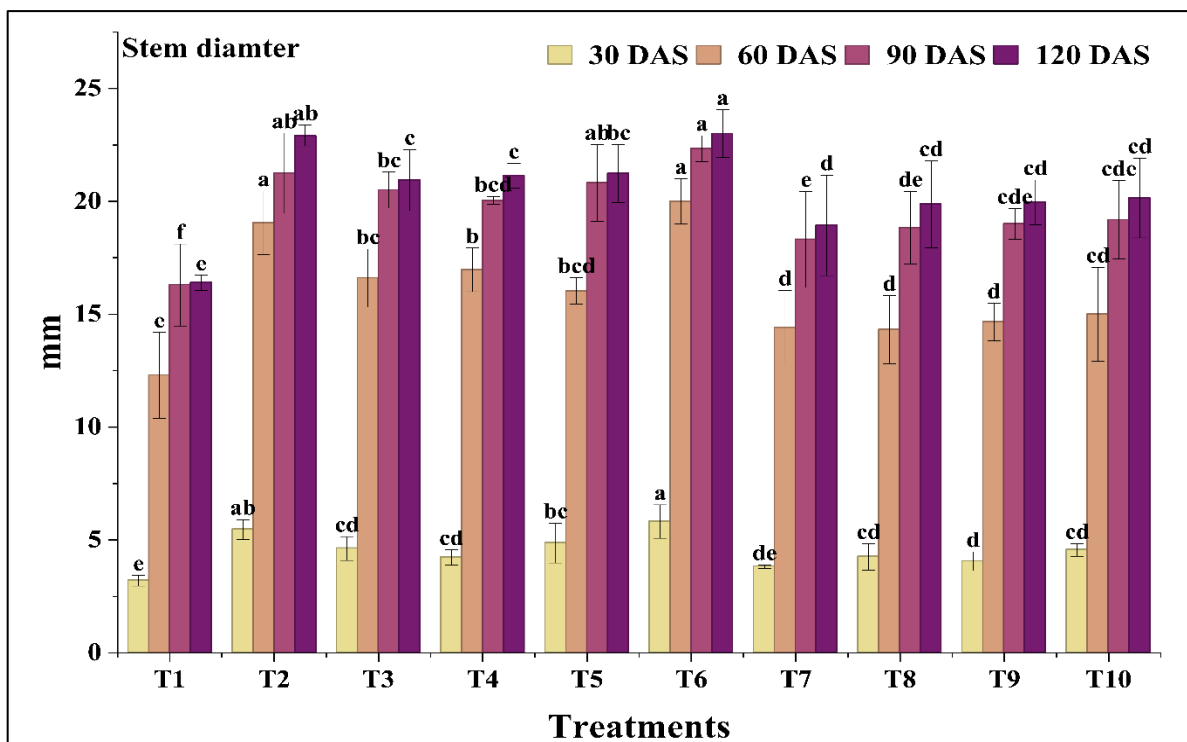


Fig 4.3: Effect of different nutrient management practices on stem diameter (mm) at 30, 60, 90, and at harvest of sweet sorghum in 2023

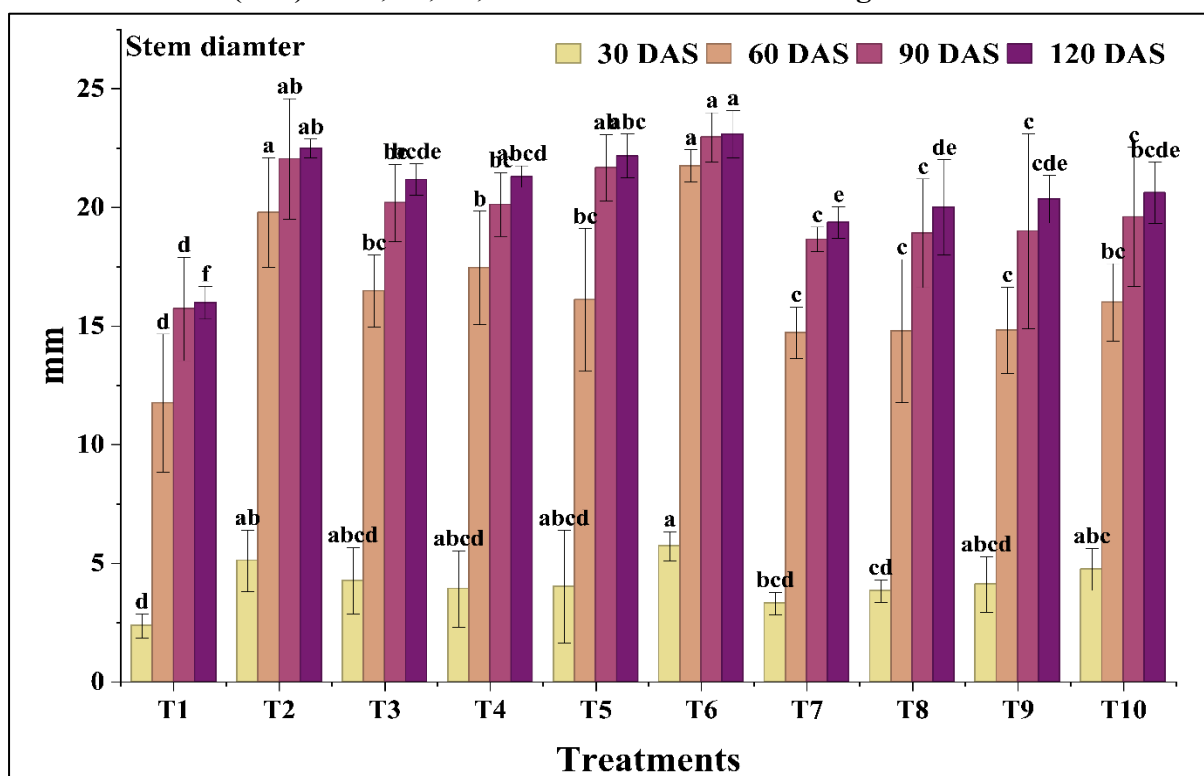


Fig 4.4: Effect of different nutrient management practices on stem diameter (mm) at 30, 60, 90, and at harvest of sweet sorghum in 2024

4.3 Number of leaves plant⁻¹

The data indicated that nutrient management practices had a significant influence on the number of leaves per plant across all growth stages (Table 3). All the treatments shown on the number of leaves plant⁻¹ were non-significant at 30 DAS.

Among the treatments, T₂ consistently outperformed the others, recording the maximum number of leaves per plant at 60 DAS (10.27 in 2023; 10.33 in 2024), compared to the control T₁, which had the lowest count of leaves per plant (6.67 and 6.17 at 60 DAS). Notably, T₂ remained statistically similar to T₆ (100% RDF), which also produced the maximum number of leaves per plant at 60 DAS. Treatments T₇ to T₉ showed statistically identical results to each other.

This trend continued at later stages, where T₆ had the maximum count of leaves plant⁻¹ at 90 DAS (16.00 cm and 16.33 cm) and harvest (14.90 cm and 14.98 cm), significantly greater than the control (12.02 cm and 12.27 at 90 DAS; 10.78 and 10.92 at harvest). T₂ also showed comparable performance, suggesting that both integrated and complete RDF treatments are effective in promoting vegetative growth. The consistently poor performance of T₁ highlights the critical role of nutrient application.

Applying RDF, along with press-mud, zeolite, and bio-neema, enhances soil fertility, retains high moisture, and stimulates microbial activity, thereby creating a suitable rhizosphere for nutrient absorption (Desalegn *et al.* 2023). Press-mud adds organic carbon and micronutrients; additionally, zeolite enhances nutrient use efficiency and water availability, while bio-neema supports root growth and reduces pest stress, ensuring better physiological performance (Hassan *et al.* 2024). Improved nutrient and water levels increase chlorophyll production and photosynthesis, promoting leaf initiation and development (Sasy and Abu-Ellail, 2021).

Table 4.3 Effect of different nutrient management strategies on the number of leaves per plant of sweet sorghum.

Treatments	30 DAS		60 DAS		90 DAS		At harvest	
	2023	2024	2023	2024	2023	2024	2023	2024
T1	3.53	3.42	6.67	6.17	12.27	12.02	10.78	10.92
T2	5.00	5.58	10.27	10.33	14.25	15.58	14.03	14.33
T3	4.33	4.58	8.73	9.08	13.28	14.75	12.70	13.78
T4	3.95	3.92	9.58	9.00	15.25	15.25	14.03	14.58
T5	4.42	4.75	9.00	9.00	15.75	16.17	13.90	14.17
T6	4.83	4.92	9.17	9.76	16.00	16.33	14.90	14.98
T7	4.42	4.45	8.08	8.85	13.08	13.72	12.07	11.67
T8	4.33	4.42	8.17	7.42	13.75	13.40	12.90	13.37
T9	4.08	4.25	8.25	8.92	13.50	14.45	11.65	12.25
T10	4.25	4.33	9.00	9.08	13.83	14.58	13.32	14.30
SEm ($\pm$)	0.29	0.63	0.54	0.56	0.66	0.54	0.55	0.73
LSD (p=0.05)	NS	NS	1.61	1.67	1.97	1.61	1.64	2.17

T1-* Control (Absolute), T2-*100 % RDF (90:40:40 NPK), T3-*75 % RDF +Zeolite (1.5 t ha⁻¹), T4*75 % RDF +Press-mud (15 t ha⁻¹), T5-*75 % RDF +Zeolite (1.5 t ha⁻¹) +Press-mud (15 t ha⁻¹), T6-*75 % RDF +Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹) +Bio-neema (5 kg ha⁻¹), T7-*Nano NPK (19:19:19) +Zeolite (1.5 t ha⁻¹), T8-*Nano NPK (19:19:19) + Press-mud (15 t ha⁻¹), T9-*Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹), T10-* Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) +Pressmud (1.5 t ha⁻¹) +Bio-neema (5 kg ha⁻¹). SEm-*Standard Error of Mean, LSD (p =0.05)-* Least Significant Difference at 5 % significance level.

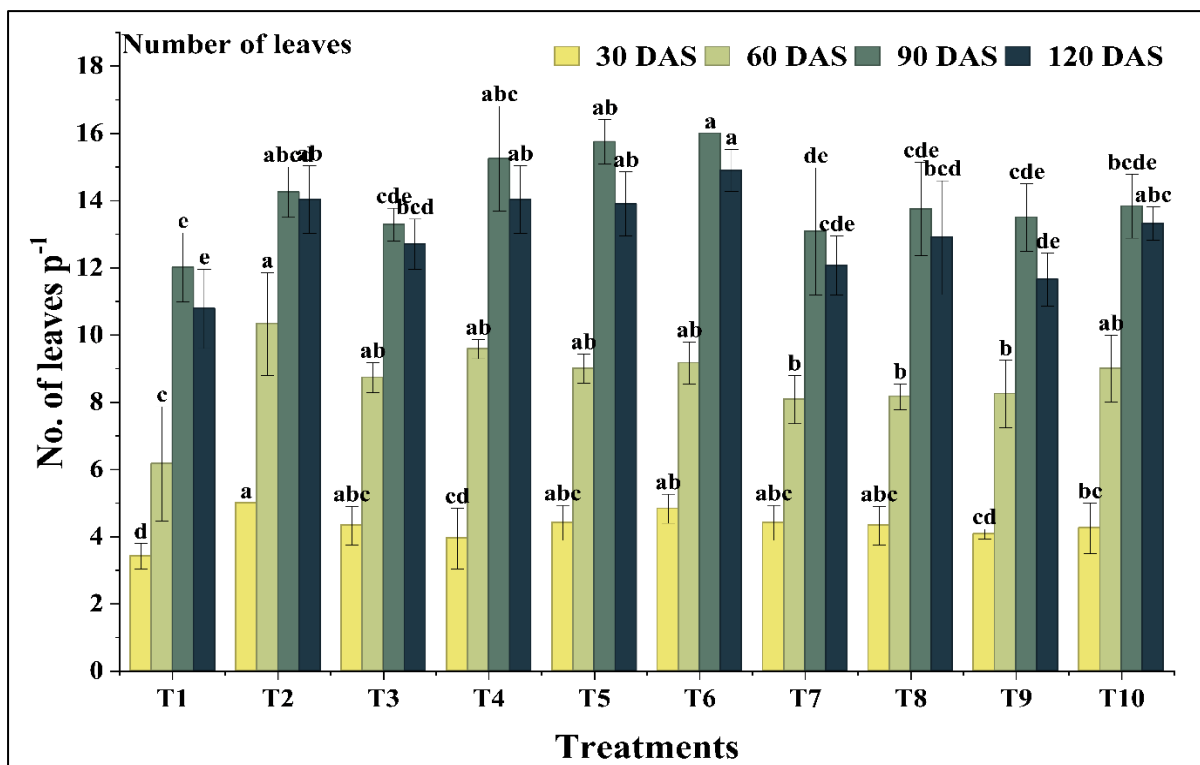


Fig 4.5: Effect of different nutrient management practices on number of leaves plant⁻¹ at 30, 60, 90, and at harvest of sweet sorghum in 2024

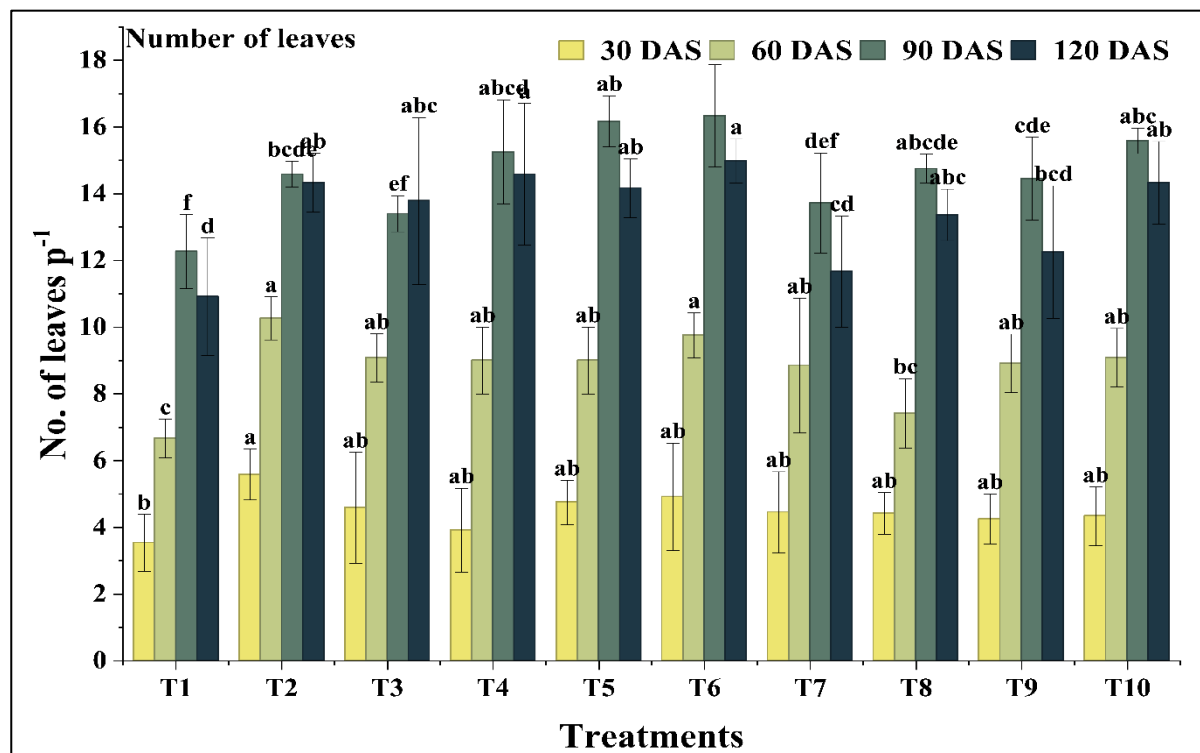


Fig 4.6: Effect of different nutrient management practices on number of leaves plant⁻¹ at 30, 60, 90, and at harvest of sweet sorghum in 2024

4.4. Leaf area (cm² p⁻¹)

A clear trend of increased leaf area, driven by better nutrient management practices, was observed throughout the growing period (Table 4).

T2 consistently led in leaf area, reaching 800.34 cm² and 862.14 cm² at 30 DAS and 60 DAS in 2023, and 6095.08 cm² and 6185.35 cm² at 60 DAS in 2024. This was notably higher than the control treatment (T1), which recorded only 257.28 cm² and 255.97 cm² at 30 DAS, and 2368.58 cm² and 2318.33 cm² at 60 DAS. T2's performance was statistically similar to T6, which included 75% RDF, zeolite, press mud, and bio-neema. In contrast, T7 to T9 showed no significant differences among themselves.

The superiority of T₆ persisted at later stages. At 90 DAS, it reached 7796.63 cm² and 8167.97 cm² in 2023 and 2024, while T₁ remained the lowest at 4663.75 cm² and 4478.59 cm². At harvest, T₆ was recorded as 6945.13 cm² and 7484.33 cm², again exceeding T₁'s final leaf area p⁻¹ (4076.39 cm² and 3938.86 cm²). T₂ continued to perform well, showing values statistically similar to T₆. These findings highlight the effectiveness of integrated nutrient management in enhancing plant growth, with T₆ proving most beneficial in optimizing leaf area per plant across all measurement intervals.

Applying RDF along with press-mud, zeolite, and bio-nema enhances the physical and chemical properties of the soil, improving moisture retention and nutrient availability. Pressmud adds organic carbon and essential micronutrients to the soil, while zeolite controls nutrient release and water retention (Mohammadnaseri and Tadayon, 2024; Prabhavathi *et al.* 2019). Bio-neema supports root vigor and reduces biotic stress. These combined effects enhance photosynthetic efficiency and stimulate cell expansion in leaves, resulting in a larger leaf area (Reddy and Umesha, 2023).

Table 4.4 Effect of different nutrient management strategies on leaf area (cm² p⁻¹) of sweet sorghum.

Treatments	30 DAS		60 DAS		90 DAS		At harvest	
	2023	2024	2023	2024	2023	2024	2023	2024
T1	257	255	2368	2318	4663	4478	4076	3938
T2	800	862	6095	6185	6817	6912	6655	6663
T3	580	615	4344	4409	6131	6140	6335	6367
T4	448	456	3642	3732	5527	5540	5099	5202
T5	519	554	4809	4896	5124	5284	4527	4561
T6	595	620	4826	4902	7796	8167	6945	7484
T7	589	591	3927	3981	5406	5217	5107	4383
T8	414	425	4081	4144	5317	5106	4909	4601
T9	476	491	3715	3877	5334	5591	4607	4706
T10	530	543	4838	4903	6023	6159	5286	5676
SEm (±)	33.79	36.88	145.04	138.80	164.36	168.79	214.57	228.30
LSD (p=0.05)	100.39	109.58	430.95	412.40	488.35	501.51	637.52	678.30

T1-* Control (Absolute), T2-*100 % RDF (90:40:40 NPK), T3-*75 % RDF +Zeolite (1.5 t ha⁻¹), T4*75 % RDF +Press-mud (15 t ha⁻¹), T5-*75 % RDF +Zeolite (1.5 t ha⁻¹) +Press-mud (15 t ha⁻¹), T6-*75 % RDF +Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹) +Bio-neema (5 kg ha⁻¹), T7-*Nano NPK (19:19:19) +Zeolite (1.5 t ha⁻¹), T8-*Nano NPK (19:19:19) + Press-mud (15 t ha⁻¹), T9-*Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹), T10-* Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) +Pressmud (1.5 t ha⁻¹) +Bio-neema (5 kg ha⁻¹). SEm-*Standard Error of Mean, LSD (p =0.05)-* Least Significant Difference at 5 % significance level.

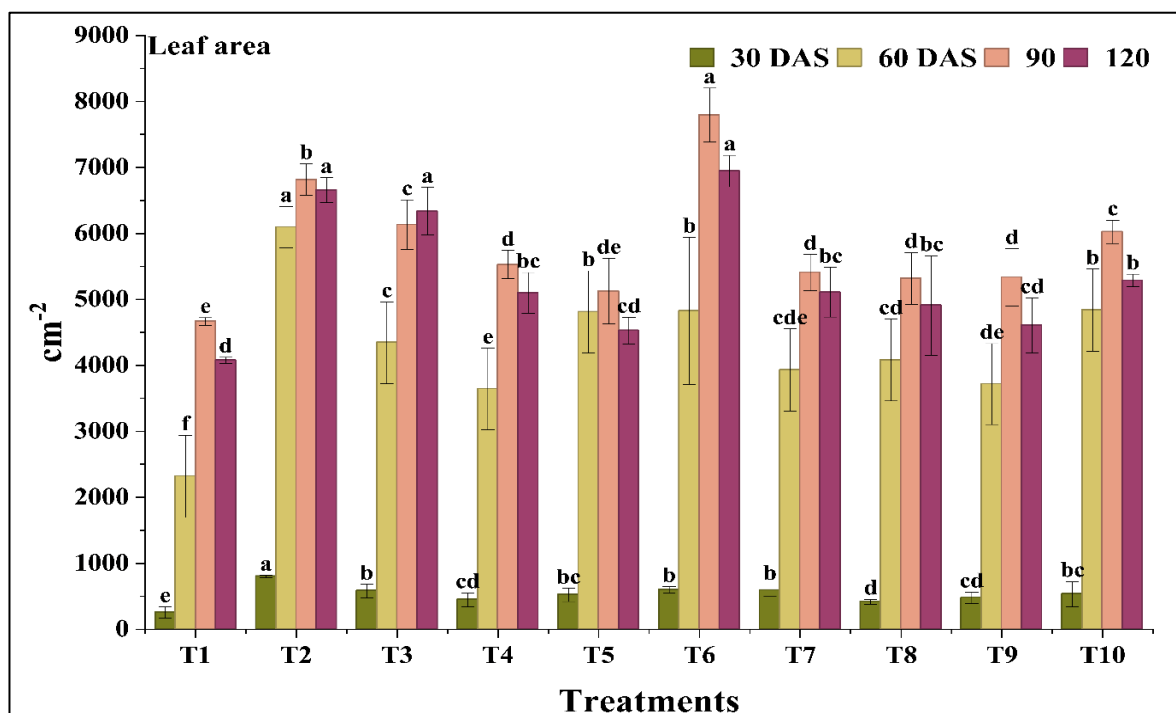


Fig 4.7: Effect of different nutrient management practices on leaves area (cm²) plant⁻¹ at 30, 60, 90, and at harvest of sweet sorghum in 2023

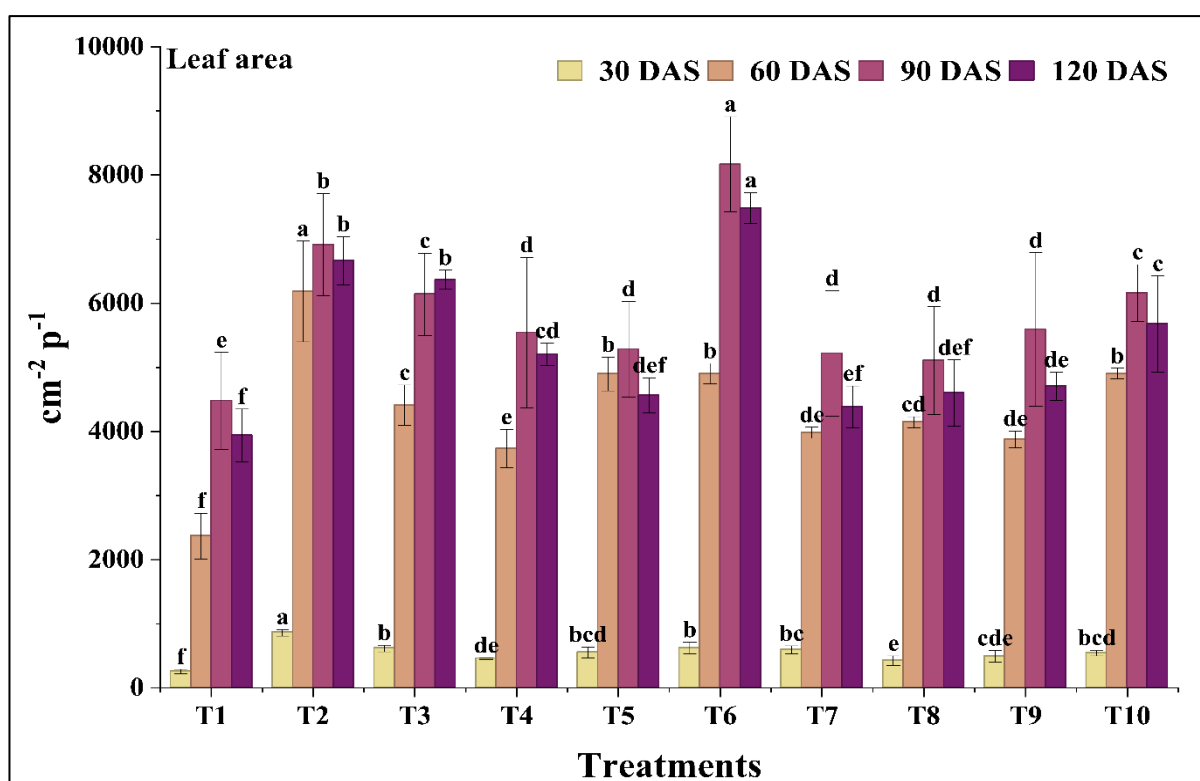


Fig 4.8: Effect of different nutrient management practices on leaves area (cm²) plant⁻¹ at 30, 60, 90, and at harvest of sweet sorghum in 2024

4.5 Leaf area index

The effect of different nutrient management on leaf area index was statistically significant across all the growth stages (Table 5).

At 30 DAS, treatment T₂ exhibited the best leaf area index, measuring 1.87 in 2023 and 1.28 in 2024. This was significantly higher than the control (T₁), which had the lowest values (0.39 and 0.38, respectively). Equally, at 60 DAS, T₂ maintained the maximum leaf area index (9.03 in 2023 and 9.16 in 2024), outperforming the control (3.51 and 3.43), followed by T₆ (7.15 and 7.26, respectively). Treatments T₇ and T₉ were found to be statistically similar to each other.

The superiority of T₆ persisted at later stages. At 90 DAS, it reached 11.55 and 12.10 in 2023 and 2024, while T₁ remained the lowest leaf area index at 6.91 and 6.63. At harvest, T₆ was recorded at 10.29 and 11.09, again exceeding T₁'s final leaf area index under control treatment (6.04 and 5.84). T₂ continued to perform well, showing values statistically similar to T₆. These results highlight the efficiency of integrated nutrient management strategies in improving growth, with T₆ verifying the most valuable in optimizing leaf area index per plant across all measurement intervals.

Integrating RDF with press-mud, zeolite, and bio-neema enhances the leaf area index of sweet sorghum by improving soil health and plant physiological functions. Press-muds increase soil organic matter and microbial activity, while zeolite improves nutrient retention and moisture supply (Hassan *et al.* 2024; Rahmad *et al.* 2019). Bio-neema encourages root growth and stress tolerance. These improvements ensure a steady supply of nutrients and water, thereby increasing chlorophyll content and boosting photosynthetic rates (Suman *et al.*, 2023). As a result, plants develop broader and more numerous leaves, elevating the leaf area index.

Table 4.5 Effect of different nutrient management strategies on leaf area index of sweet sorghum

Treatments	30 DAS		60 DAS		90 DAS		At harvest	
	2023	2024	2023	2024	2023	2024	2023	2024
T1	0.39	0.38	3.51	3.43	6.91	6.63	6.04	5.84
T2	1.19	1.28	9.03	9.16	10.10	10.24	9.86	9.87
T3	0.86	0.91	6.44	6.53	9.08	9.10	9.39	9.43
T4	0.66	0.68	5.40	5.53	8.19	8.21	7.56	7.71
T5	0.77	0.82	7.12	7.25	7.59	7.83	6.71	6.76
T6	0.88	0.92	7.15	7.26	11.55	12.10	10.29	11.09
T7	0.87	0.88	5.82	5.90	8.01	7.73	7.57	6.49
T8	0.61	0.63	6.05	6.14	7.88	7.57	7.27	6.82
T9	0.71	0.73	5.50	5.74	7.90	8.28	6.83	6.97
T10	0.79	0.81	7.17	7.26	8.92	9.13	7.83	8.41
SEm ($\pm$)	0.05	0.06	0.21	0.21	0.24	0.25	0.32	0.34
LSD (p=0.05)	0.15	0.16	0.64	0.61	0.72	0.74	0.94	1.00

T1-* Control (Absolute), T2-*100 % RDF (90:40:40 NPK), T3-*75 % RDF +Zeolite (1.5 t ha⁻¹), T4*75 % RDF +Press-mud (15 t ha⁻¹), T5-*75 % RDF +Zeolite (1.5 t ha⁻¹) +Press-mud (15 t ha⁻¹), T6-*75 % RDF +Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹) +Bio-neema (5 kg ha⁻¹), T7-*Nano NPK (19:19:19) +Zeolite (1.5 t ha⁻¹), T8-*Nano NPK (19:19:19) + Press-mud (15 t ha⁻¹), T9-*Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹), T10-* Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) +Pressmud (1.5 t ha⁻¹) +Bio-neema (5 kg ha⁻¹). SEm-*Standard Error of Mean, LSD (p =0.05)-* Least Significant Difference at 5 % significance level.

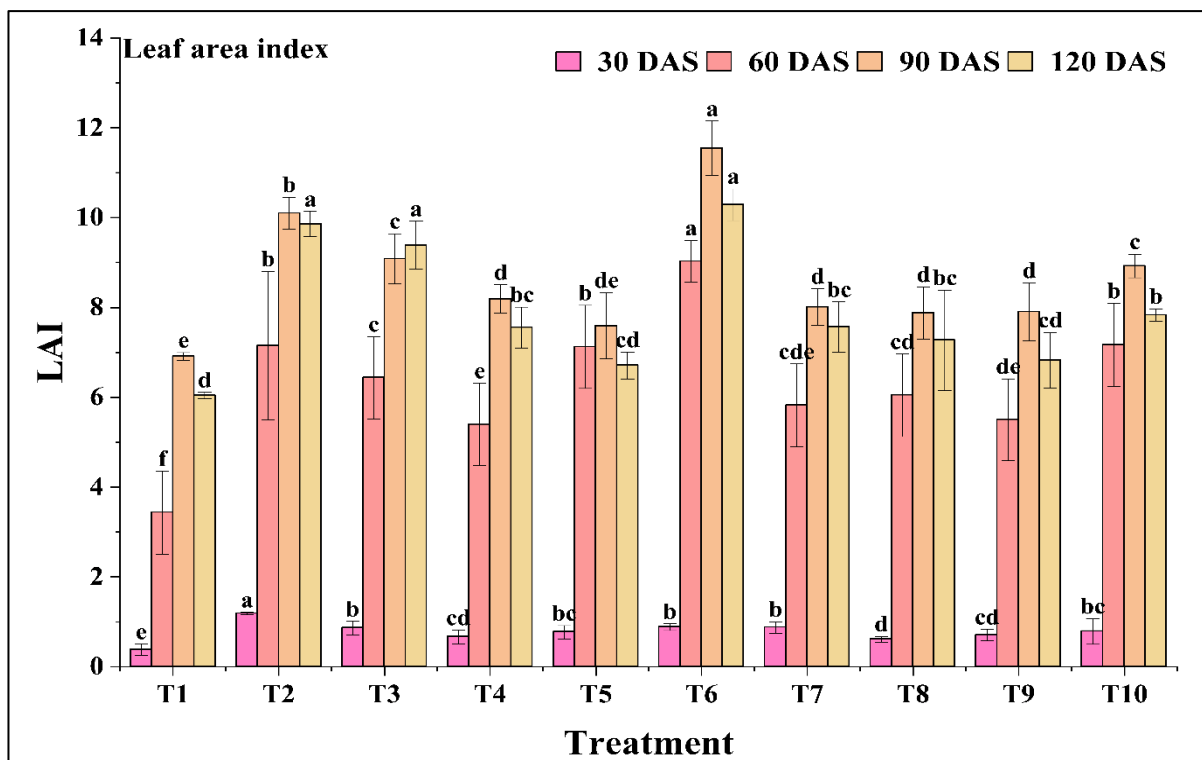


Fig 4.9: Effect of different nutrient management practices on leaves area index plant⁻¹ at 30, 60, 90, and at harvest of sweet sorghum in 2023

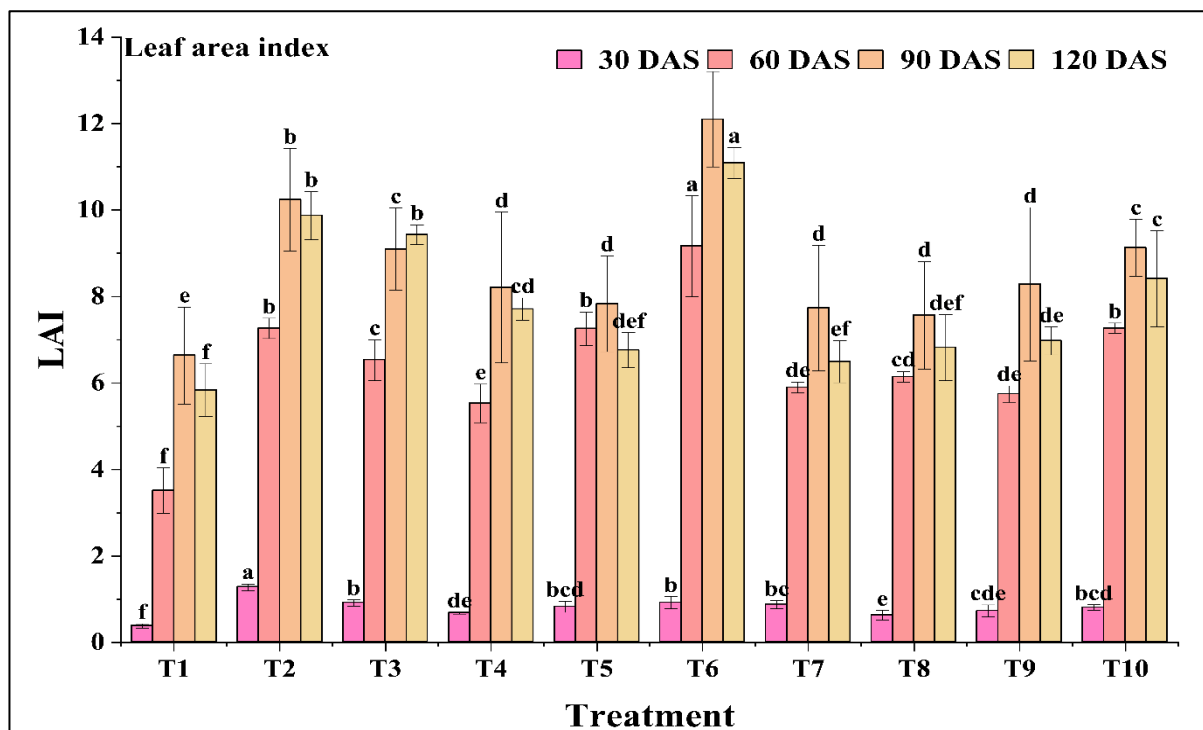


Fig 4.10: Effect of different nutrient management practices on leaves area index plant⁻¹ at 30, 60, 90, and at harvest of sweet sorghum in 2024

4.6 Fresh weight (g plant⁻¹)

Fresh weight increased significantly with different nutrient management treatments. T₆ showed the best results at all growth stages (Table 6).

At 30 days after sowing (DAS), T₆ reached 69.74 g in 2023 and 70.10 g in 2024, while the control (T₁) had the lowest fresh weight at 30 g in both years. By 60 DAS, T₆ reached about 605.40 g, compared to around 255 g for the control. T₆ was also similar to T₅, which had slightly lower but statistically comparable fresh weight.

As the plant measured, the trend continued. At 90 DAS, T₆ reached up to 770.22 g, compared to just 363.88 g in the control. At harvest, T₆ maintained its lead with fresh weight of 825.48 g in 2023 and 826.48 g in 2024. Again, T₅ showed similar growth to accumulate maximum weight, while the control remained the lowest. Treatments T₇ to T₁₀ showed no significant differences among themselves. These results clearly demonstrate that applying the proper nutrients significantly enhances plant growth.

The combined use of RDF with press-mud, zeolite, and bio-neema greatly increases the fresh weight of sweet sorghum by improving soil fertility, structure, and moisture retention. Press-mud adds organic carbon and micronutrients to the soil, boosting microbial activity and nutrient cycling. Zeolite functions as a slow-release reservoir for nutrients and water, minimizing losses and providing a steady supply to the crop. Bio-neema promotes root growth and reduces pest-related stress, leading to enhanced nutrient absorption. This synergy enhances chlorophyll production, photosynthesis, and carbohydrate buildup, resulting in greater biomass. These results supported by (Mohammadnaseri and Tadayon, 2024; Prabhavathi *et al.* 2019)

Table 4.6 Effect of fresh weight (g) of sweet sorghum through the various nutrient management practices.

Treatments	30 DAS		60 DAS		90 DAS		At harvest	
	2023	2024	2023	2024	2023	2024	2023	2024
T1	30.92	30.78	258.82	256.49	366.72	361.05	400.54	395.87
T2	68.33	68.96	573.27	575.27	756.38	757.59	802.14	805.48
T3	57.96	56.30	556.93	556.27	697.66	698.70	717.50	719.17
T4	50.35	54.56	543.77	545.43	700.42	699.35	718.23	720.56
T5	67.80	69.77	603.95	609.61	766.16	770.45	818.64	821.64
T6	69.74	70.10	607.28	610.61	767.87	772.72	825.48	826.48
T7	37.57	39.20	491.55	494.55	654.06	658.88	688.76	691.10
T8	42.48	42.87	484.63	488.30	624.24	627.03	694.76	695.43
T9	40.21	40.41	499.85	502.52	619.73	617.03	657.05	658.05
T10	46.98	53.71	514.70	516.70	607.76	621.51	665.33	667.67
SEm ($\pm$)	1.06	1.27	1.86	2.48	2.53	1.78	2.25	1.32
LSD (p=0.05)	3.15	3.77	5.51	7.35	7.51	5.30	6.68	3.93

T1-* Control (Absolute), T2-*100 % RDF (90:40:40 NPK), T3-*75 % RDF +Zeolite (1.5 t ha^{-1}), T4*75 % RDF +Press-mud (15 t ha^{-1}), T5-*75 % RDF +Zeolite (1.5 t ha^{-1}) +Press-mud (15 t ha^{-1}), T6-*75 % RDF +Zeolite (1.5 t ha^{-1}) + Press-mud (15 t ha^{-1}) +Bio-neema (5 kg ha^{-1}), T7-*Nano NPK (19:19:19) +Zeolite (1.5 t ha^{-1}), T8-*Nano NPK (19:19:19) + Press-mud (15 t ha^{-1}), T9-*Nano NPK (19:19:19) + Zeolite (1.5 t ha^{-1}) + Press-mud (15 t ha^{-1}), T10-* Nano NPK (19:19:19) + Zeolite (1.5 t ha^{-1}) +Pressmud (1.5 t ha^{-1}) +Bio-neema (5 kg ha^{-1}). SEm-*Standard Error of Mean, LSD (p =0.05)-* Least Significant Difference at 5 % significance level.

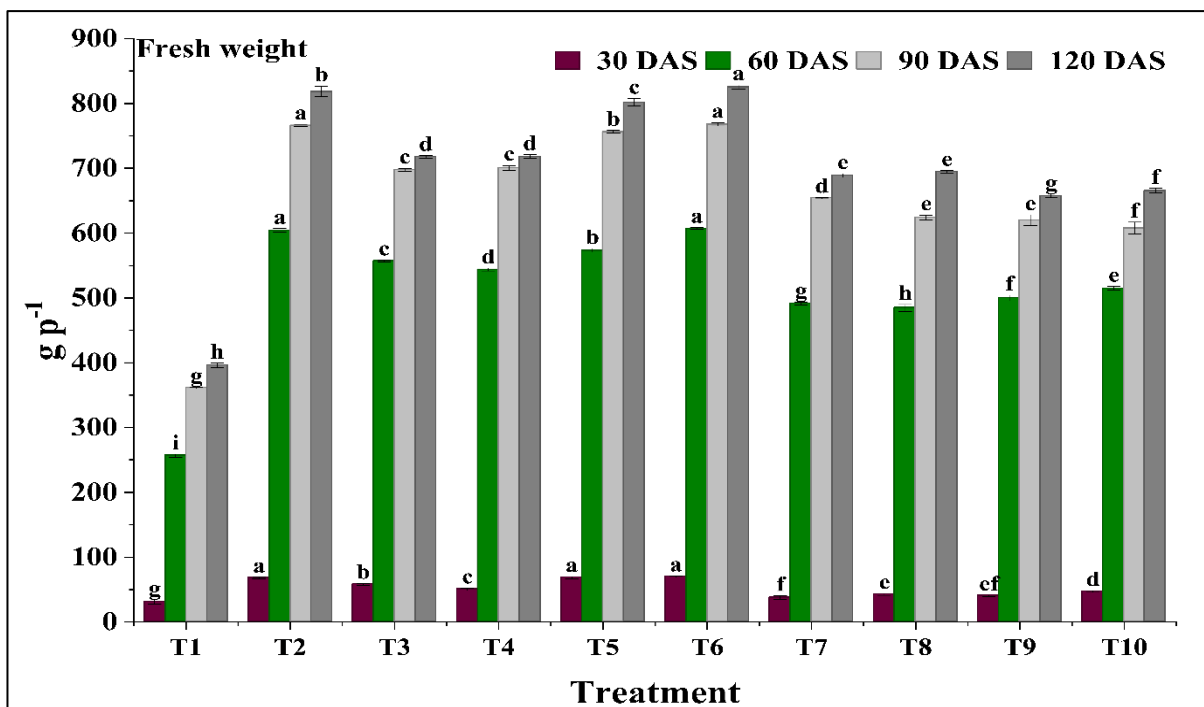


Fig 4.11: Effect of different nutrient management practices on fresh weight plant⁻¹ at 30, 60, 90, and at harvest of sweet sorghum in 2023

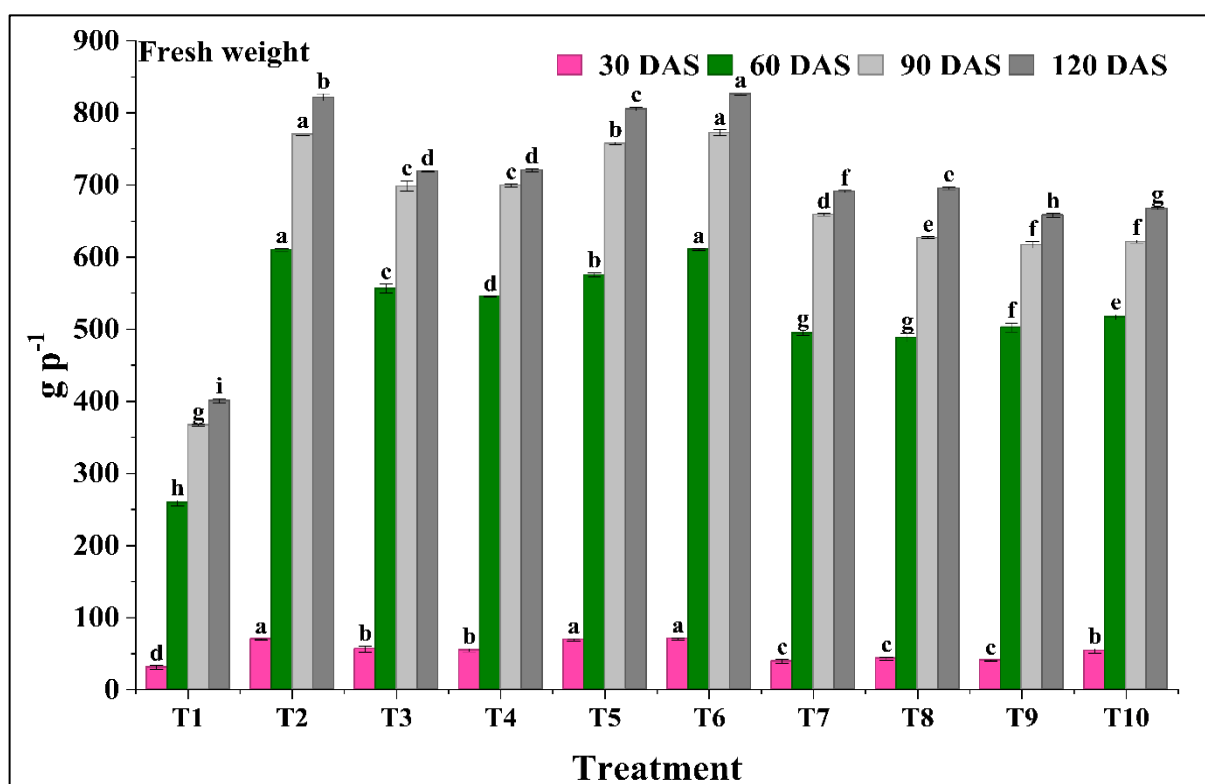


Fig 4.12: Effect of different nutrient management practices on fresh weight plant⁻¹ at 30, 60, 90, and at harvest of sweet sorghum in 2024

4.7 Dry matter accumulation (g plant⁻¹)

The effect of different nutrient management treatments on dry matter accumulation was statistically significant across all growth stages (Table 7).

At 30 DAS, treatment T₆ exhibited the highest dry matter accumulation, recording 22.17 g in 2023 and 23.29 g in 2024. This was significantly higher than the control (T₁), which recorded the lowest values (14.38 g and 13.67 g, respectively). Similarly, at 60 DAS, T₆ maintained the maximum dry matter accumulation (92.76 g in 2023 and 97.17 g in 2024), outperforming the control (45.22 g and 42.41 g, respectively), followed by T₃ and T₅ (71.43, 72.56 g and 72.90, and 76.98 g respectively). Treatments T₈ and T₁₀ were found to be statistically similar to each other.

At 90 DAS, T₆ continued to show the highest dry matter accumulation (312.47 g in 2023 and 320.16 g in 2024), closely followed by T₅ (270.52 g and 271.35 g), both significantly surpassing the control (126.61 g and 125.50 g). At harvest, T₆ again recorded the greatest dry matter accumulation (399.73 g in 2023 and 405.82 g in 2024), with T₅ next (351.71 g and 356.56 g). The control (T₁) exhibited the lowest values (155.14 g and 152.78 g). These results demonstrate the superior performance of T₆, and to a lesser extent T₅, in promoting plant growth under the specified agro-climatic conditions.

The integration of nutrients plays a significant role in enhancing dry matter accumulation and overall growth performance of the crop. From a soil perspective, the application of press-mud and bio-neema enhances organic matter content, improves soil structure, and stimulates microbial populations. Additionally, bio-neema helps reduce soilborne diseases, promoting healthier root growth, which collectively increases nutrient mineralization and availability (Lucena *et al* 2018). It also supplies secondary and micronutrients, such as Ca, Mg, Fe, and Zn, that support balanced nutrition. Due to the high cation exchange capacity of zeolite, it can retain essential nutrients such as ammonium and potassium while maintaining optimal soil moisture (Hassan *et al.* 2024). This slow and sustained nutrient release ensures continuous availability throughout the crop's growth stages, reducing nutrient losses and enhancing water-use efficiency. Physiologically, these soil improvements promote stronger root growth, higher chlorophyll levels, and greater photosynthetic efficiency, enabling the plant to utilize resources more effectively. Increased nutrient and water availability support vigorous

vegetative growth, improved leaf expansion, and efficient carbohydrate assimilation, all of which contribute to greater dry matter accumulation (Reddy and Umesha, 2023).

Table 4.7 Effect of different nutrient management strategies on dry matter accumulation (g) per plant of sweet sorghum

Treatments	30 DAS		60 DAS		90 DAS		At harvest	
	2023	2024	2023	2024	2023	2024	2023	2024
T1	14.38	13.67	45.22	42.41	126.61	125.50	155.14	152.78
T2	19.57	21.69	66.82	69.62	224.02	228.44	290.63	304.10
T3	20.68	20.84	71.43	72.56	242.59	244.06	301.07	299.52
T4	19.08	20.11	67.45	71.71	245.00	249.49	304.48	305.12
T5	19.47	22.52	72.90	76.98	270.52	271.35	351.71	356.56
T6	22.17	23.29	92.76	97.17	312.47	320.16	399.73	405.82
T7	17.70	17.70	57.93	62.24	187.92	185.04	230.73	227.64
T8	18.99	19.56	60.89	64.31	190.88	192.55	234.22	233.24
T9	18.34	18.79	59.66	59.63	188.87	192.19	233.08	235.39
T10	18.44	19.30	65.33	67.03	200.20	204.58	245.47	250.57
SEm ($\pm$)	0.38	0.87	1.89	1.21	2.32	1.40	2.42	2.88
LSD (p=0.05)	0.14	2.60	5.60	3.60	6.89	4.15	7.19	8.56

T1-* Control (Absolute), T2-*100 % RDF (90:40:40 NPK), T3-*75 % RDF +Zeolite (1.5 t ha⁻¹), T4-*75 % RDF +Press-mud (15 t ha⁻¹), T5-*75 % RDF +Zeolite (1.5 t ha⁻¹) +Press-mud (15 t ha⁻¹), T6-*75 % RDF +Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹) +Bio-neema (5 kg ha⁻¹), T7-*Nano NPK (19:19:19) +Zeolite (1.5 t ha⁻¹), T8-*Nano NPK (19:19:19) + Press-mud (15 t ha⁻¹), T9-*Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹), T10-* Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) +Pressmud (1.5 t ha⁻¹) +Bio-neema (5 kg ha⁻¹). SEm-*Standard Error of Mean, LSD (p =0.05)-* Least Significant Difference at 5 % significance level.

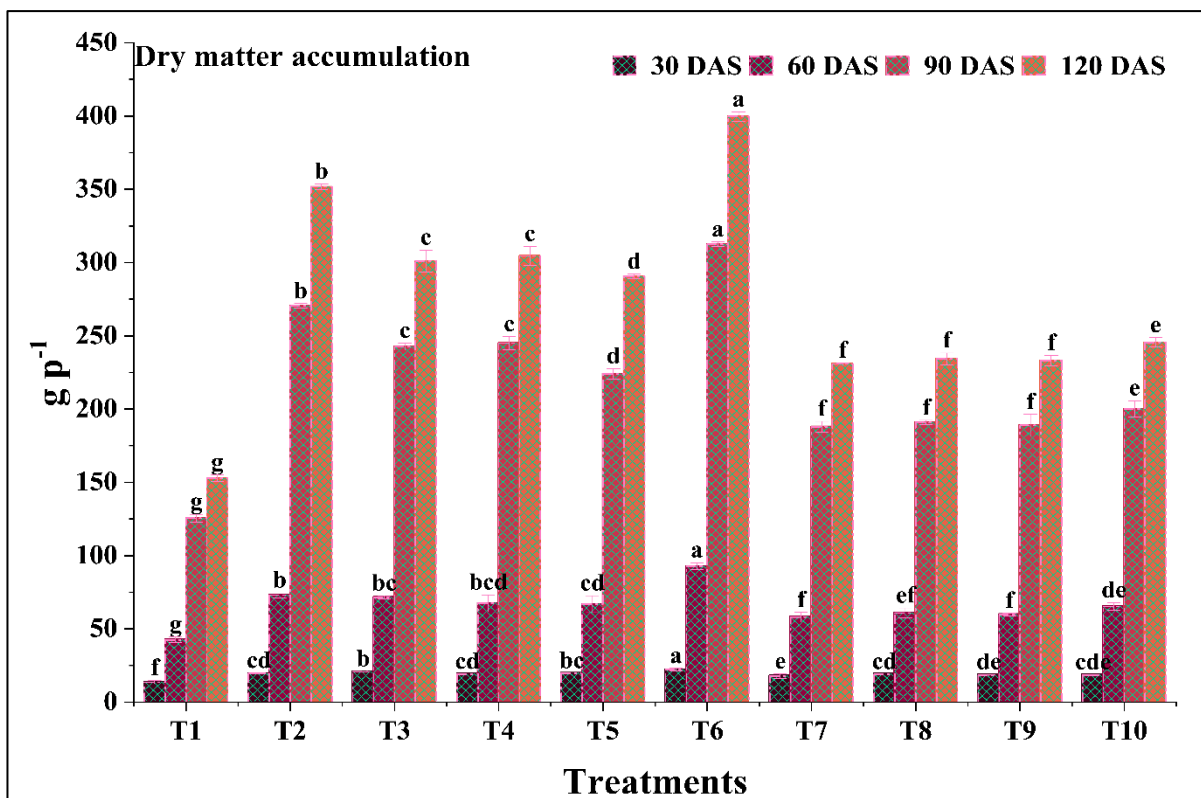


Fig 4.13: Effect of different nutrient management practices on dry matter accumulation plant⁻¹ at 30, 60, 90, and at harvest of sweet sorghum in 2023

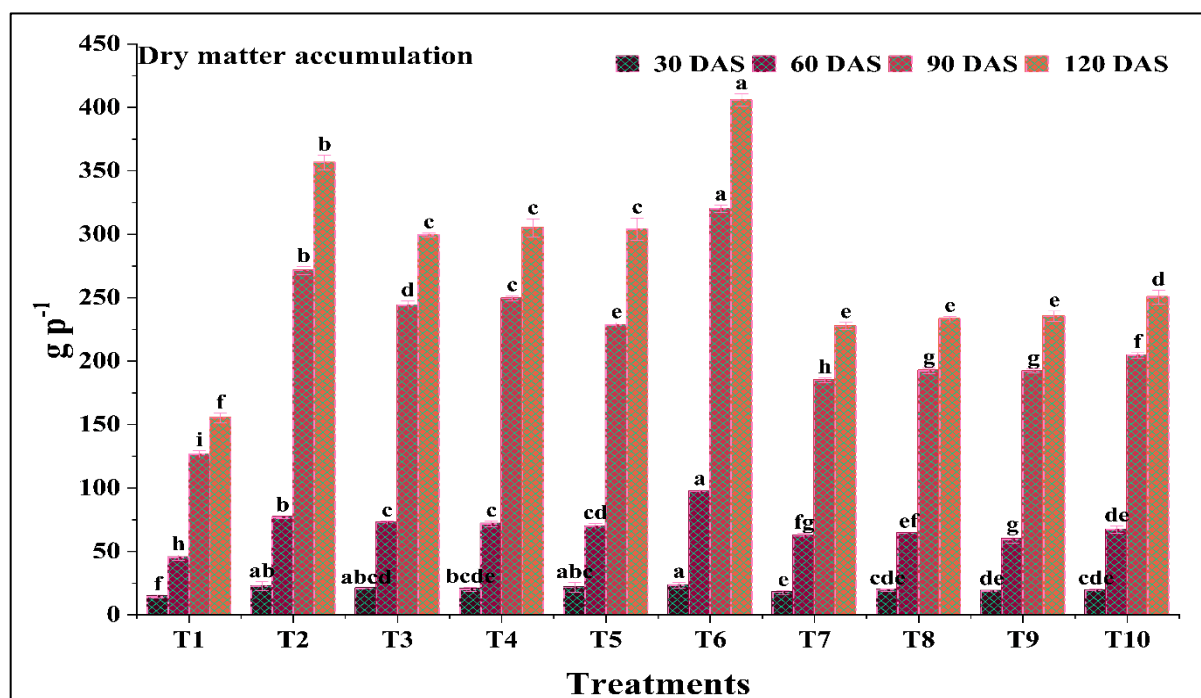


Fig 4.14: Effect of different nutrient management practices on dry matter accumulation plant⁻¹ at 30, 60, 90, and at harvest of sweet sorghum in 2024

4.8 Crop growth rate ($\text{g m}^{-2} \text{ day}^{-1}$)

The data showed that nutrient management practices significantly affected crop growth rates at all growth stages (Table 8).

Among the treatments, T6 consistently performed better than the others, recording the highest crop growth rates at 30-60 DAS ($34.86 \text{ g m}^{-2} \text{ day}^{-1}$ in 2023; $36.49 \text{ g m}^{-2} \text{ day}^{-1}$ in 2024) and 60-90 DAS ($108.50 \text{ g m}^{-2} \text{ day}^{-1}$ and $110.12 \text{ g m}^{-2} \text{ day}^{-1}$). In comparison, control T1 had the lowest crop growth rates ($15.23 \text{ g m}^{-2} \text{ day}^{-1}$ and $14.19 \text{ g m}^{-2} \text{ day}^{-1}$ at 30-60 DAS; $41.03 \text{ g m}^{-2} \text{ day}^{-1}$ and $40.19 \text{ g m}^{-2} \text{ day}^{-1}$ at 60-90 DAS). Treatments T7 and T8 showed statistically similar results. Treatments T3 to T5, which also produced more dry matter, exhibited higher crop growth rates at both stages.

This trend persisted in the later stages, where T6 exhibited the highest crop growth rate at 90 days to harvest ($43.09 \text{ g m}^{-2} \text{ day}^{-1}$ and $42.30 \text{ g m}^{-2} \text{ day}^{-1}$), significantly higher than the control ($14.29 \text{ g m}^{-2} \text{ day}^{-1}$ and $14.09 \text{ g m}^{-2} \text{ day}^{-1}$). T5 also performed similarly, indicating that both integrated and complete RDF treatments effectively enhance vegetative growth. The consistently poor performance of T1 underscores the importance of nutrient application.

The combined use of nutrients significantly enhances CGR by improving soil nutrient dynamics and strengthening plant physiological processes. Zeolite, with its high cationexchange capacity, retains essential nutrients such as ammonium and potassium and slowly releases them, ensuring a steady nutrient supply during the vegetative stages. This supports continuous chlorophyll synthesis, higher photosynthetic efficiency, and sustained leaf expansion, which are key factors driving CGR (Rahmani *et al.* 2023). Press-mud and bioneema provide additional organic matter along with macro- and micronutrients, promoting root growth and increasing nutrient uptake efficiency, leading to faster biomass buildup. They also help maintain healthy root systems for better water and nutrient absorption (Reddy and Umesha, 2023). Together, these amendments create a synergistic environment that optimizes nutrient availability, physiological efficiency, and stress resilience, resulting in a measurable increase in CGR.

Table 4.8 Effect of different nutrient management strategies on crop growth rate (g m⁻² day⁻¹) of sweet sorghum.

Treatments	30-60 DAS		60-90 DAS		90 to harvest	
	2023	2024	2023	2024	2023	2024
T1	15.23	14.19	41.03	40.19	14.29	14.09
T2	23.33	23.67	77.63	78.43	32.90	37.36
T3	25.06	25.54	84.52	84.70	31.18	27.38
T4	23.89	25.49	87.68	87.79	29.37	27.47
T5	26.39	26.89	97.59	95.99	40.10	42.08
T6	34.86	36.49	108.50	110.12	43.09	42.30
T7	19.87	22.00	64.19	60.64	21.96	21.03
T8	20.69	22.10	64.20	63.33	22.22	20.09
T9	20.40	20.17	63.81	65.46	22.66	21.34
T10	23.16	23.57	66.60	67.92	24.00	22.71
SEm (±)	0.97	0.75	1.31	0.92	1.74	1.72
LSD (p=0.05)	2.87	2.23	3.90	2.75	5.16	5.10

T1-* Control (Absolute), T2-*100 % RDF (90:40:40 NPK), T3-*75 % RDF +Zeolite (1.5 t ha⁻¹), T4*75 % RDF +Press-mud (15 t ha⁻¹), T5-*75 % RDF +Zeolite (1.5 t ha⁻¹) +Press-mud (15 t ha⁻¹), T6-*75 % RDF +Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹) +Bio-neema (5 kg ha⁻¹), T7-*Nano NPK (19:19:19) +Zeolite (1.5 t ha⁻¹), T8-*Nano NPK (19:19:19) + Press-mud (15 t ha⁻¹), T9-*Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹), T10-* Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) +Pressmud (1.5 t ha⁻¹) +Bio-neema (5 kg ha⁻¹). SEm-*Standard Error of Mean, LSD (p =0.05)-* Least Significant Difference at 5 % significance level.

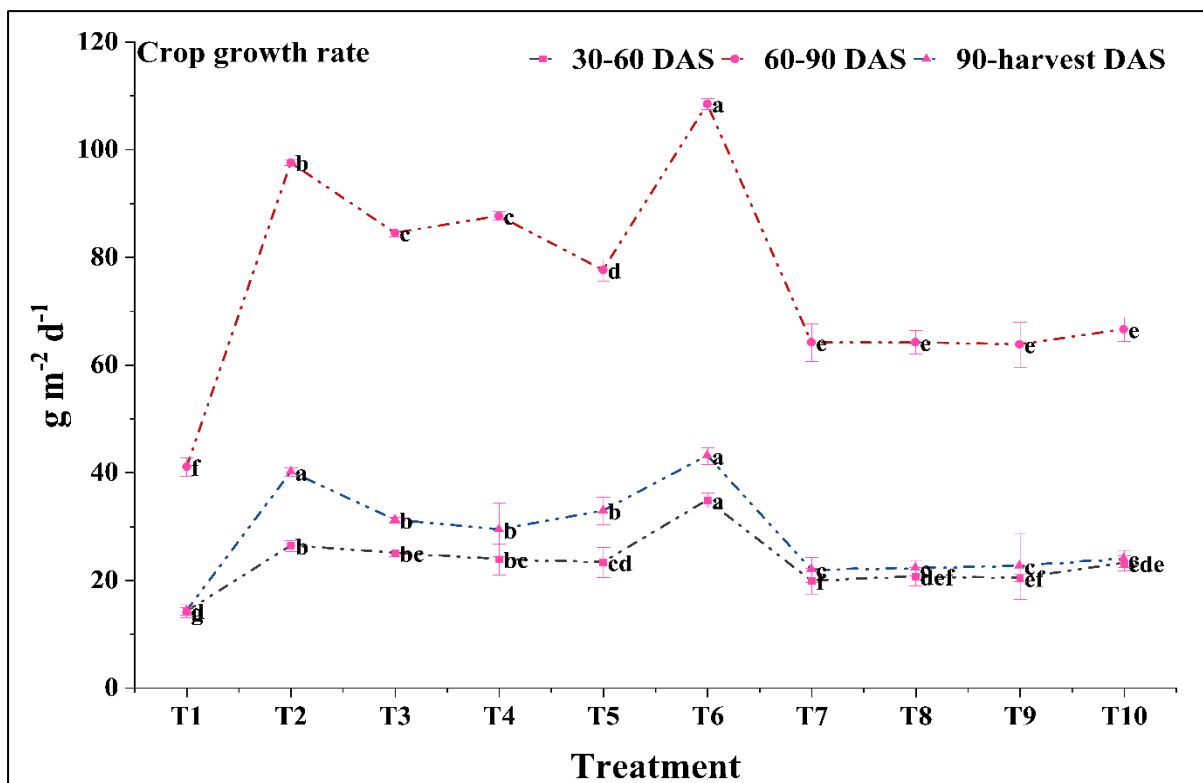


Fig 4.15: Effect of different nutrient management practices on crop growth rate at 3060, 60-90, and 90 to harvest of sweet sorghum in 2023

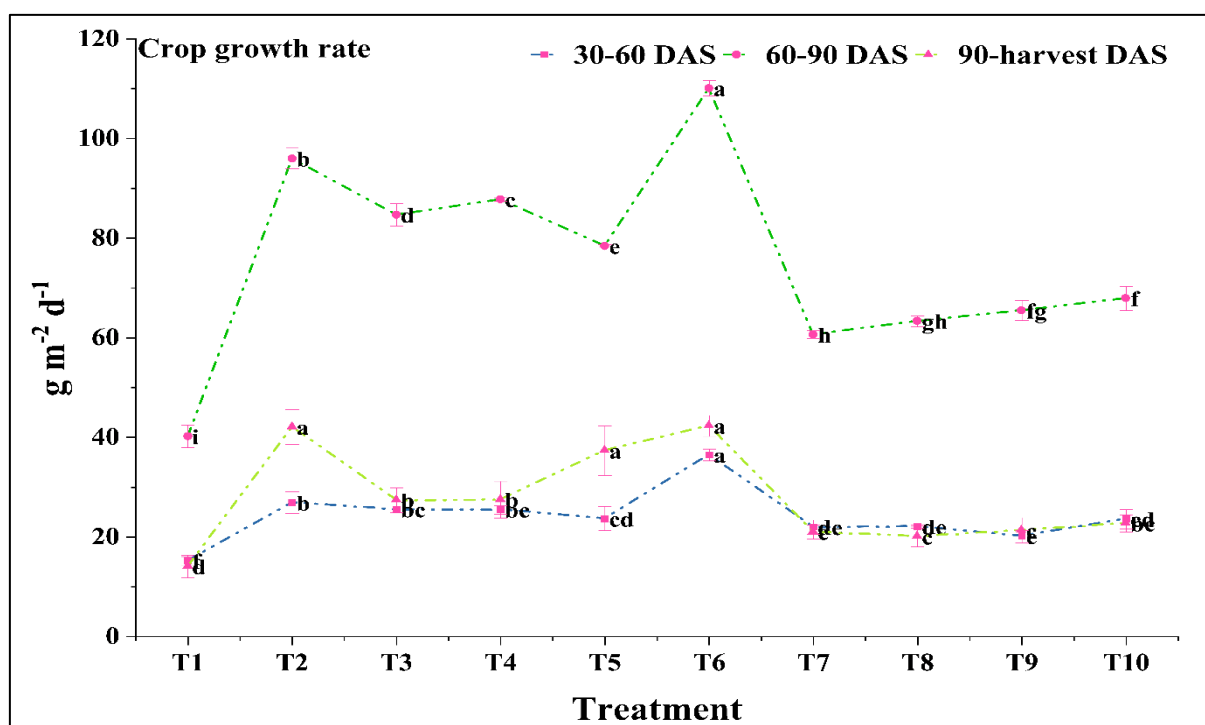


Fig 4.16: Effect of different nutrient management practices on crop growth rate at 30, 60, 60-90, and 90 to harvest of sweet sorghum in 2024

4.9 Relative growth rate ($\text{mg g}^{-1} \text{ day}^{-1}$)

The data showed that nutrient management practices significantly affected crop relative growth rates at all growth stages (Table 9).

Among the treatments, T6 consistently outperformed the others, recording the highest relative crop growth at 30-60 DAS ($47.72 \text{ mg m}^{-2} \text{ day}^{-1}$ in 2023; $47.73 \text{ mg m}^{-2} \text{ day}^{-1}$ in 2024) and 60-90 DAS ($43.71 \text{ mg m}^{-2} \text{ day}^{-1}$ and $42.00 \text{ mg m}^{-2} \text{ day}^{-1}$), compared to the control T1, which had the lowest crop growth rate ($38.25 \text{ mg g m}^{-2} \text{ day}^{-1}$ and $37.80 \text{ mg m}^{-2} \text{ day}^{-1}$ at 30-60 DAS; $36.19 \text{ mg m}^{-2} \text{ day}^{-1}$ and $34.34 \text{ mg m}^{-2} \text{ day}^{-1}$ at 60-90 DAS, respectively). Treatments T7 and T8 showed statistically similar results. Treatments T2, T3, T4 through T5, which also produced more dry matter, recorded higher crop growth rates at both stages.

This trend persisted in the later stages, where T6 exhibited the highest crop growth rate at 90 days to harvest ($8.21 \text{ mg m}^{-2} \text{ day}^{-1}$ and $9.53 \text{ mg m}^{-2} \text{ day}^{-1}$), significantly surpassing the control ($6.77 \text{ mg m}^{-2} \text{ day}^{-1}$ and $6.56 \text{ mg m}^{-2} \text{ day}^{-1}$). T5 also demonstrated comparable performance, indicating that both integrated and full RDF treatments effectively promote vegetative growth. The consistently poor performance of T1 underscores the importance of nutrient application.

The relative growth rate rises when plant physiology shifts toward faster biomass production per unit of existing mass. Improved nutrient availability increases chlorophyll content, boosting photosynthesis and carbon fixation. Higher phosphorus supply speeds up ATP-driven cell division, while improved root activity enhances nutrient and water uptake. Reduced stress helps preserve functional leaf area and maintains efficient stomatal conductance, supporting a steady flow of assimilates (Wu *et al.* 2019). These combined effects promote rapid conversion of photosynthates into new tissues, resulting in a measurable increase in RGR (Sharma *et al.* 2014).

Table 4.9 Effect of different nutrient management strategies on relative growth (mg g⁻¹ day⁻¹) of sweet sorghum.

Treatments	30-60 DAS		60-90 DAS		90-at harvest	
	2023	2024	2023	2024	2023	2024
T1	38.25	37.80	36.19	34.34	6.77	6.56
T2	42.01	39.16	40.40	39.62	8.68	7.90
T3	44.00	41.58	40.76	40.44	7.19	6.83
T4	41.32	42.46	43.08	39.75	7.24	6.70
T5	42.16	41.23	40.49	41.57	8.75	9.10
T6	40.85	47.73	43.71	42.00	8.21	9.53
T7	47.72	41.99	39.26	36.33	6.84	6.91
T8	39.57	39.70	38.12	36.56	6.82	6.39
T9	38.80	38.52	38.40	39.04	7.03	6.76
T10	39.33	41.52	37.34	37.21	6.80	6.76
SEm (±)	1.26	1.47	1.02	0.71	0.55	0.44
LSD (p=0.05)	3.75	4.37	3.02	2.11	1.64	1.32

T1-* Control (Absolute), T2-*100 % RDF (90:40:40 NPK), T3-*75 % RDF +Zeolite (1.5 t ha⁻¹), T4*75 % RDF +Press-mud (15 t ha⁻¹), T5-*75 % RDF +Zeolite (1.5 t ha⁻¹) +Press-mud (15 t ha⁻¹), T6-*75 % RDF +Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹) +Bio-neema (5 kg ha⁻¹), T7-*Nano NPK (19:19:19) +Zeolite (1.5 t ha⁻¹), T8-*Nano NPK (19:19:19) + Press-mud (15 t ha⁻¹), T9-*Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹), T10-* Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) +Pressmud (1.5 t ha⁻¹) +Bio-neema (5 kg ha⁻¹). SEm-*Standard Error of Mean, LSD (p =0.05)-* Least Significant Difference at 5 % significance level.

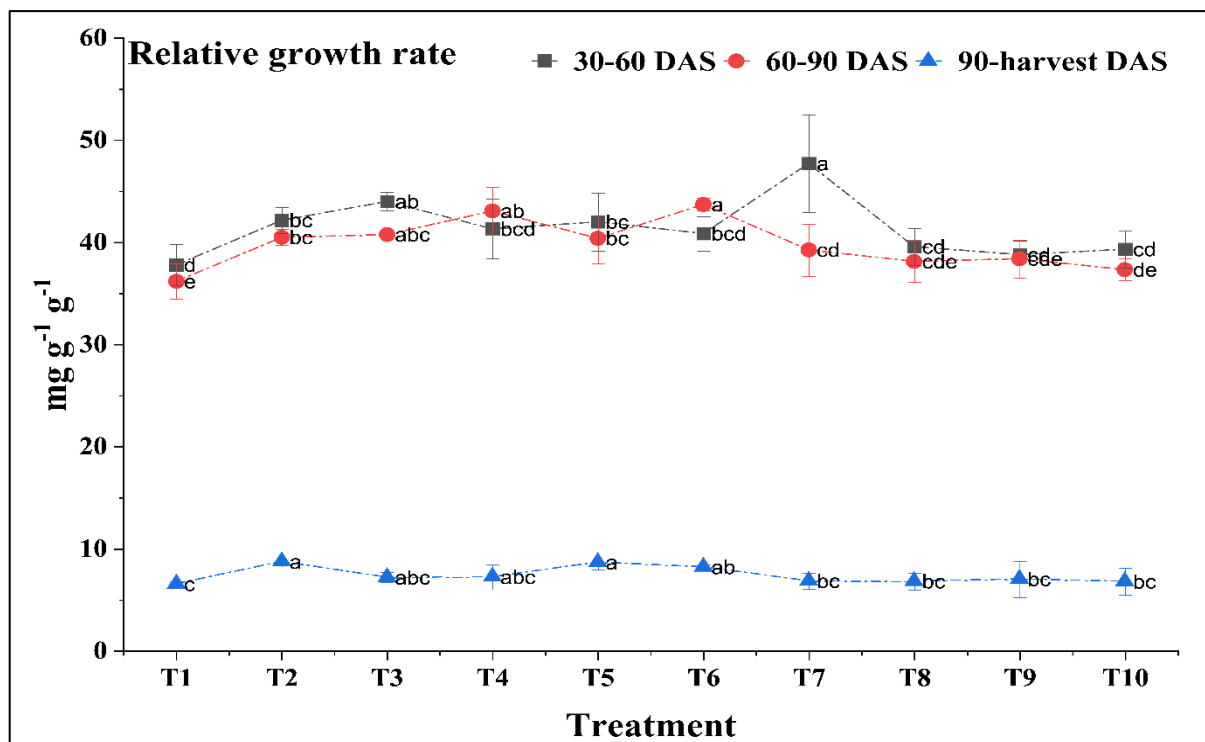


Fig 4.17: Effect of different nutrient management practices on relative growth rate at 30-60, 60-90, and 90 to harvest of sweet sorghum in 2023

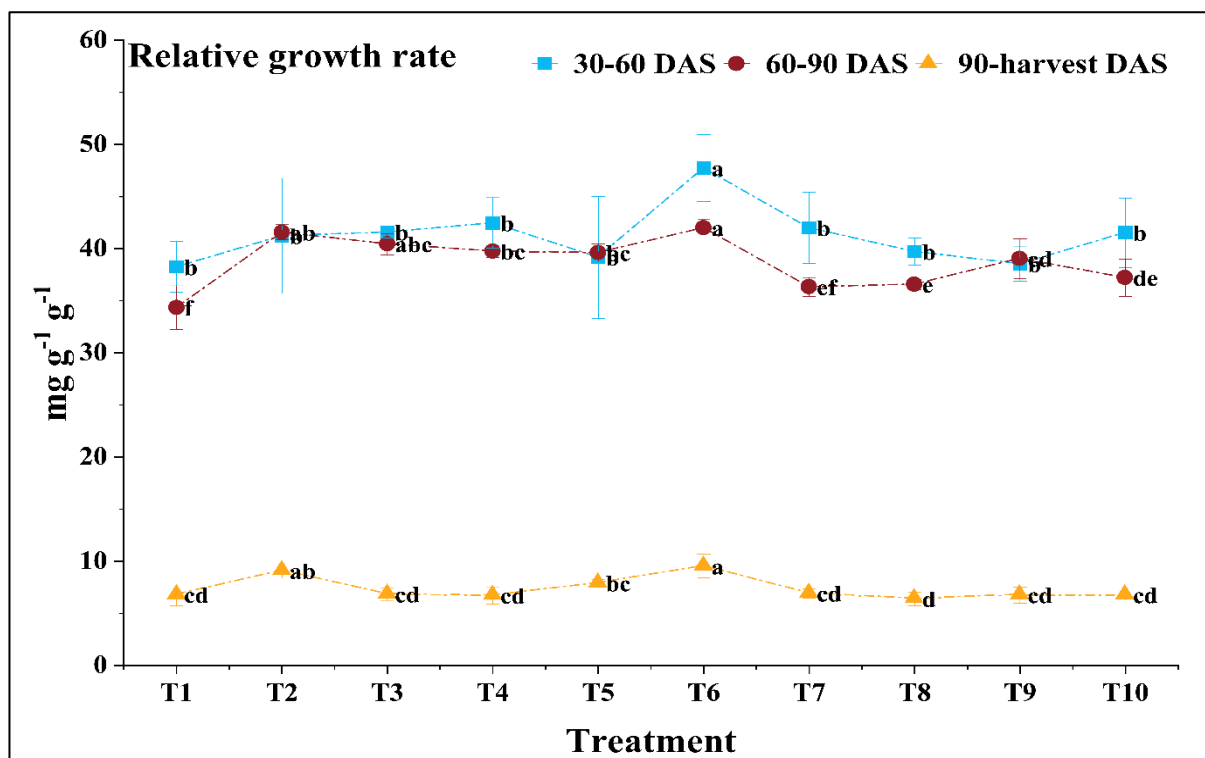


Fig 4.18: Effect of different nutrient management practices on relative growth rate at 30-60, 60-90, and 90 to harvest of sweet sorghum in 2024

4.10 Chlorophyll index (SPAD value)

The data showed that nutrient management strategies had a significant effect on the chlorophyll index at all growth stages (Table 10).

Among the treatments, T6 consistently performed better, recording the highest chlorophyll index at 30 DAS (46.81 in 2023 and 47.67 in 2024) and 60 DAS (48.33 and 48.94), compared to the control T1, which had the lowest index (36.48 and 33.48 at 30 DAS; 38.48 and 36.68 at 60 DAS). Importantly, T6 remained statistically similar to T2 (100% RDF), indicating better chlorophyll content at both stages. Treatments T3 to T5 also showed relatively higher chlorophyll indexes in both years.

From 90 DAS, the reflected chlorophyll index remained relatively consistent across all treatments, with T6 showing the highest chlorophyll index (SPAD values of 45.53 and 48.54), significantly exceeding the control (36.15 and 34.48). T2 also performed comparably. In contrast, T7 to T9 displayed the lowest chlorophyll content, as indicated by reduced SPAD values toward maturity, suggesting that photosynthetic activity can be enhanced during vegetative growth with both integrated and complete RDF treatments. The consistently poor performance of T1 highlights the importance of nutrient application.

The chlorophyll index (SPAD value) shows the relative amount of chlorophyll pigments and reflects a plant's nitrogen status, photosynthetic ability, and overall health. Higher SPAD readings indicate efficient light absorption and more active physiological processes. The rise in SPAD values with zeolite, press-mud, bio-neema, and inorganic fertilizer is due to improved nutrient availability and healthier leaf function (Khaliq *et al.* 2024). At the same time, zeolite helps retain nitrogen and potassium for ongoing chlorophyll production; however, press-mud and bio-neema provide organic carbon and phosphorus that promote root activity and pigment formation (Dotaniya *et al.* 2025). Together, these amendments increase chlorophyll production, resulting in higher SPAD values.

Table 4.10 Effect of different nutrient management strategies on chlorophyll index (SPAD value) of sweet sorghum

Treatments	30 DAS		60 DAS		90 DAS	
	2023	2024	2023	2024	2023	2024
T1	36.48	33.48	38.48	36.68	36.15	34.48
T2	46.30	46.63	47.03	47.97	44.74	47.41
T3	42.46	44.16	45.32	47.16	40.82	43.16
T4	41.37	44.21	44.32	46.21	41.21	44.21
T5	40.73	43.54	45.03	45.88	40.37	44.37
T6	46.81	47.67	48.33	48.94	45.53	48.54
T7	40.25	40.92	42.73	42.13	35.68	37.68
T8	40.36	40.36	43.19	43.69	36.36	37.69
T9	41.17	41.50	43.27	43.17	38.17	39.84
T10	42.04	42.37	43.04	43.45	42.45	42.78
SEm ($\pm$)	0.73	0.89	1.01	1.39	2.13	2.19
LSD ($p=0.05$)	2.17	2.63	3.01	4.12	6.33	6.50

T1-* Control (Absolute), T2-*100 % RDF (90:40:40 NPK), T3-*75 % RDF +Zeolite (1.5 t ha^{-1}), T4*75 % RDF +Press-mud (15 t ha^{-1}), T5-*75 % RDF +Zeolite (1.5 t ha^{-1}) +Press-mud (15 t ha^{-1}), T6-*75 % RDF +Zeolite (1.5 t ha^{-1}) + Press-mud (15 t ha^{-1}) +Bio-neema (5 kg ha^{-1}), T7-*Nano NPK (19:19:19) +Zeolite (1.5 t ha^{-1}), T8-*Nano NPK (19:19:19) + Press-mud (15 t ha^{-1}), T9-*Nano NPK (19:19:19) + Zeolite (1.5 t ha^{-1}) + Press-mud (15 t ha^{-1}), T10-* Nano NPK (19:19:19) + Zeolite (1.5 t ha^{-1}) +Pressmud (1.5 t ha^{-1}) +Bio-neema (5 kg ha^{-1}). SEm-*Standard Error of Mean, LSD ($p =0.05$)-* Least Significant Difference at 5 % significance level.

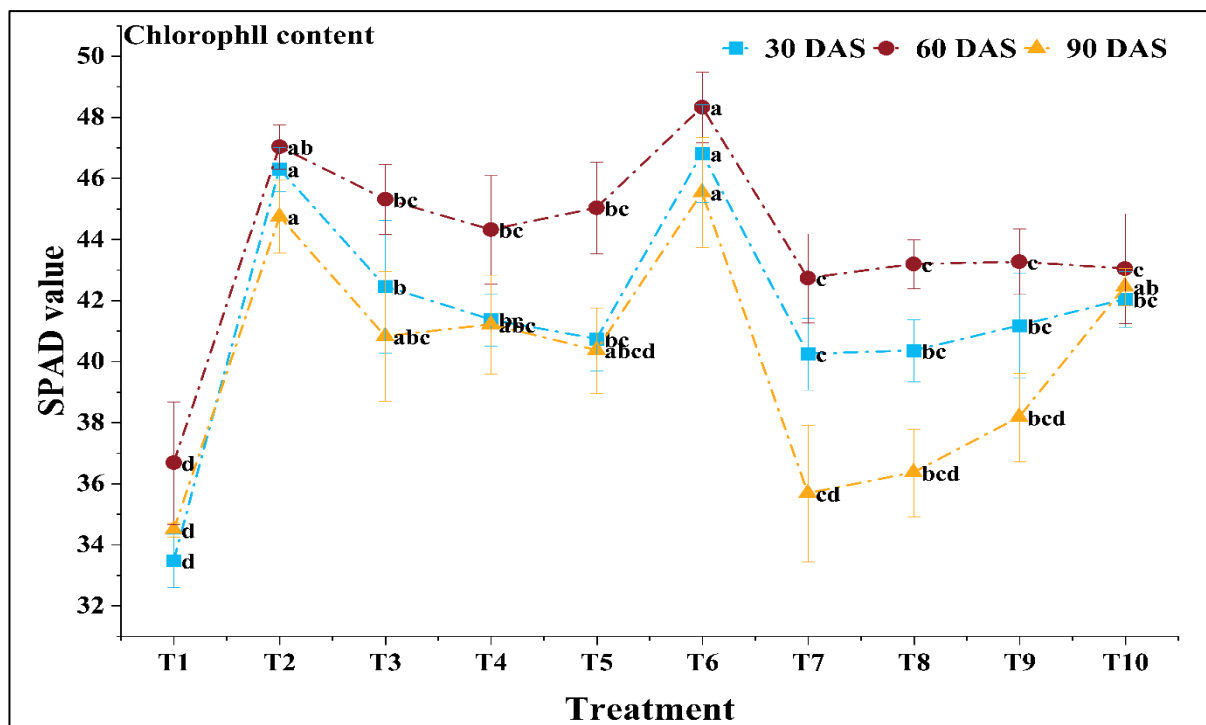


Fig 4.19: Effect of different nutrient management practices on SPAD at 30, 60, and 90 of sweet sorghum in 2023

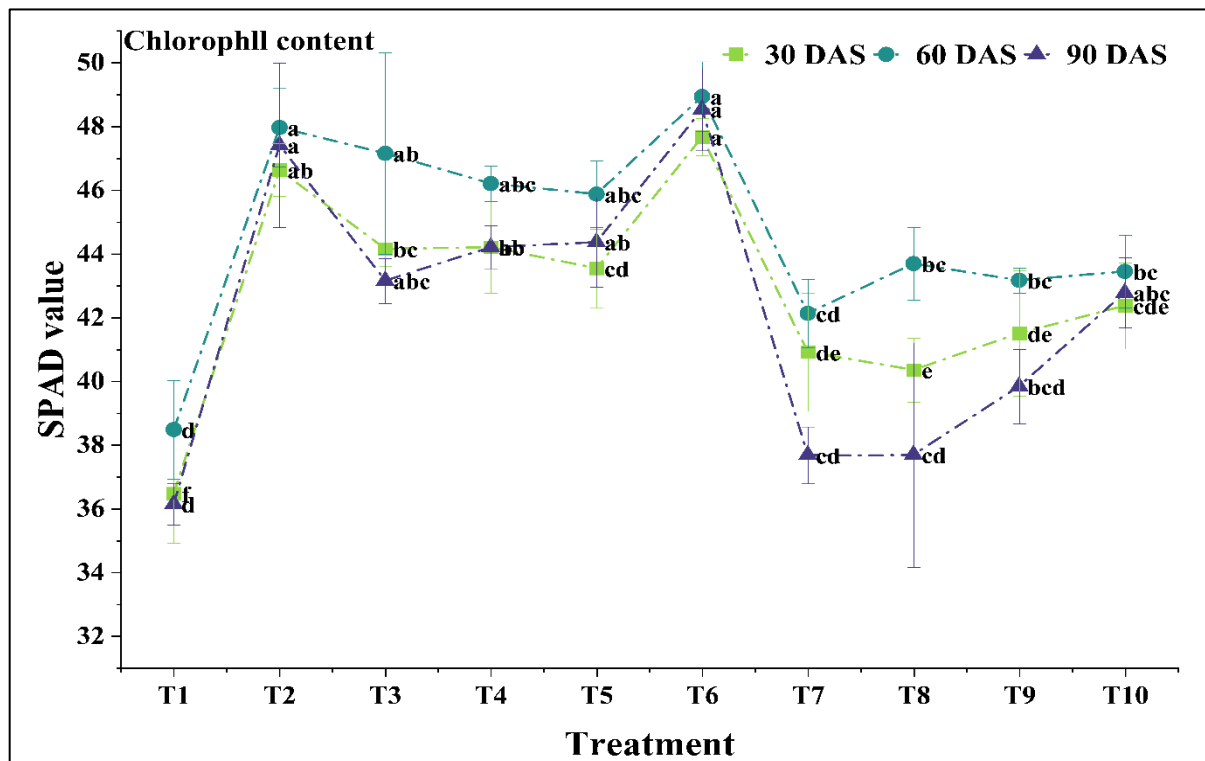


Fig 4.20: Effect of different nutrient management practices on SPAD at 30, 60, and 90 of sweet sorghum in 2024

4.11 Internode length (cm)

Internode length increased significantly with different nutrient management practices, as observed at harvest (Table 11).

T6 showed the highest results in terms of internode length, reaching 16.40 cm in 2023 and 16.55 cm in 2024, which was statistically similar to the other treatments. Meanwhile, the control (T1) had the shortest internode length at about 13.36 cm in both years. These findings clearly demonstrate that applying appropriate nutrients greatly enhances internode length.

Internode length increases with zeolite, press-mud, and bio-neema due to improved nutrient supply, better stem physiology, and reduced stress. This combination provides sustained nitrogen, enhancing cell elongation, promoting root activity, and maintaining hormonal balance, which are essential for stem extension (Hazrati *et al.* 2017). However, minimize pest damage to preserve auxin and gibberellin activity, which drive internode growth. Together, these amendments support longer, healthier internodes (Ram *et al.* 2024; Suman *et al.* 2023).

4.12 Number of internodes plant⁻¹

The data showed that nutrient management strategies significantly affected the total number of internodes at harvest (Table 11).

T6 had the highest number of internodes per plant (14.67 in 2023 and 14.68 in 2024), markedly exceeding the control (10.88 and 10.77). However, T6 was statistically similar to T2, T3, T4, T5, and T10. Treatments T7, T8, and T9 also showed no significant differences among themselves. These results clearly demonstrate that proper nutrient application greatly increases internode length.

The number of internodes per plant increases under integrated nutrient management practices, due to improved nutrient and hormonal regulation and reduced biotic stress. These combinations provide consistent nitrogen and potassium availability, supporting ongoing cell division at stem nodes (Prabhavathi and Ramakrishna Parama, 2019). While boosting root activity, supporting active meristem growth, and maintaining hormone flow, which are essential for node formation, these changes collectively encourage vigorous stem development, resulting in more internodes per plant (Bybordi *et al.* 2018).

Table 4.11 Effect of different nutrient management strategies on the number of internodes and length of internode (cm) of sweet sorghum

Treatments	Length of internode (cm)		Number of internodes	
	2023	2024	2023	2024
T1	13.59	13.54	10.97	10.90
T2	16.05	16.32	14.48	14.75
T3	15.17	15.91	14.45	14.75
T4	15.00	15.11	14.07	14.37
T5	15.09	15.52	14.45	14.28
T6	16.40	16.55	14.67	14.68
T7	15.00	15.00	13.25	13.49
T8	14.99	14.78	13.25	13.69
T9	14.97	14.85	13.38	13.64
T10	15.00	15.10	13.71	13.68
SEm ($\pm$)	0.58	0.61	0.42	0.60
LSD ($p=0.05$)	1.72	1.82	1.24	1.78

T1-* Control (Absolute), T2-*100 % RDF (90:40:40 NPK), T3-*75 % RDF +Zeolite (1.5 t ha^{-1}), T4*75 % RDF +Press-mud (15 t ha^{-1}), T5-*75 % RDF +Zeolite (1.5 t ha^{-1}) +Press-mud (15 t ha^{-1}), T6-*75 % RDF +Zeolite (1.5 t ha^{-1}) + Press-mud (15 t ha^{-1}) +Bio-neema (5 kg ha^{-1}), T7-*Nano NPK (19:19:19) +Zeolite (1.5 t ha^{-1}), T8-*Nano NPK (19:19:19) + Press-mud (15 t ha^{-1}), T9-*Nano NPK (19:19:19) + Zeolite (1.5 t ha^{-1}) + Press-mud (15 t ha^{-1}), T10-* Nano NPK (19:19:19) + Zeolite (1.5 t ha^{-1}) +Pressmud (1.5 t ha^{-1}) +Bio-neema (5 kg ha^{-1}). SEm-*Standard Error of Mean, LSD ($p =0.05$)-* Least Significant Difference at 5 % significance level.

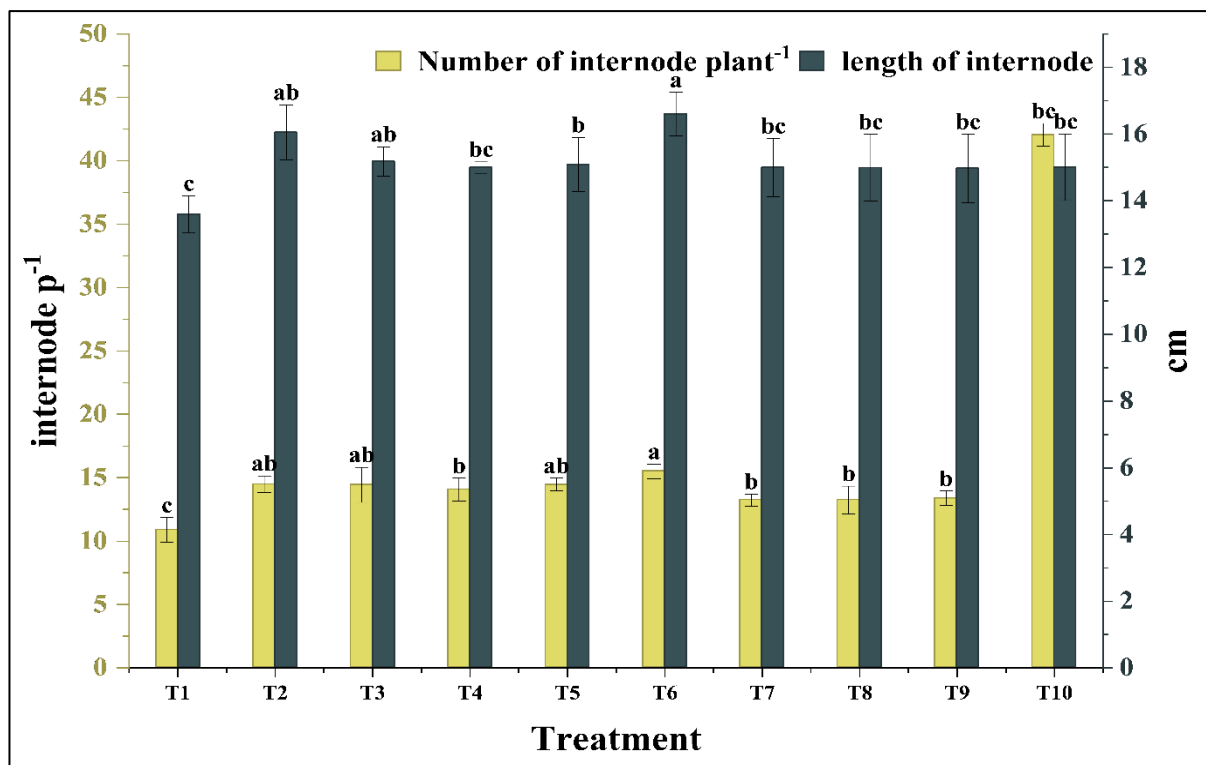


Fig 4.21: Effect of different nutrient management practices on number of internode and length of nodes at harvest of sweet sorghum in 2023

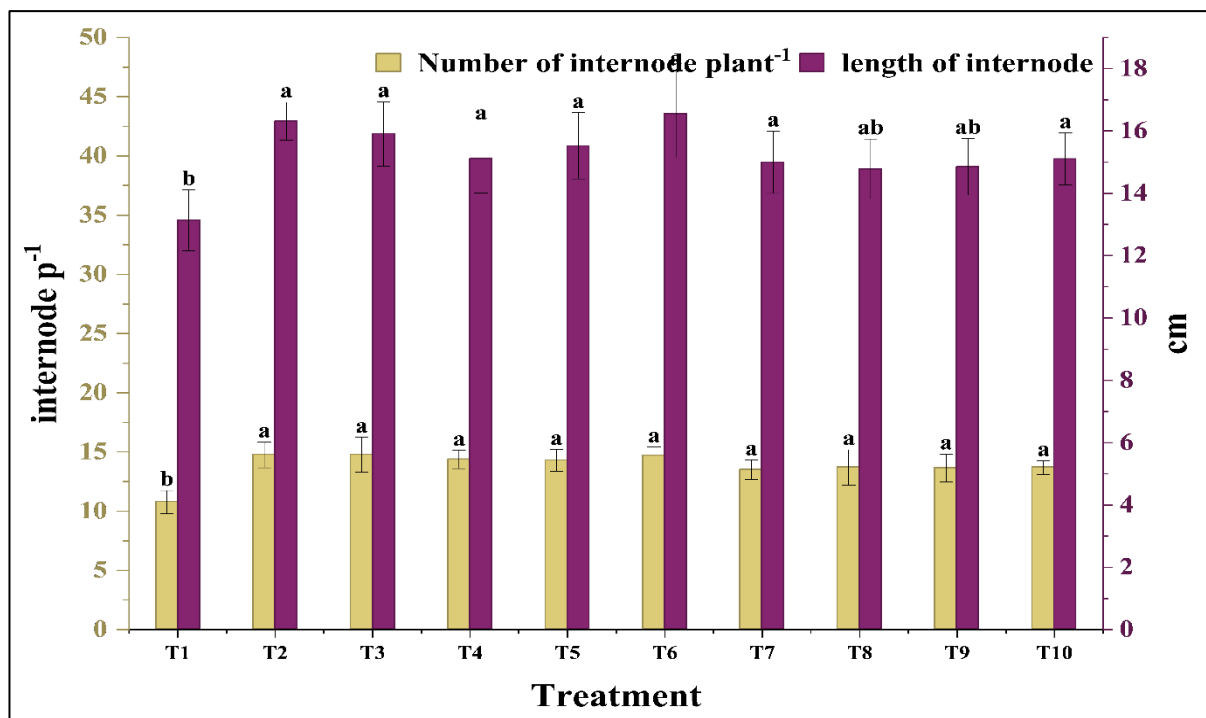


Fig 4.22: Effect of different nutrient management practices on number of internode and length of nodes at harvest of sweet sorghum in 2024

4.2 Yield parameters

Yield and yield attributes as influenced by the different nutrient management practices in sweet sorghum in 2023 and 2024.

4.2.1 Number of panicle (Head⁻¹)

The data on the number of panicle heads per plant were significantly affected by different nutrient management practices (Table 12).

T6 produced the highest number of panicles per ear head, reaching 42.99 in 2023 and 45.66 in 2024. These values were statistically similar to those of T5, which recorded 41.44 and 42.11 in the same years, followed by T3, T4, and T5. Conversely, the untreated control (T1) consistently showed the lowest yield, with values of 31.65 in 2023 and 26.98 in 2024. Treatments T7, T8, T9, and T10 yielded results that were statistically comparable.

An increase in panicle number occurs when plants receive balanced nutrition, improved soil conditions, and minimal stress. Inorganic fertilizers quickly supply essential macro and micronutrients, encouraging vigorous vegetative growth. While zeolite and press-mud regulate development throughout the growth stage, they increase soil organic matter and microbial activity, strengthening the root system (Rahmani *et al.* 2023). Moreover, this nutrient combination enhances nutrient retention and moisture availability, supporting cytokinin-mediated cell division that promotes continuous vegetative growth, leading to higher nutrient accumulation and more panicle initiation (Jha *et al.* 2017).

4.2.2 Number of grains head⁻¹

Significant differences in the number of grains per ear head were observed among the treatments (Table 12).

The highest number of grains was recorded in T6 (1805.72 in 2023 and 2169.72 in 2024), which was statistically similar to T5 (1740.48 in 2023 and 2076.48 in 2024). Treatments T2, T3, and T4 also contributed to higher grain counts per ear head. The untreated control (T1) resulted in the lowest number of grains per ear head in both years, with counts of 1329.30 and 1130.30.

The increase in the number of grain heads may be due to higher nutrient uptake, which is strongly associated with the maximum number of grains per head. These combinations provide readily available macro- and micronutrients that enhance panicle

length, floret initiation, and pollen development, ensuring higher ovule fertility and grain-setting efficiency in more viable spikelet's (Wu *et al.* 2019; Shenoy, 2020). Together, these inputs enhance spikelet fertility, improve grain-set efficiency, and ultimately increase the number of grains per head. The results closely support these findings by Prabhavathi and Ramakrishna Parama (2019).

4.2.3 Length of ear head (cm)

The data on ear head length (cm) were significantly influenced by different nutrient management strategies (Table 12).

Results showed that the maximum ear head length was achieved with treatment T6, measuring 17.67 cm in 2023 and 19.67 cm in 2024. This yield was statistically similar to T5, which recorded 16.33 cm in 2023 and 18.50 cm in 2024. Additionally, T2, T3, T4, and T10 also showed relatively longer ear heads. In contrast, the absolute control (T1) had the shortest ear head length in both years, with values of 12.58 cm in 2023 and 11.33 cm in 2024.

The length of the ear head increases when nutrient availability, panicle meristem activity, and the structural development of the reproductive shoot are optimized through combined nutrient application. These amendments quickly supply nutrients, boosting panicle elongation, cell division, and vascular differentiation within the rachis. Furthermore, zeolite enhances soil nutrient retention and moisture stability, maintaining a continuous nitrogen supply that supports internode expansion along the ear head axis (Rahmani *et al.* 2023). Pressmud and bio-neema provide organic carbon and micronutrients that strengthen root structure and increase carbohydrate translocation to the developing head (Lucena *et al.* 2018). Overall, these inputs improve soil health, stabilize plant metabolism, enhance assimilate supply, and sustain reproductive health, resulting in a significantly longer ear head with greater yield potential.

4.2.4 Girth of ear head (cm)

The data on the girth of the ear head are significantly affected by various nutrient management practices (Table 13).

T6 produced the largest ear head girth (cm), reaching 5.75 cm in 2023 and 5.98 cm in 2024. These values were statistically similar to those of T5 (5.29 cm and 5.57 cm), T3 (4.93 cm and 5.24 cm), T4 (5.29 and 5.42 cm), and T2 (5.43 cm and 5.39 cm). In the same year, treatments T7 to T10 showed statistically comparable results, while

the control (T1) consistently recorded the smallest girth, with 4.36 cm in 2023 and 4.11 cm in 2024.

The girth of the ear head increases when soil nutrient dynamics, moisture levels, and reproductive tissue development are enhanced through zeolite, press-mud, and a neema-based botanical protectant. While zeolite improves nutrient buffering and water retention, it also supports turgor-driven cell expansion and strengthens vascular bundles within the developing ear head (Rahmani *et al.* 2023). Press-mud enriches the soil with organic carbon, phosphorus, and micronutrients, enhancing root efficiency and increasing assimilate transport to reproductive tissues. The bio-neema botanical protectant reduces biotic stress, maintaining the hormonal balance needed for uniform spikelet enlargement and strong rachis development (Kalviavan and Hattab, 2016). Together, these amendments optimize physiological and anatomical growth, resulting in a thicker, healthier ear head.

Table 4.12 Effect of different nutrient management strategies on the number of panicles per ear head, number of grains per ear head, and length of ear head (cm) of sweet sorghum

Treatments	Number of panicles ear head-1		Number of grains ear head-1		Length of ear head (cm)	
	2023	2024	2023	2024	2023	2024
T1	31.65	26.98	1329.30	1130.30	12.58	11.33
T2	34.77	41.77	1460.48	1852.48	15.33	17.82
T3	37.00	43.00	1554.00	1806.00	13.96	15.45
T4	34.55	41.55	1451.10	1759.10	13.66	15.65
T5	41.44	42.11	1740.48	2076.48	16.33	18.50
T6	42.99	45.66	1805.72	2169.72	17.67	19.67
T7	32.44	36.44	1362.48	1530.48	12.78	15.03
T8	32.00	39.33	1343.86	1651.86	12.89	14.44
T9	32.77	38.11	1376.48	1600.48	13.66	14.58
T10	39.88	40.13	1675.10	1899.10	14.66	16.12
SEm ($\pm$)	0.86	1.46	36.20	80.32	0.44	0.35
LSD (p=0.05)	2.56	4.35	107.57	238.65	1.31	1.03

T1-* Control (Absolute), T2-*100 % RDF (90:40:40 NPK), T3-*75 % RDF +Zeolite (1.5 t ha⁻¹), T4*75 % RDF +Press-mud (15 t ha⁻¹), T5-*75 % RDF +Zeolite (1.5 t ha⁻¹) +Press-mud (15 t ha⁻¹), T6-*75 % RDF +Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹) +Bio-neema (5 kg ha⁻¹), T7-*Nano NPK (19:19:19) +Zeolite (1.5 t ha⁻¹), T8-*Nano NPK (19:19:19) + Press-mud (15 t ha⁻¹), T9-*Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹), T10-* Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) +Pressmud (1.5 t ha⁻¹) +Bio-neema (5 kg ha⁻¹). SEm-*Standard Error of Mean, LSD (p =0.05)-* Least Significant Difference at 5 % significance level.

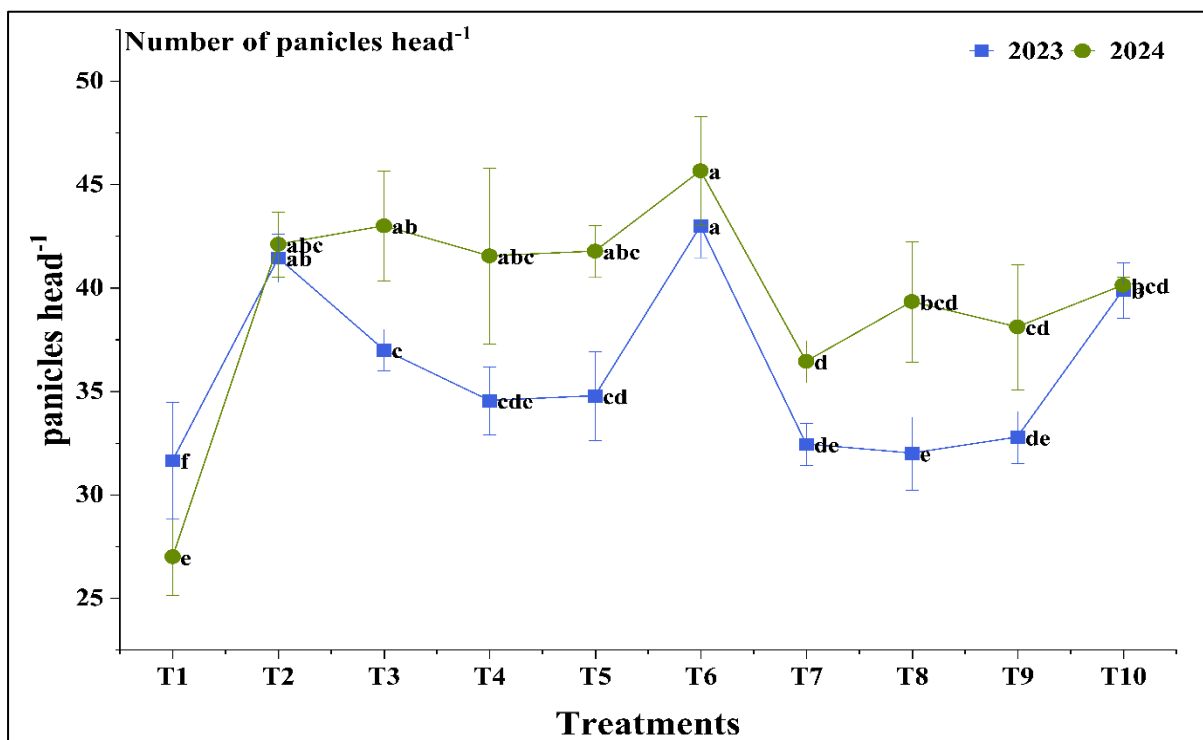


Fig 4.23: Effect of different nutrient management practices on number of panicles in 2023 and 2024 of sweet sorghum

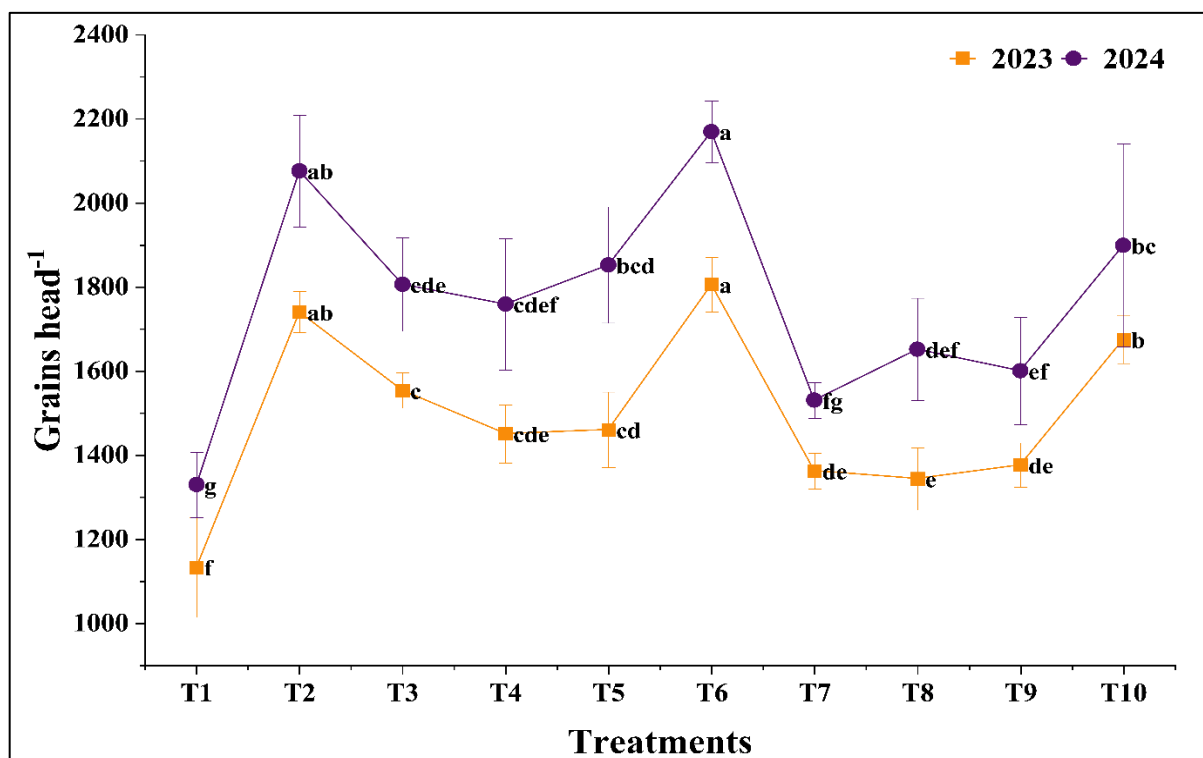


Fig 4.24: Effect of different nutrient management practices on number of grains in 2023 and 2024 of sweet sorghum

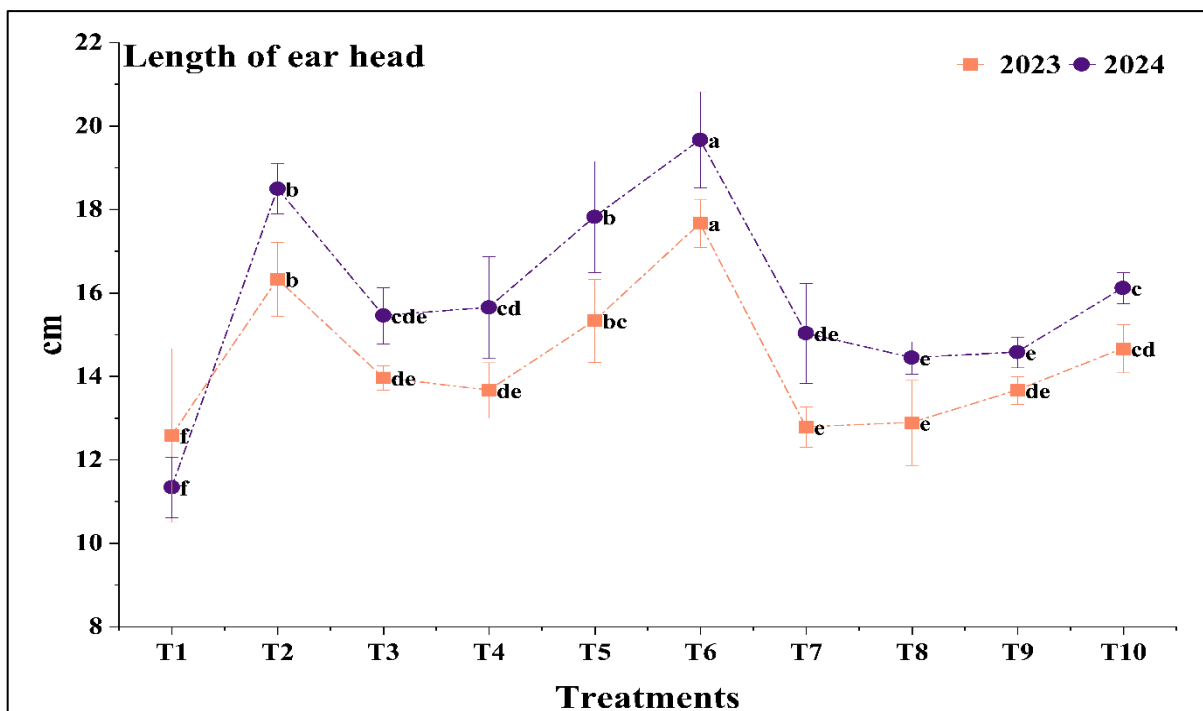


Fig 4.25: Effect of different nutrient management practices on length of ear head in 2023 and 2024 of sweet sorghum

4.2.5 Weight of grain ear head⁻¹

Significant differences in grain weight per ear head were observed among the treatments (Table 13).

The highest weight was recorded in T6 (87.76 g in 2023 and 95.35 g in 2024), which was statistically similar to T5 (75.60 g head⁻¹ and 92.61 g head⁻¹), followed by T2, T3, and T4. Treatments T7 to T10 showed statistically comparable results. The absolute control (T1) resulted in the lowest grain weight per head in both years, recording 52.20 g and 43.18 g.

The grain weight per head may increase due to optimized nutrient supply, assimilate distribution, and reproductive tissue health through an integrated approach to nutrient management practices. Furthermore, zeolite and press-mud retain nutrients, maintain vigorous photosynthetic activity, and ensure a continuous flow of carbohydrates to developing grains (Shahsavari *et al.* 2014). This composition also improves soil organic matter, strengthens roots, and enhances source-sink translocation efficiency during grain filling. Bio-neema reduces stress, protects spikelets' integrity, and maintains the hormonal balance necessary for full grain development and higher

grain mass. Collectively, these amendments improve grain set, filling rate, and overall grain weight per ear head (Xing *et al.* 2025; Basavaraja *et al.* 2017)

4.2.6 Test weight (g)

The data on test weight (g) were significantly influenced by different nutrient management practices (Table 13).

Results indicated that the highest test weight (g) was obtained with treatment T6, recording 47.67 g in 2023 and 47.91 g in 2024. This yield was statistically similar to treatments T2 through T5 in both years. Additionally, T7 to T10 were statistically comparable to each other across both years. In contrast, the absolute control (T1) had the lowest test weight, with values of 38.46 g in 2023 and 38.22 g in 2024.

A notable increase in test weight was observed with inorganic fertilizer, along with zeolite, press-mud, and bio-neema plant protectant applications, indicating improved grain development and filling efficiency (Poria *et al.* 2022). These nutrients enhanced photosynthetic carbon fixation, starch biosynthesis, and source-sink coordination, supported by extended nutrient availability, boosting enzymatic activity and hormonal balance, thereby promoting dense starch deposition, and resulting in heavier, well-filled grains (Bybordi *et al.* 2018).

4.2.7 Grain yield (q ha⁻¹)

The data indicated that nutrient management strategies significantly affected grain yield (q ha⁻¹) across both years (Table 13).

Among the treatments, T6 consistently outperformed the others, achieving the highest grain yields of 30.78 q ha⁻¹ in 2023 and 31.02 q ha⁻¹ in 2024. Conversely, the control T1 recorded the lowest yields, with 14.07 q ha⁻¹ and 13.65 q ha⁻¹. Importantly, T6 remained statistically similar to T5, which yielded 29.45 q ha⁻¹ in 2023 and 30.37 q ha⁻¹ in 2024, both showing higher yields. Treatments T7 through T10 produced results that were statistically comparable to each other.

The increase in sweet sorghum grain yield may be attributed to the availability of nutrients for timely uptake by the crop, likely due to the temporary retention of soil-exchangeable NH⁺, macro- and micronutrients in treatments with zeolite, press-mud, bioneema, and inorganic fertilizer compared to fully inorganic fertilizers (Akhzari and Alipoor 2019). These amendments act as stabilizers and regulators of mineral fertilizers, serve as nutrient sources, and help improve soil physico-chemical and

biological properties by providing essential food for microbes, thereby maximizing nutrient transfer from sources to sinks and boosting grain yield (Manikandan and Subramanian, 2016; Jha *et al.* 2017).

Table 4.13 Effect of different nutrient management practices on weight of grain per ear head (g), girth of ear head (cm), test weight (g), and grain yield (q) of sweet sorghum

Treatments	Weight of grain ear head ⁻¹ (g)		Girth of ear head (cm)		Test weight (g)		Grain yield (q ha ⁻¹)	
	2023	2024	2023	2024	2023	2024	2023	2024
T1	51.20	43.18	4.36	4.11	38.22	38.46	14.07	13.65
T2	67.90	86.95	5.43	5.39	46.38	47.08	26.66	27.57
T3	67.45	77.92	4.93	5.24	45.73	46.85	25.68	26.39
T4	67.61	80.75	5.29	5.42	46.55	46.82	23.98	24.80
T5	75.60	92.61	5.29	5.57	47.33	47.35	29.45	30.37
T6	87.76	95.35	5.75	5.98	47.67	47.91	30.78	31.02
T7	55.45	66.46	4.65	5.07	40.67	43.46	16.67	17.69
T8	57.13	70.17	4.51	4.57	42.55	42.32	17.44	18.82
T9	55.76	68.03	4.87	4.89	41.51	42.44	17.70	18.00
T10	70.30	81.53	4.65	4.96	42.93	43.10	18.33	19.67
SEm (±)	2.30	3.79	0.27	0.25	0.63	0.60	0.72	0.74
LSD (p=0.05)	6.85	11.27	0.81	0.74	1.87	1.78	2.12	2.21

T1-* Control (Absolute), T2-*100 % RDF (90:40:40 NPK), T3-*75 % RDF +Zeolite (1.5 t ha⁻¹), T4*75 % RDF +Press-mud (15 t ha⁻¹), T5-*75 % RDF +Zeolite (1.5 t ha⁻¹) +Press-mud (15 t ha⁻¹), T6-*75 % RDF +Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹) +Bio-neema (5 kg ha⁻¹), T7-*Nano NPK (19:19:19) +Zeolite (1.5 t ha⁻¹), T8-*Nano NPK (19:19:19) + Press-mud (15 t ha⁻¹), T9-*Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹), T10-* Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) +Pressmud (1.5 t ha⁻¹) +Bio-neema (5 kg ha⁻¹). SEm-*Standard Error of Mean, LSD (p =0.05)-* Least Significant Difference at 5 % significance level.

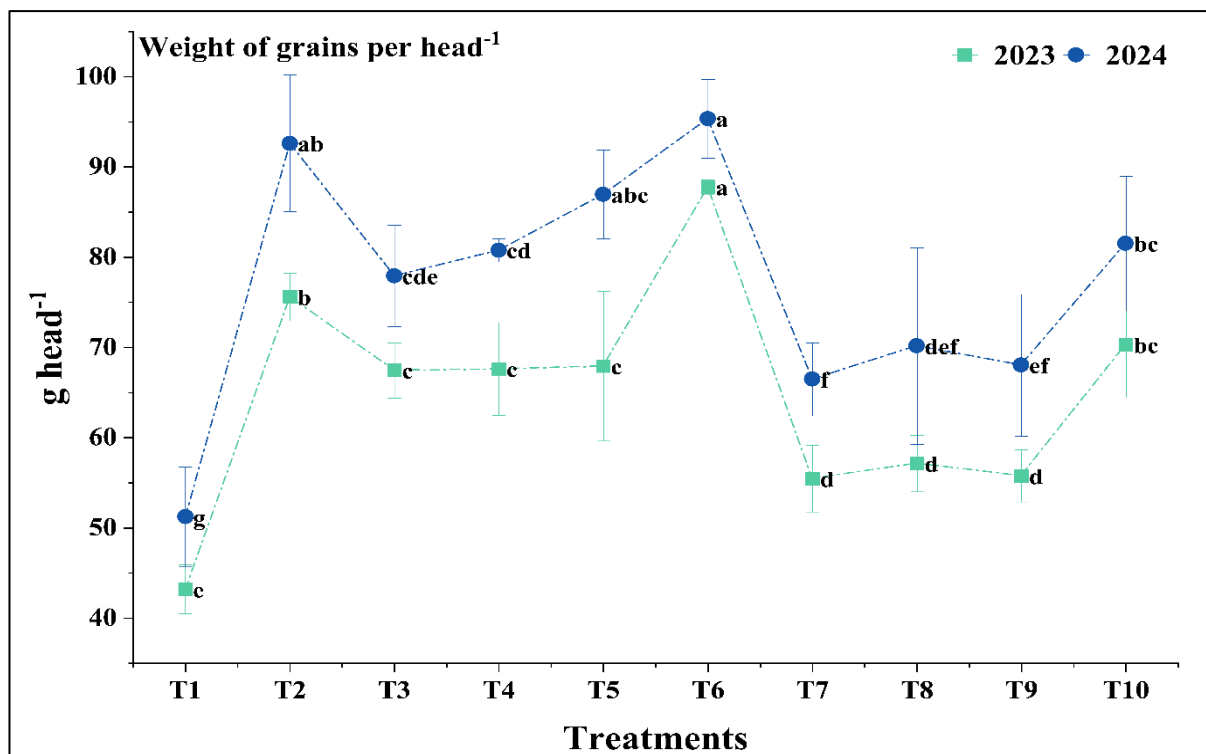


Fig 4.26: Effect of different nutrient management practices on weight of grains head⁻¹ in 2023 and 2024 of sweet sorghum

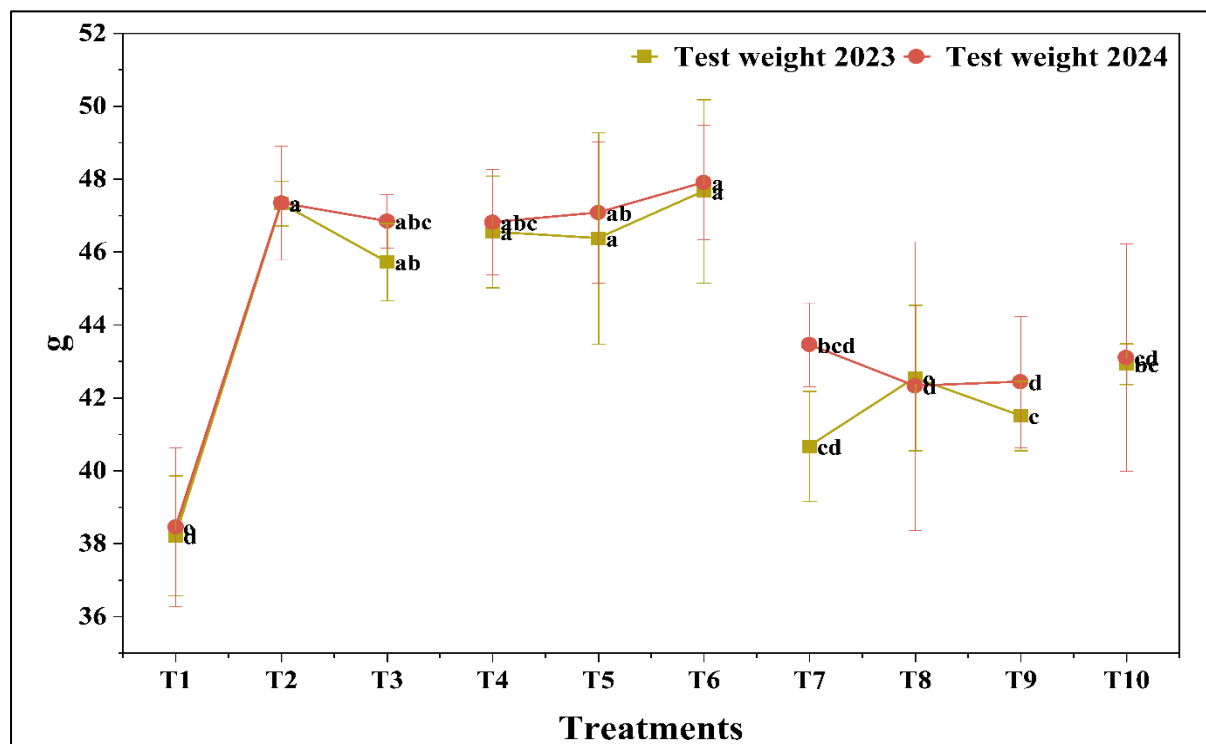


Fig 4.27: Effect of different nutrient management practices on test weight of grains in 2023 and 2024 of sweet sorghum

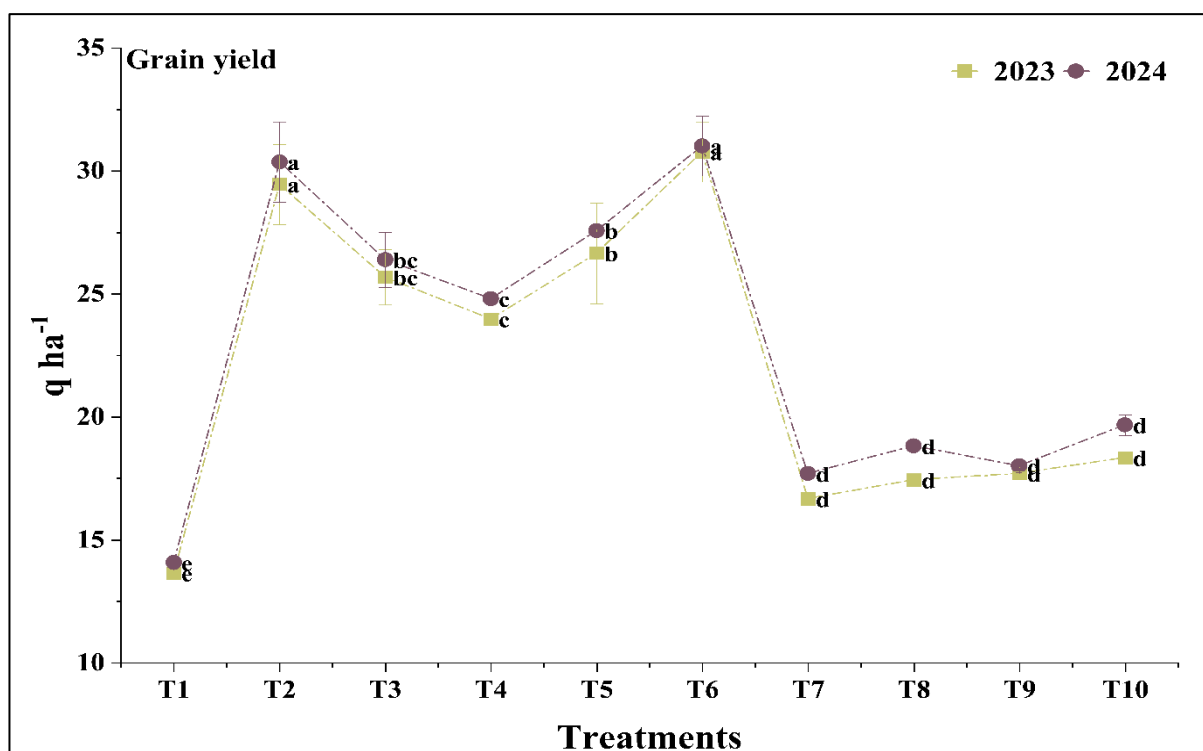


Fig 4.28: Effect of different nutrient management practices on grains yield in 2023 and 2024 of sweet sorghum

4.3 Sugar parameters

Sugar attributes as influenced by the various nutrient management strategies in sweet sorghum in 2023 and 2024.

4.3.1 Fresh stalk (t ha⁻¹)

The data on fresh stalk production is significantly influenced by various nutrient management strategies (Table 14).

T6 achieved the highest stalk yield per hectare, reaching 62.65 t ha⁻¹ in 2023 and 62.77 t ha⁻¹ in 2024. These results were statistically similar to those of T5, which recorded 59.05 and 60.83 t ha⁻¹ in the same years, followed by T2, T3, and T4. However, the absolute control (T1) consistently produced the lowest stalk yields, with values of 29.38 t ha⁻¹ and 28.18 t ha⁻¹ in 2023 and 2024, respectively. Treatments T7 to T10 showed statistically similar results to each other.

The improvement in fresh stalk yield of the crop may be ascribed to improved growth due to N fertilization, which facilitated photosynthesis and increased the translocation of organic food material towards the reproductive organs, thereby

enhancing the formation of more internodes and longer, as well wider internodes. While zeolite, with a permanent negative charge, adsorbs nutrient cations and releases them by ion exchange throughout the crop growth period, press-mud and bio-neema decomposition release carbon dioxide (Khaliq *et al.* 2024).

At the same time, the production of mucus and nitrogen excrements contributes to increased nitrogen levels in the soil. It increases the availability of nitrogen and other nutrients for plants compared to other treatments (Singh *et al.* 2021; Truong *et al.* 2023)

4.3.2 Juice extraction (%)

The data showed that nutrient management practices had a significant impact on juice extraction in sweet sorghum (Table 14).

Among the treatments, T6 consistently performed better than the others, recording the highest juice extraction rates, which reached 46.99% in 2023 and 47.81% in 2024. In comparison, the control T1 had the lowest juice extraction rates at 29.08% and 27.99%. Notably, T6 was followed by T2, T3, T4, and T5. Treatments T7 to T10 showed statistically similar results to each other.

The rise in juice extraction percentage might be due to the improved nutrient supply and use efficiency due to the honeycomb-like structure of zeolite-entrapped cation, which increases the macro and micro nutrient uptake to helped healthier plant and through organic sources like press-mud and bio-neema enhanced P concentration and uptake in soil expanding the solubilisation of Phosphorus either by microorganism activation with excretion of organic acid like citric, glutamic, and lactic acid to indicate more biomass which is lead to maximum extract (Mohammadnaseri and Tadayon, 2024). Increase yield due to varying levels of nutrients has also been reported (Basavaraja *et al.* 2017; Ozbahce *et al.* 2015)

4.3.3 Juice yield (l ha⁻¹)

The data on juice yield per hectare of litter were significantly influenced by different nutrient management practices (Table 14).

T6 produced the highest juice yield per hectare, reaching 29505.11 liters in 2023 and 30005.59 liters in 2024, followed by T2 (25701.60 liters and 27454.51 liters), T4 (25108.49 liters and 25348.51 liters), and T5 (25781.36 liters and 25957.72 liters). While the absolute control (T1) consistently resulted in the lowest values, with 8546.52

liters in 2023 and 7,872.98 liters in 2024. Treatments T7, T8, and T9 yielded statistically similar results.

The significant increases in nutrient uptake, maximum plant height, and biomass accumulation resulted in the highest juice yield in sweet stalks. The positive effects of zeolite, press-mud, and bio-neema in increasing soil inorganic fertilizer use efficiency, along with higher available water-holding capacity, greater adsorption capacity, and improved nutrient use efficiency by increasing the availability and uptake of macro- and micronutrients, could lead to increased juice yield in sweet sorghum (Ozbahce *et al.* 2015; Shenoy, 2020; Kavvadias *et al.* 2023)

Table 4.14 Effect of different nutrient management strategies on fresh stalk (t ha⁻¹), juice extraction percentage (%), juice yield (l ha⁻¹), and bagasse's content (%) of sweet sorghum

Treatments	Fresh stalk (t/ha)		Juice extraction percentage (%)		Juice yield (l ha ⁻¹)	
	2023	2024	2023	2024	2023	2024
T1	29.38	28.18	29.08	27.99	8546.52	7872.98
T2	58.33	58.49	44.07	44.37	25701.60	25957.72
T3	55.38	56.27	43.81	44.86	24269.55	25232.37
T4	57.38	56.81	43.74	44.63	25108.49	25348.51
T5	59.05	60.83	43.67	45.13	25781.36	27454.51
T6	62.65	62.77	46.99	47.81	29505.11	30005.59
T7	37.28	38.10	34.88	34.60	13019.13	13169.89
T8	36.83	37.94	34.58	35.12	12744.32	13307.27
T9	36.58	38.29	35.24	35.79	12893.17	13707.30
T10	37.38	38.73	36.92	37.88	13807.66	14672.41
SEm (±)	1.46	1.18	0.90	0.65	419.10	380.83
LSD (p=0.05)	4.34	3.51	2.66	1.92	1245.21	1131.51

T1-* Control (Absolute), T2-*100 % RDF (90:40:40 NPK), T3-*75 % RDF +Zeolite (1.5 t ha⁻¹), T4*75 % RDF +Press-mud (15 t ha⁻¹), T5-*75 % RDF +Zeolite (1.5 t ha⁻¹) +Press-mud (15 t ha⁻¹), T6-*75 % RDF +Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹)

+Bio-neema (5 kg ha⁻¹), T7-*Nano NPK (19:19:19) +Zeolite (1.5 t ha⁻¹), T8-*Nano NPK (19:19:19) + Press-mud (15 t ha⁻¹), T9-*Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹), T10-* Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) +Pressmud (1.5 t ha⁻¹) +Bio-neema (5 kg ha⁻¹). SEM-*Standard Error of Mean, LSD (p =0.05)-* Least Significant Difference at 5 % significance level.

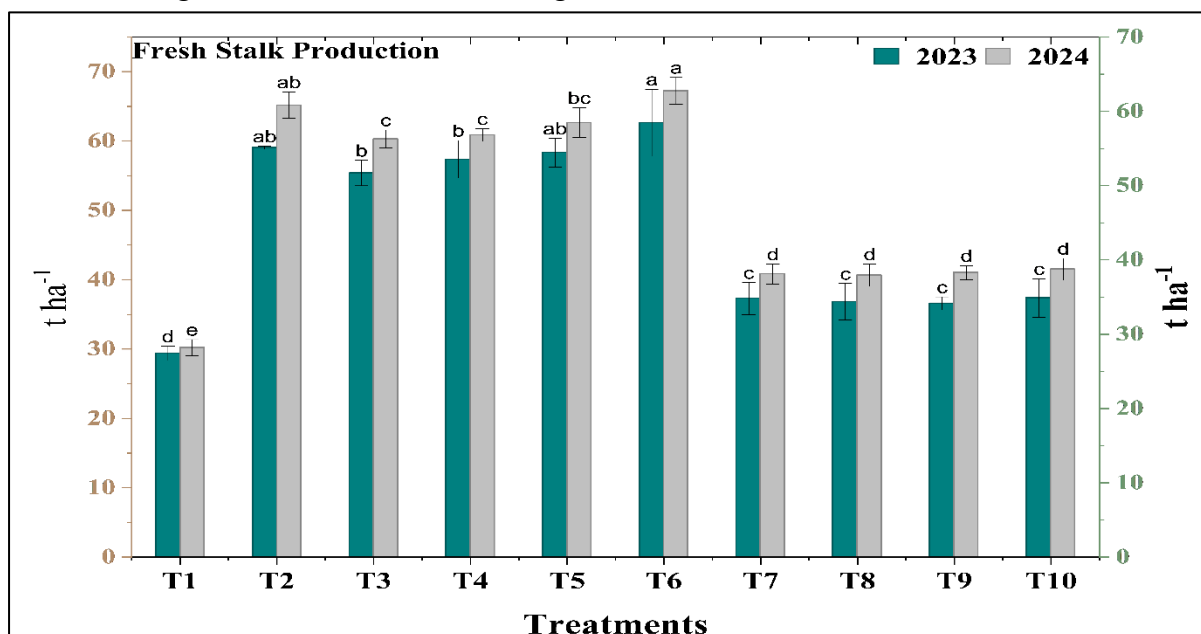


Fig 4.29: Effect of different nutrient management practices on fresh stalk yield in 2023 and 2024 of sweet sorghum

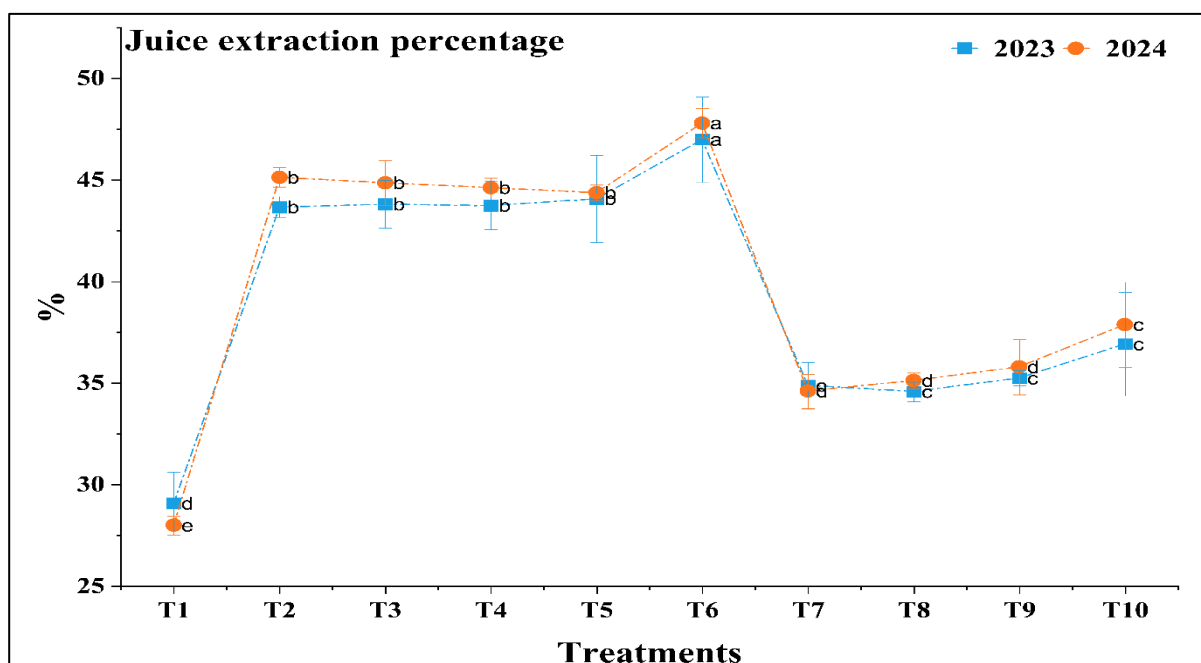


Fig 4.30: Effect of different nutrient management practices on juice extraction in 2023 and 2024 of sweet sorghum

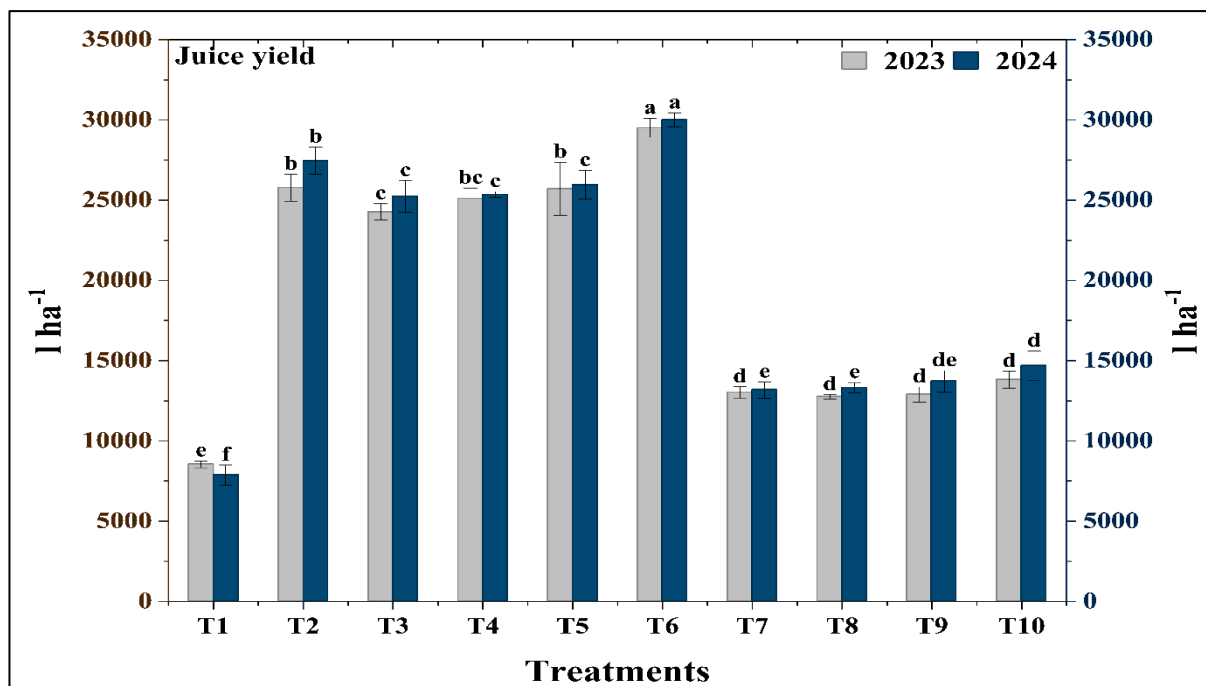


Fig 4.31: Effect of different nutrient management practices on juice yield in 2023 and 2024 of sweet sorghum

4.3.4 Fresh bagasse's content (%)

A significant variation in the percentage of fresh bagasse content was observed among the treatments (Table 15).

The highest levels of fresh bagasse were recorded in T1 (70.92% in 2023 and 72.01% in 2024), followed by T7 (65.12% and 65.40%), T8 (65.42% and 64.88%), T9 (64.76% and 64.21%), and T10 (63.08% and 62.12%) in 2023 and 2024, respectively. Treatment T6 (75% RDF + press-mud + zeolite + bio-neema) showed the lowest fresh bagasse content in 2023 (53.01%) and 2024 (52.19%). Treatments T2, T3, and T4 produced statistically similar results.

It is significantly influenced by stalk structure, moisture status, and overall plant physiology. Maximum availability of nutrients through combined sources of fertilizers enhances cell wall development and lignocellulose deposition, contributing to stronger and healthy plant along with organic specially press-mud and bio-neema to help in turn improvement in these characters was due to slow and steady rate of nutrient releases into soil solution to match the absorption pattern of crop, which lead to maximum fibrous tissue (Villarreal-Núñez *et al.* 2015; Basavaraja *et al.*, 2017; Cataldo *et al.* 2021)

4.3.5 Potential ethanol yield (l ha⁻¹)

The data on potential ethanol yield are significantly affected by various nutrient management practices (Table 15).

Among the treatments, T6 consistently performed better than the others, achieving the highest yields, reaching 2457.35 l ha⁻¹ in 2023 and 2646.02 l ha⁻¹ in 2024. This was followed by T5, which produced 2158.20 l ha⁻¹ and 2389.40 l ha⁻¹, compared to the control T1, which had the lowest potential ethanol yields of 545.12 l ha⁻¹ and 485.74 l ha⁻¹ in 2023 and 2024. Notably, treatments T8, T9, and T10 yielded statistically similar results.

Significantly higher ethanol output is achieved due to the plant accumulating more fermentable sugar, primarily sucrose, glucose, and fructose, in its stalk. Integrated nutrient management helped build a strong root system, boosting nutrient translocation toward the stalk (Mondal *et al.* 2021). Better water and nutrient buffering-maintained turgor pressure needed for sucrose storage, while reducing pest and oxidative stress preserved enzymatic pathways involved in sucrose synthesis and invertase activity, preventing assimilate diversion toward defence mechanisms. This elevated sugar concentration directly boosts ethanol yield (Prabhavathi *et al.* 2019)

4.3.6 Brix ratio (%)

The data showed that nutrient management practices significantly affected the Brix ratio (%) of sweet sorghum (Table 15).

Among the treatments, T6 consistently performed well, recording the highest Brix ratios (%), reaching 17.37% in 2023 and 18.26% in 2024, compared to the control T1, which had the lowest Brix ratios (%) at 13.20% and 12.80%. However, treatment T6 was statistically similar to T2, T3, and T5, and treatments T8 to T10 also showed statistically comparable results to each other in 2023 and 2024.

A high Brix value (ratio) might be due to high photosynthetic efficiency, optimized nutrient uptake, and carbohydrate translocation to the stalk. While zeolite and organic amendments improve soil properties and organic matter, and capture water and nutrients due to their high maximum pore space, which is most favourable for soil micro-organisms, helping increase nutrient availability and leading to higher sugar accumulation in the stalk, resulting in a higher brix ratio of sugar (Ram *et al.* 2024; Shahsavari *et al.* 2014; Eifediyi *et al.*, 2017).

Table 4.15 Effect of different nutrient management strategies on fresh bagasse's content (%), potential ethanol yield (l ha⁻¹), and brix ratio (%) of sweet sorghum

Treatments	Fresh bagasse's content (%)		Potential ethanol yield (l ha ⁻¹)		Brix (%)	
	2023	2024	2023	2024	2023	2024
T1	70.92	72.01	545.12	485.74	13.20	12.80
T2	55.93	55.63	2017.76	2139.89	16.27	17.08
T3	56.19	55.14	1850.85	2017.32	15.82	16.55
T4	56.26	55.37	1905.94	1989.52	15.67	16.25
T5	56.33	54.87	2158.20	2389.40	17.34	18.00
T6	53.01	52.19	2457.35	2646.02	17.37	18.26
T7	65.12	65.40	851.88	886.40	13.49	13.93
T8	65.42	64.88	928.62	901.91	15.11	14.05
T9	64.76	64.21	890.82	1026.83	14.30	15.51
T10	63.08	62.12	931.06	1042.12	14.00	14.67
SEm (±)	0.90	0.65	70.13	61.06	0.65	0.49
LSD (p=0.05)	2.66	1.92	208.38	181.43	1.92	1.46

T1-* Control (Absolute), T2-*100 % RDF (90:40:40 NPK), T3-*75 % RDF +Zeolite (1.5 t ha⁻¹), T4*75 % RDF +Press-mud (15 t ha⁻¹), T5-*75 % RDF +Zeolite (1.5 t ha⁻¹) +Press-mud (15 t ha⁻¹), T6-*75 % RDF +Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹) +Bio-neema (5 kg ha⁻¹), T7-*Nano NPK (19:19:19) +Zeolite (1.5 t ha⁻¹), T8-*Nano NPK (19:19:19) + Press-mud (15 t ha⁻¹), T9-*Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹), T10-* Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) +Pressmud (1.5 t ha⁻¹) +Bio-neema (5 kg ha⁻¹). SEm-*Standard Error of Mean, LSD (p =0.05)-* Least Significant Difference at 5 % significance level.

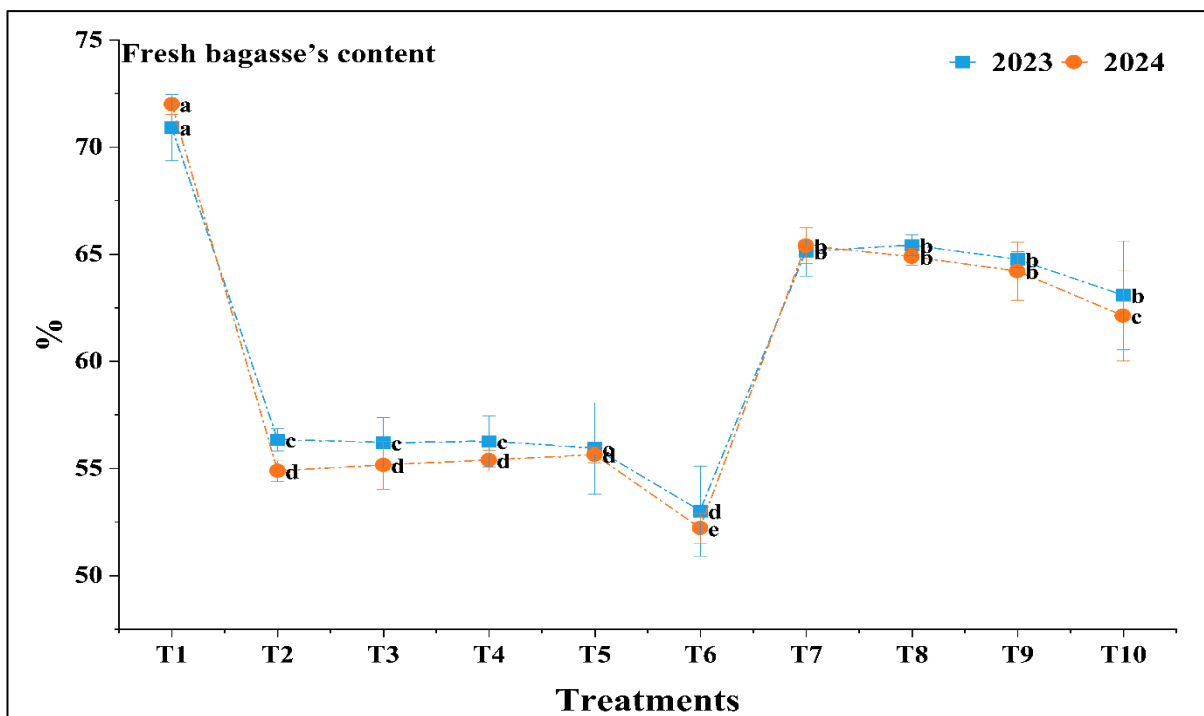


Fig 4.32: Effect of different nutrient management practices on fresh bagasse's content in 2023 and 2024 of sweet sorghum

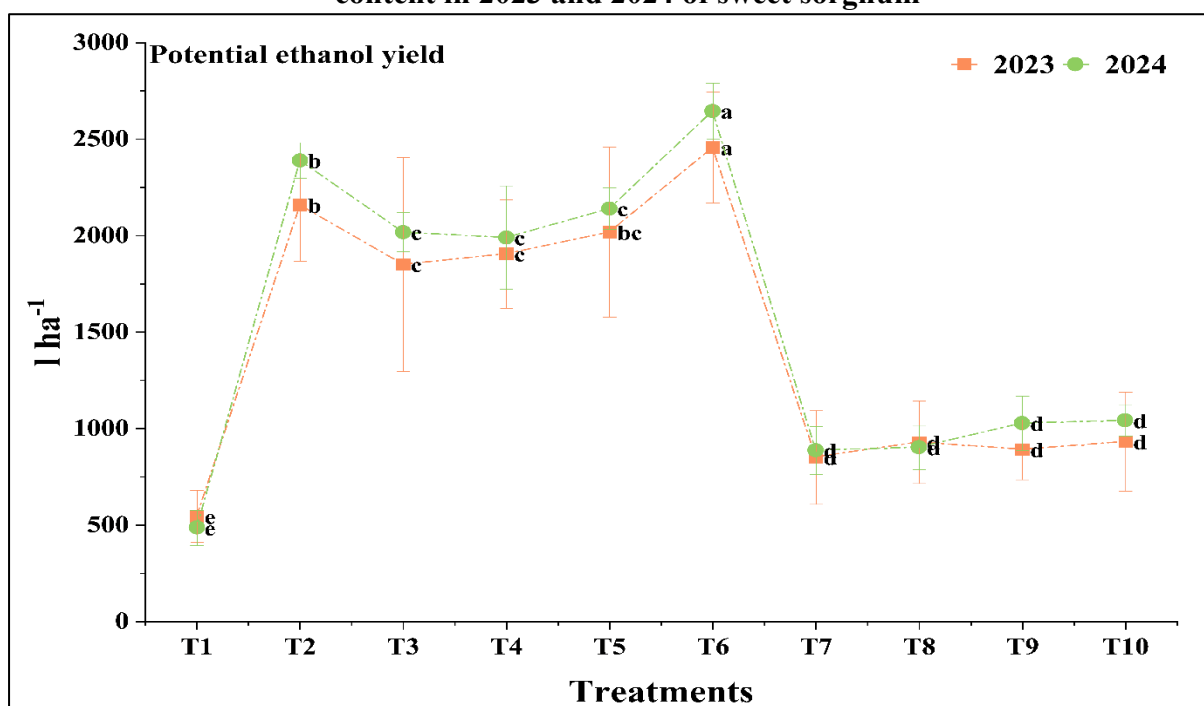


Fig 4.33: Effect of different nutrient management practices on potential ethanol yield in 2023 and 2024 of sweet sorghum

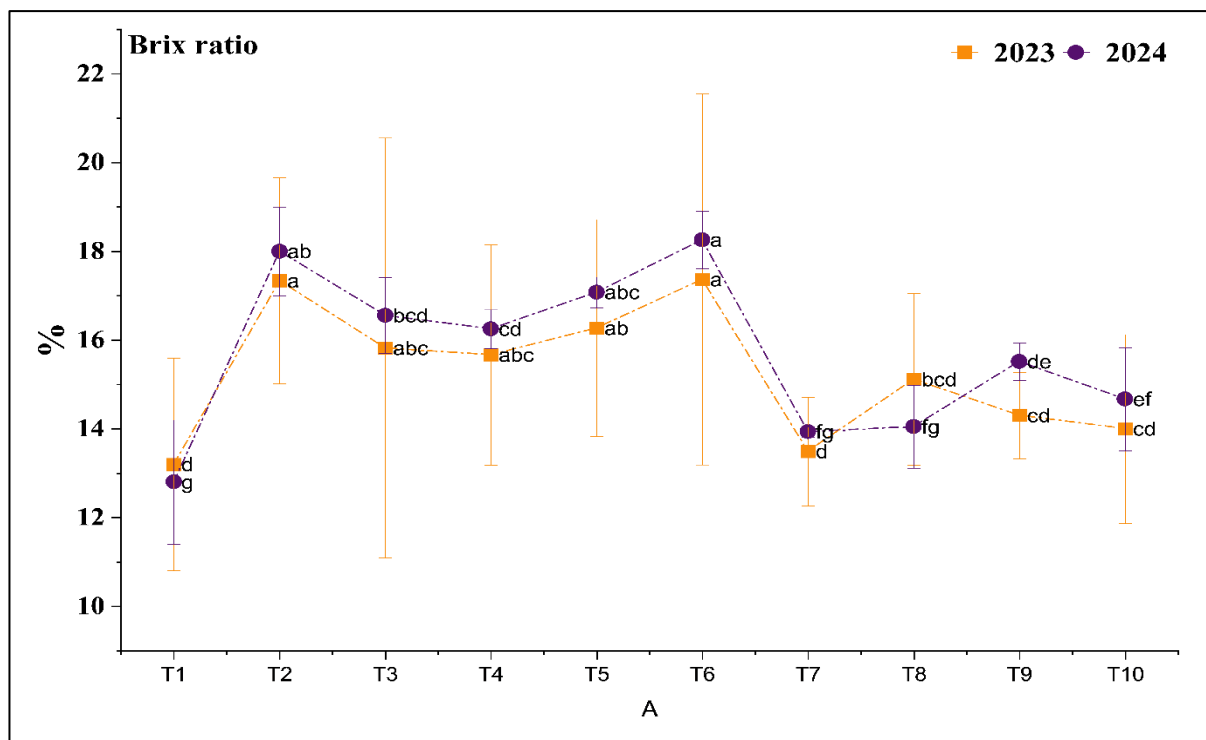


Fig 4.34: Effect of different nutrient management practices on brix ratio in 2023 and 2024 of sweet sorghum

4.3.7 Sugar yield (t ha^{-1})

Significant differences in sugar yield (t ha^{-1}) were observed among the treatments (Table 16).

The highest yield was recorded in T6 (4.49 t ha^{-1} in 2023 and 4.84 t ha^{-1} in 2024), which was statistically similar to T5 (3.95 t ha^{-1} and 4.37 t ha^{-1}), followed by T2, T3, and T4. Treatments T7 to T10 showed statistically similar results in both years. The absolute control (T1) produced the lowest sugar levels in both years, with 1 t ha^{-1} in 2023 and 0.89 t ha^{-1} in 2024.

The increase in sugar yield might be attributed to improved nutrient availability, higher stalk biomass, and greater accumulation of soluble sugar, which together enhance the overall extractable sugar content (Palanivell *et al.* 2019). Enhanced physiological activity resulting from balanced nutrient availability promotes efficient photosynthesis and better translocation of assimilates toward the stalk, thereby increasing juice volume and brix percentage. These findings agree with earlier reports (references) showing that improved soil nutrient buffering and moisture retention from soil amendments such as zeolite with inorganic fertilizers significantly enhanced crop quality (Lucena *et al.* 2018; Silva *et al.* 2024).

4.3.8 TSS (%)

The data showed that nutrient management practices significantly influenced the total soluble solids (%) of sweet sorghum (Table 16).

Among the treatments, T6 consistently performed well, recording the highest total soluble solids (%), at 15.32% in 2023 and 16.10% in 2024, compared to the control T1, which had the lowest total soluble solids (%) at 11.67% and 11.33%. However, treatment T6 was statistically similar to T2, T3, T4, and T5, and treatments T8 to T10 also produced statistically similar results to each other in 2023 and 2024.

The results indicate that zeolite is a storehouse of major macro- and micronutrients and provides a steady nutrient supply throughout the crop growth period. The honeycomb structure of zeolite with permanent negative charge is responsible for the absorption of nutrient cations and their subsequent release by ion exchange throughout the growth period of sweet sorghum (Bybordi *et al.* 2018). Organic amendments like press-mud and bio-neema rice in beneficial microorganism which aid in mineralization of plant nutrient in the soil and make them amenable to the plant roots and these microbes produce enzyme and growth regulator along with amino acids and many other organic acids which help to increase more nutrient uptake and accumulate biomass in stalk which helped improve total soluble solid (Latifah *et al.*, 2017; Nath *et al.*, 2020)

4.3.9 Juice pH (Acidity)

The data showed that nutrient management practices significantly affected the juice acidity (pH) of sweet sorghum juice (Table 16).

In T6, the highest pH value was 5.72 in 2023 and 5.93 in 2024. The other treatments also performed well, though slightly lower. The control plot (T1) had the lowest juice pH, with values of 4.96 and 4.97 in 2023 and 2024, respectively.

The increase in juice acidity was observed with the application of inorganic fertilizer along with zeolite, press-mud, and bio-neema, which might be due to zeolite stabilizing soil pH and providing a steady nutrient release via ion exchange, creating an optimal environment. The organic amendments introduce beneficial microorganisms that release enzymes, accelerating nutrient mineralization and making essential elements highly available (Chen *et al.* 2017). These microbes, along with the plant itself

under optimal nutrition, produce organic acids and metabolic byproducts to enhance nutrient uptake. These high-quality, balanced nutrient status ultimately leads to the accumulation of these organic acids within the sweet sorghum stalk, directly influencing and improving the titratable acidity and quality of juice. These findings are closely supported by (Sudha *et al.*, 2024)

Table 4.16 Effect of different nutrient management strategies on sugar yield (t ha⁻¹), TSS (%), and juice pH (acidity) of sweet sorghum

Treatments	Sugar yield (t ha ⁻¹)		TSS (%)		Juice pH	
	2023	2024	2023	2024	2023	2024
T1	1.00	0.89	11.67	11.33	4.96	4.97
T2	3.69	3.91	14.36	15.07	5.13	5.47
T3	3.39	3.69	13.97	14.61	5.41	5.42
T4	3.49	3.64	13.83	14.34	5.63	5.68
T5	3.95	4.37	15.30	15.88	5.62	5.75
T6	4.49	4.84	15.32	16.10	5.72	5.93
T7	1.56	1.63	11.93	12.32	5.28	5.28
T8	1.70	1.65	13.35	12.42	5.56	5.62
T9	1.65	1.88	12.64	13.70	5.26	5.28
T10	1.71	1.91	12.38	12.96	5.03	5.37
SEm (±)	0.13	0.11	0.57	0.43	0.19	0.19
LSD (p=0.05)	0.38	0.33	1.68	1.27	0.58	0.56

T1-* Control (Absolute), T2-*100 % RDF (90:40:40 NPK), T3-*75 % RDF +Zeolite (1.5 t ha⁻¹), T4-*75 % RDF +Press-mud (15 t ha⁻¹), T5-*75 % RDF +Zeolite (1.5 t ha⁻¹) +Press-mud (15 t ha⁻¹), T6-*75 % RDF +Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹) +Bio-neema (5 kg ha⁻¹), T7-*Nano NPK (19:19:19) +Zeolite (1.5 t ha⁻¹), T8-*Nano NPK (19:19:19) + Press-mud (15 t ha⁻¹), T9-*Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹), T10-* Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) +Pressmud (1.5 t ha⁻¹) +Bio-neema (5 kg ha⁻¹). SEm-*Standard Error of Mean, LSD (p =0.05)-* Least Significant Difference at 5 % significance level.

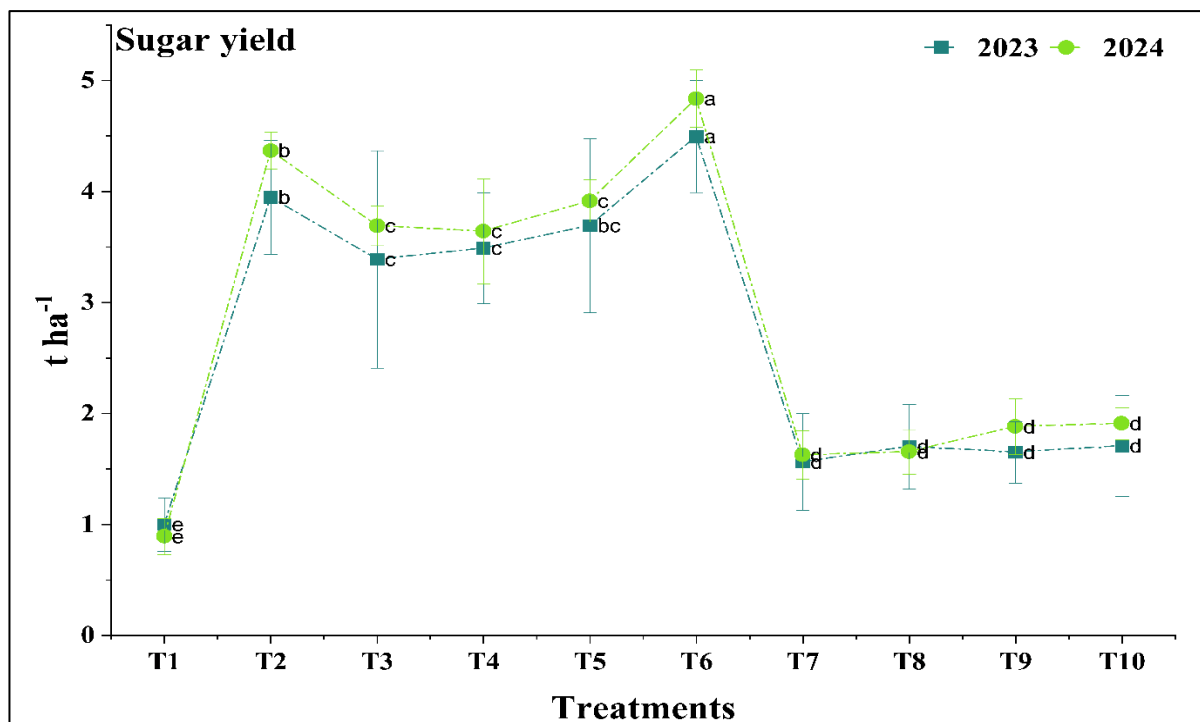


Fig 4.35: Effect of different nutrient management practices on sugar yield in 2023 and 2024 of sweet sorghum

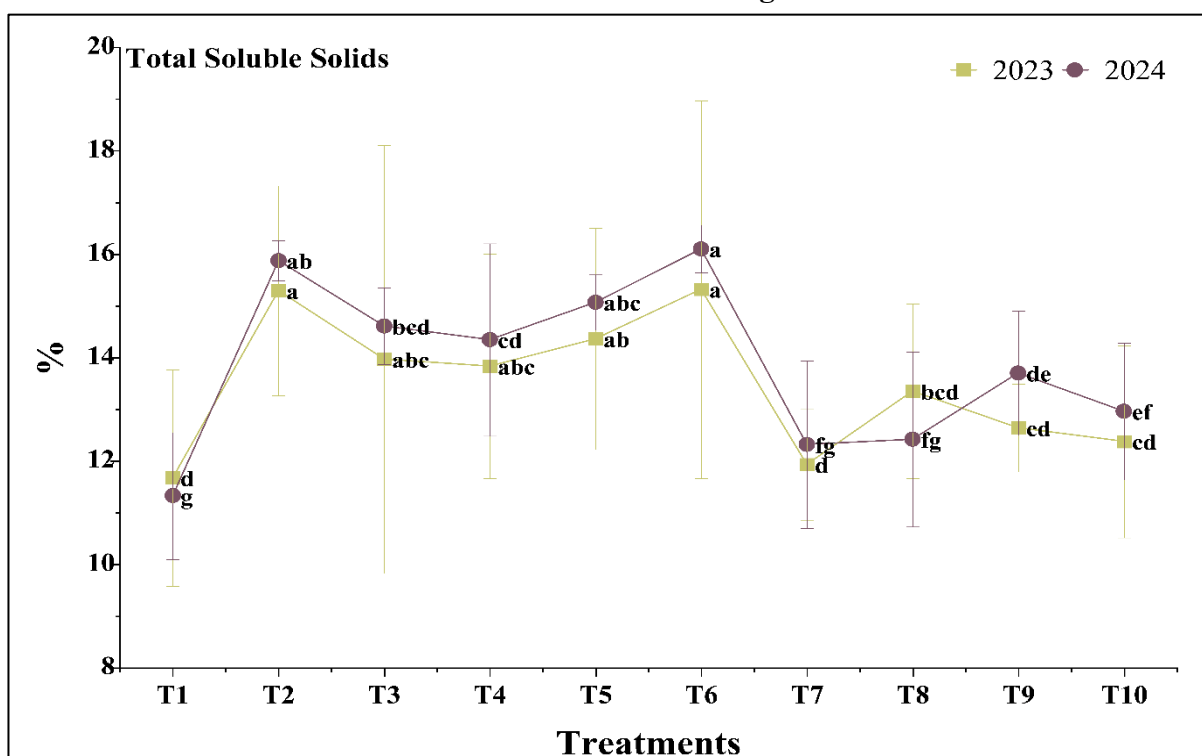


Fig 4.36: Effect of different nutrient management practices on total soluble solids (TSS) in 2023 and 2024 of sweet sorghum

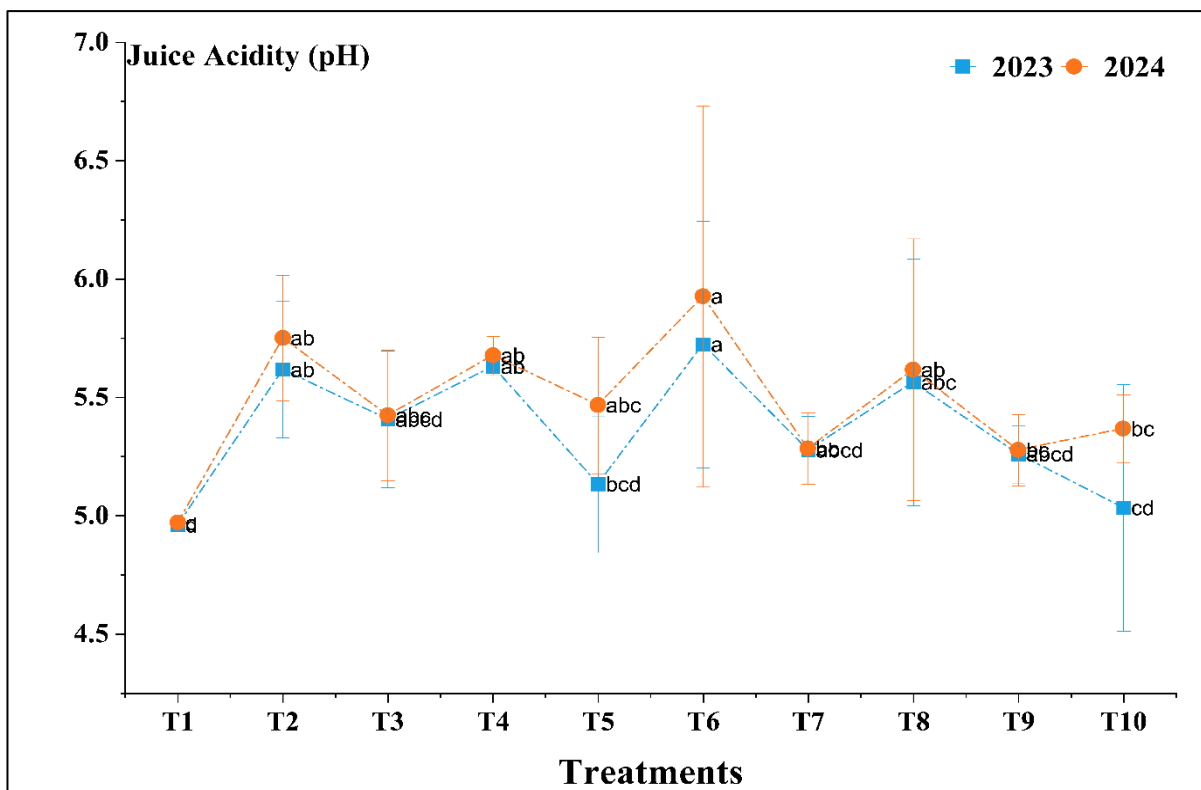


Fig 4.37: Effect of different nutrient management practices on juice acidity (pH) in 2023 and 2024 of sweet sorghum

4.3.10 Reducing sugar (%).

The data showed that nutrient management practices significantly affected the juice acidity (pH) of sweet sorghum juice (Table 16).

The highest reducing percentage (%) was observed in T6 (5.61% in 2023 and 5.88% in 2024), which was statistically similar to the other treatments. The absolute control (T1) had the lowest reducing sugar percentage recorded (3.89% and 3.94%) in 2023 and 2024.

The increased reducing sugar might be due to a powerful synergy between nutrients. At the same time, zeolite ensures a continuous, balanced nutrient supply by controlling the release of inorganic fertilizers (Kavvadias *et al.* 2023). However, organic amendments and microbes enhance overall plant metabolism and health, accelerating enzyme activity to support robust sugar production and translocation to the sweet sorghum stalk. (Naeem *et al.* 2022)

4.3.11 Non-reducing sugar (%)

The data on non-reducing sugars were greatly affected by different nutrient management practices (Table 17).

Treatment T6 showed the highest non-reducing sugar (%), reaching 10.32% in 2023 and 10.53% in 2024. These values were statistically similar to the rest of the treatments, including the absolute control.

The results indicate that non-reducing sugars increased steadily with the combined application of soil amendments and inorganic fertilizers. The increase in the K status might be attributed to the adsorption of K^+ ions within the honeycomb-like structure, which was released through alternate wetting and drying of the soil and ion exchange, ensuring a steady, constant supply of K to support efficient translocation and sucrose synthesis (Seif *et al.* 2016). This combined support maximizes the plant capacity for high-quality sugar storage and accumulation in sweet sorghum stalk (Bashir *et al.* 2021).

4.3.12 Total sugar index (%)

The data indicated that nutrient management strategies significantly increased the total sugar index of sweet sorghum during both years (Table 17).

Among the treatments, T6 consistently performed well; other treatments recorded the highest total sugar indices (%), reaching 15.93% in 2023 and 16.41% in 2024, compared to control T1, which had the lowest total sugar index (12.56% and 12.92%) in 2023 and 2024. However, T6 remained statistically similar to the other treatments.

The increase in total sugar index may be due to maximum nutrient uptake of sweet sorghum crop might be due to combined effect of organic sources of nutrient and inorganic fertilizers with zeolite is attributes the unique characters that influenced soil CEC and in turn increased the nutrient use efficiency especially nitrogen and potassium which maximizing photosynthesis and sugar production and the organic sources of nutrient enhance microbes, soil health, and metabolism supporting the efficient synthesis, transport and successful accumulation of total sugar index (reducing and non-reducing) in stalk (Sahebi *et al.* 2020; Maqsood *et al.* 2025)

Table 4.17 Effect of different nutrient management strategies on TSS (%), juice pH, total sugar index (%), reducing sugar, and non-reducing sugar (%) of sweet sorghum

Treatments	Reducing sugar (%)		Non-reducing sugar (%)		Total sugar index (%)	
	2023	2024	2023	2024	2023	2024
T1	3.86	3.94	8.70	8.98	12.56	12.92
T2	5.36	5.38	10.36	10.48	15.72	15.86
T3	5.46	5.53	10.10	10.41	15.56	15.94
T4	5.43	5.43	10.42	10.75	15.85	16.18
T5	5.52	5.54	10.48	10.57	16.00	16.10
T6	5.61	5.88	10.32	10.53	15.93	16.41
T7	5.19	5.21	9.89	9.81	15.08	15.02
T8	5.07	5.09	9.84	9.89	14.91	14.98
T9	5.08	5.12	9.81	9.69	14.89	14.81
T10	5.26	5.47	9.95	9.67	15.21	15.14
SEm ($\pm$)	0.40	0.38	0.49	0.39	0.74	0.60
LSD ($p=0.05$)	1.19	1.12	1.47	1.16	2.19	1.79

T1-* Control (Absolute), T2-*100 % RDF (90:40:40 NPK), T3-*75 % RDF +Zeolite (1.5 t ha^{-1}), T4*75 % RDF +Press-mud (15 t ha^{-1}), T5-*75 % RDF +Zeolite (1.5 t ha^{-1}) +Press-mud (15 t ha^{-1}), T6-*75 % RDF +Zeolite (1.5 t ha^{-1}) + Press-mud (15 t ha^{-1}) +Bio-neema (5 kg ha^{-1}), T7-*Nano NPK (19:19:19) +Zeolite (1.5 t ha^{-1}), T8-*Nano NPK (19:19:19) + Press-mud (15 t ha^{-1}), T9-*Nano NPK (19:19:19) + Zeolite (1.5 t ha^{-1}) + Press-mud (15 t ha^{-1}), T10-* Nano NPK (19:19:19) + Zeolite (1.5 t ha^{-1}) +Pressmud (1.5 t ha^{-1}) +Bio-neema (5 kg ha^{-1}). SEm-*Standard Error of Mean, LSD ($p =0.05$)-* Least Significant Difference at 5 % significance level.

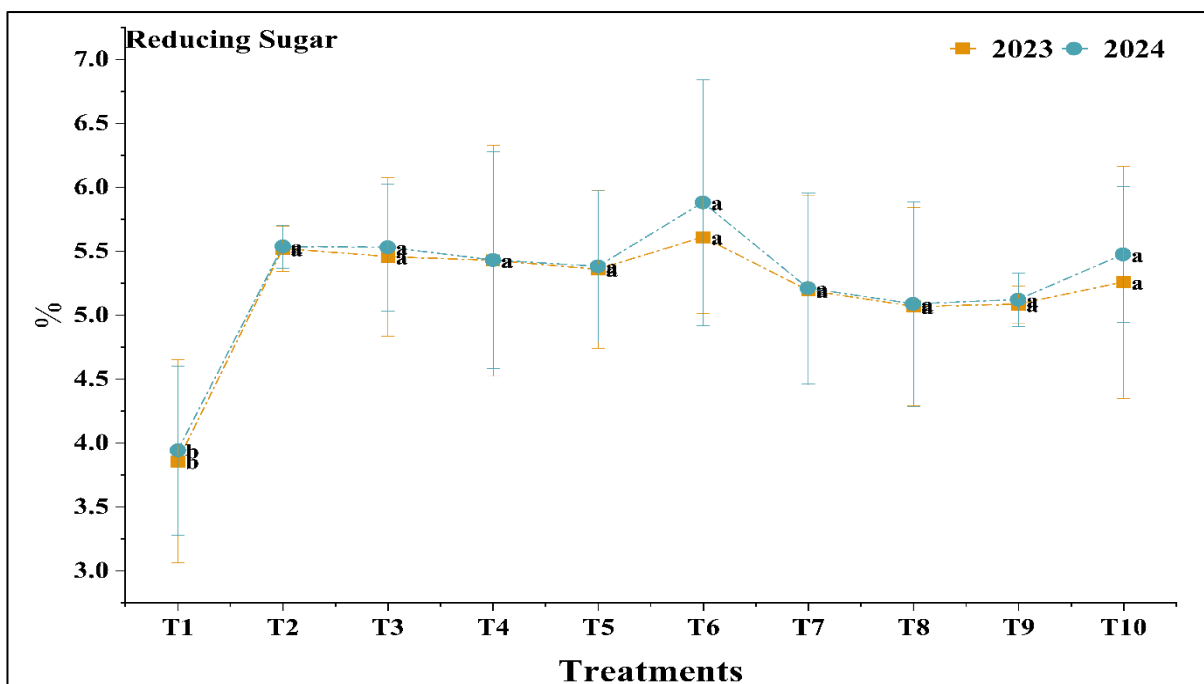


Fig 4.38: Effect of different nutrient management practices on reducing sugar in 2023 and 2024 of sweet sorghum

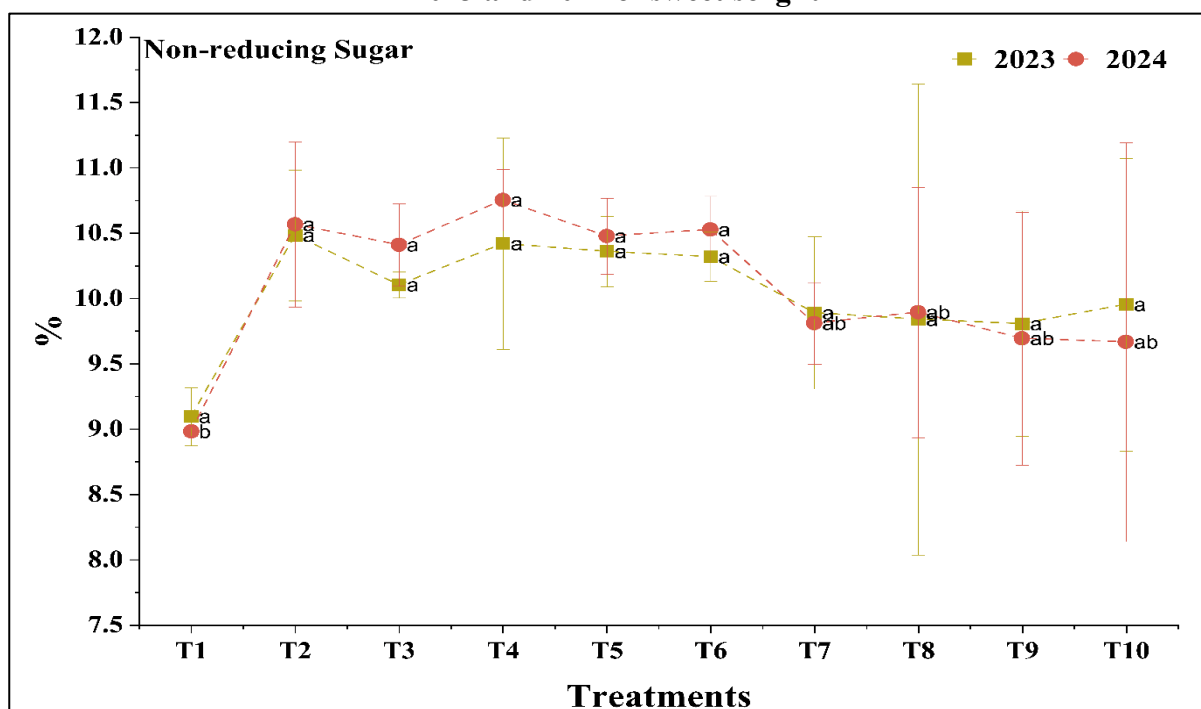


Fig 4.39: Effect of different nutrient management practices on non-reducing sugar in 2023 and 2024 of sweet sorghum

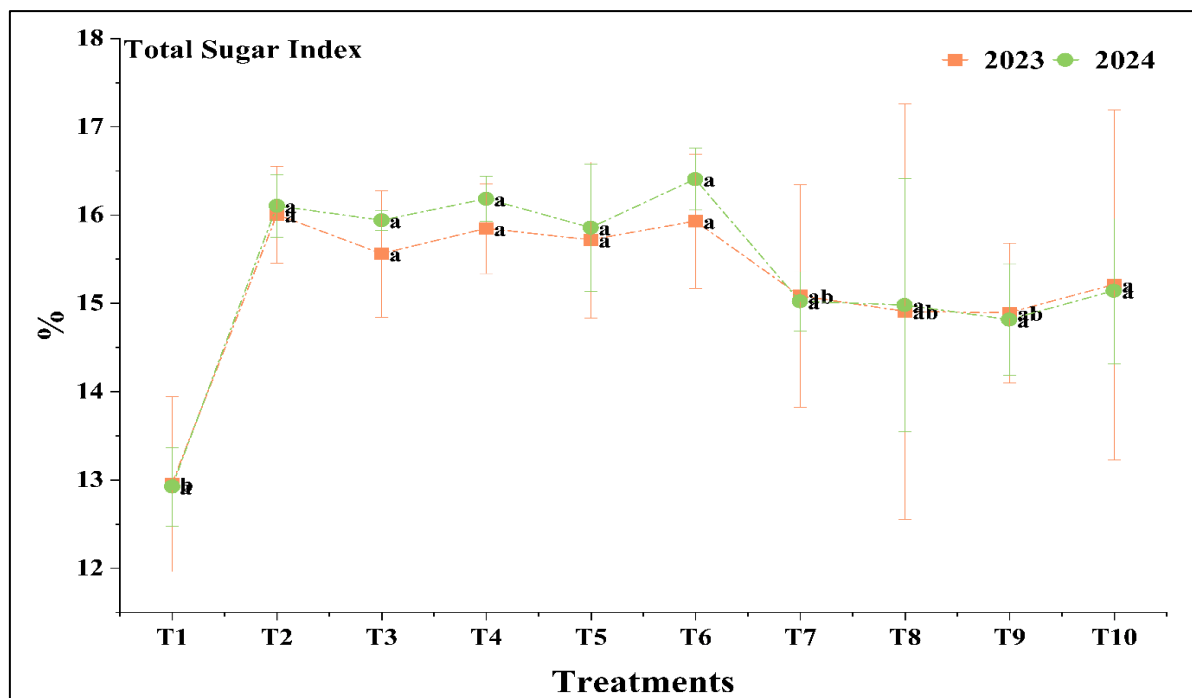


Fig 4.40: Effect of different nutrient management practices on total sugar index in 2023 and 2024 of sweet sorghum

4.4. Quality parameters

4.4.1 Chlorophyll 'a'

The data on sweet sorghum's chlorophyll content is affected by various nutrient management treatments at 30, 60, and 90 days during 2023 and 2024 (Table 18).

Chlorophyll a level increased significantly with different nutrient management strategies. T6 showed the highest chlorophyll 'a' content throughout the growth stages, at 30 days after sowing (DAS). T6 reached 1.27 mg g^{-1} in 2023 and 1.30 mg g^{-1} in 2024, while at 60 days after sowing, values were 1.66 mg g^{-1} in 2023 and 1.67 mg g^{-1} in 2024. This was significantly higher than the control (T1), which had the lowest chlorophyll content, around 0.95 mg g^{-1} in both years.

The superior of T6 persisted in later stages. At 90 DAS, it reached 1.39 mg g^{-1} in 2023 and 1.41 mg g^{-1} in 2024. Therefore, T1 remained the lowest, recorded at 1.02 mg g^{-1} and 1.07 mg g^{-1} , respectively. T5 continued to perform well, showing values statistically similar to T6.

The chlorophyll pigment increased significantly with the integrated nutrient application approach in the crop. Macronutrients like N and P, and micronutrients like Mg and Fe, are directly involved in the production of chlorophyll pigments, and zinc is associated with an enzyme that regulates several vital physiological functions in plants

(Ozbahce *et al.* 2018). It also governs the synthesis of chlorophyll, tryptophan, and ascorbic acid in plants. The application of inorganic fertilizers, along with soil amendments such as zeolite, press-mud, and bio-neema, might also have ensured the supply of these macro- and micronutrients, thereby increasing chlorophyll pigment content in sweet sorghum (Arulazhagan *et al.* 2024)

Table 4.18 Effect of different nutrient management strategies on chlorophyll ‘a’ of sweet sorghum

Treatments	Chlorophyll a 30 DAS		Chlorophyll a 60 DAS		Chlorophyll a 90 DAS	
	2023	2024	2023	2024	2023	2024
T1	0.97	0.96	1.12	1.13	1.02	1.07
T2	1.17	1.15	1.54	1.55	1.28	1.34
T3	1.23	1.16	1.53	1.60	1.26	1.32
T4	1.25	1.24	1.44	1.49	1.29	1.34
T5	1.18	1.19	1.55	1.58	1.28	1.37
T6	1.27	1.30	1.66	1.67	1.39	1.41
T7	1.16	1.15	1.31	1.35	1.19	1.23
T8	1.17	1.14	1.42	1.49	1.21	1.28
T9	1.14	1.11	1.31	1.34	1.16	1.20
T10	1.15	1.14	1.37	1.42	1.20	1.25
SEm ($\pm$)	0.04	0.03	0.06	0.08	0.04	0.06
LSD ($p=0.05$)	0.13	0.10	0.16	0.23	0.13	0.17

T1-* Control (Absolute), T2-*100 % RDF (90:40:40 NPK), T3-*75 % RDF +Zeolite (1.5 t ha⁻¹), T4-*75 % RDF +Press-mud (15 t ha⁻¹), T5-*75 % RDF +Zeolite (1.5 t ha⁻¹) +Press-mud (15 t ha⁻¹), T6-*75 % RDF +Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹) +Bio-neema (5 kg ha⁻¹), T7-*Nano NPK (19:19:19) +Zeolite (1.5 t ha⁻¹), T8-*Nano NPK (19:19:19) + Press-mud (15 t ha⁻¹), T9-*Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹), T10-* Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) +Pressmud (1.5 t ha⁻¹) +Bio-neema (5 kg ha⁻¹). SEm-*Standard Error of Mean, LSD ($p =0.05$)-* Least Significant Difference at 5 % significance level.

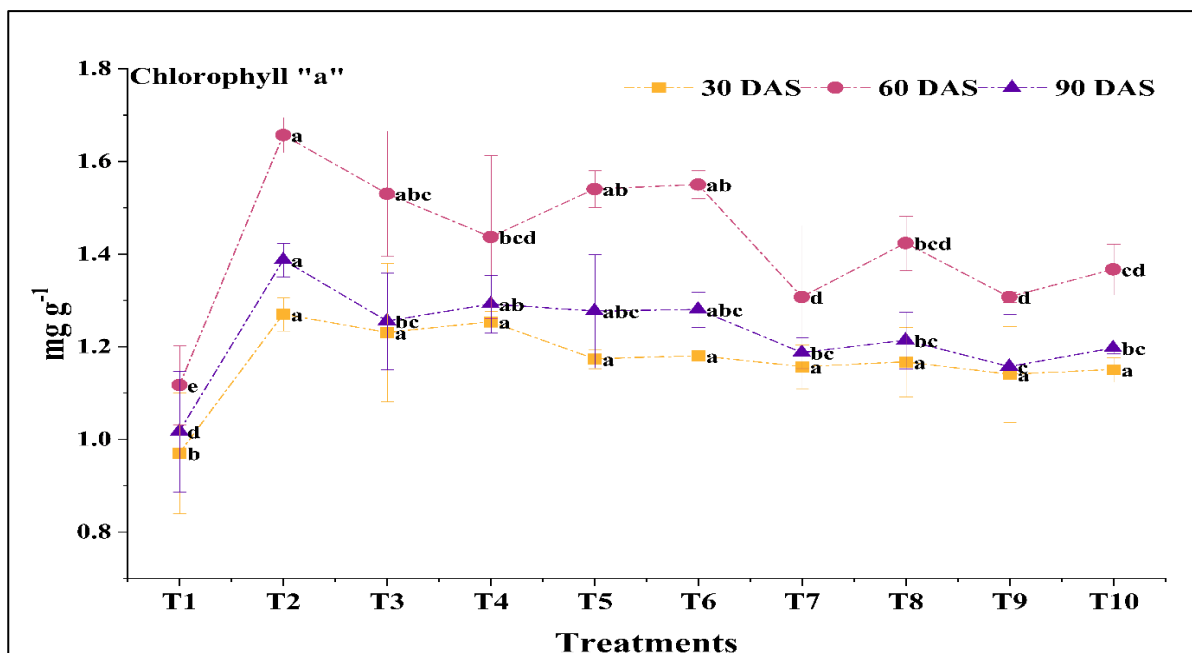


Fig 4.41: Effect of different nutrient management practices on chlorophyll content a in 2023 of sweet sorghum

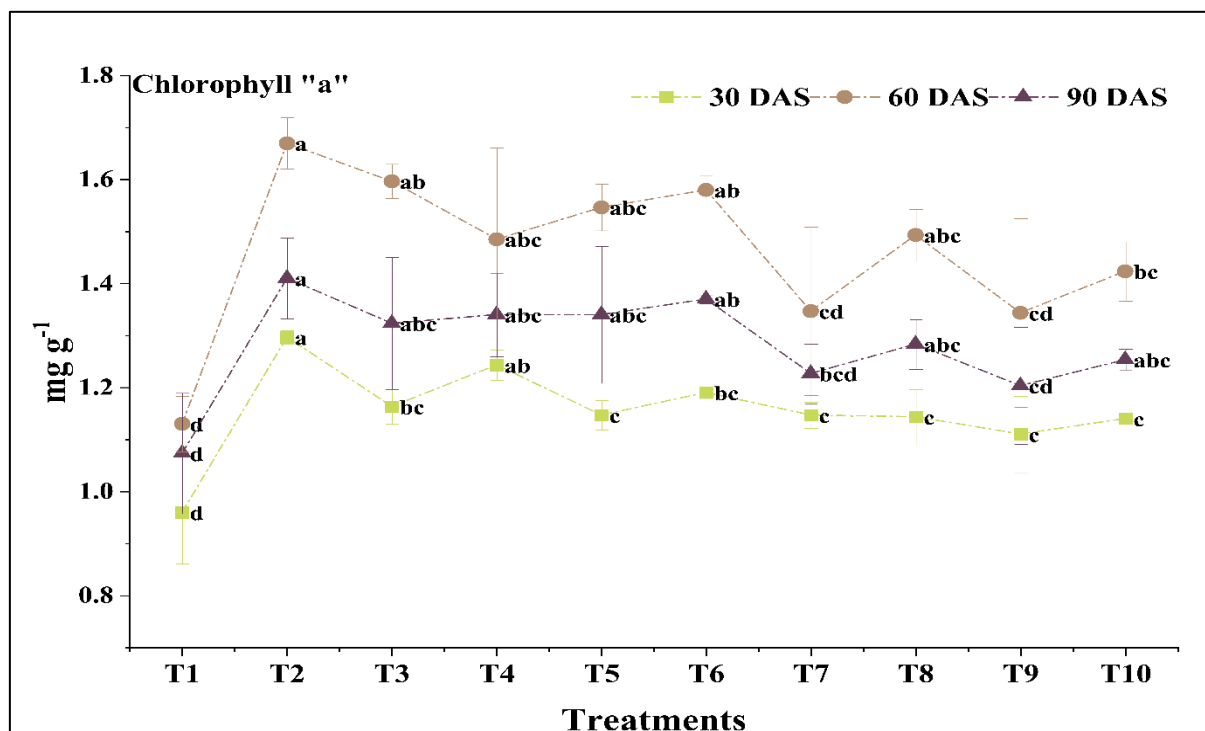


Fig 4.42: Effect of different nutrient management practices on chlorophyll content a in 2024 of sweet sorghum

4.4.2 Chlorophyll 'b'

The data on the chlorophyll content of sweet sorghum 'b' is influenced by different nutrient management treatments at 30, 60, and 90 days during 2023 and 2024 (Table 19).

The effect of different nutrient management practices on chlorophyll 'b' (mg g^{-1}) was statistically significant across the growth stages. At 30 DAS, treatment T6 showed the highest chlorophyll levels, measuring 1.20 mg g^{-1} in 2023 and 1.15 mg g^{-1} in 2024. This was significantly higher than the control (T1), which recorded the lowest values (0.85 mg g^{-1} and 0.84 mg g^{-1}).

Similarly, at 60 DAS, T6 maintained the highest chlorophyll 'b' content (1.29 mg g^{-1} in 2023 and 1.34 mg g^{-1} in 2024), outperforming the control (0.98 mg g^{-1} and 0.99 mg g^{-1}), which was statistically on par with the other treatments except the control, respectively.

At 90 DAS, T6 maintained the highest chlorophyll content (1.14 mg g^{-1} in 2023 and 1.19 mg g^{-1} in 2024), followed by T3 and T4, both of which were significantly higher than the control (0.93 mg g^{-1} and 0.97 mg g^{-1} , respectively). Treatments T2, T5, T7, T8, and T9 showed results statistically similar to one another.

The increase in chlorophyll 'b' content may result from a balanced, integrated nutrient supply, especially of essential macro- and micronutrients. Nitrogen and phosphorus are crucial for pigment synthesis and related proteins. Meanwhile, magnesium forms the core of the chlorophyll molecule, and iron and zinc serve as cofactors for enzymes that regulate synthesis (Chen *et al.* 2017). The zeolite offers a steady, controlled release of these elements from the inorganic fertilizer, and the organic amendments boost microbial mobilisation, ensuring that all necessary building blocks are available for optimal development of the photosynthetic apparatus, including the accumulation of the light-harvesting which leads to the pigment chlorophyll b (Kalaivanan and Hattab, 2016)

Table 4.19 Effect of different nutrient management strategies on chlorophyll ‘b’ of sweet sorghum

Treatments	Chlorophyll b 30 DAS		Chlorophyll b 60 DAS		Chlorophyll b 90 DAS	
	2023	2024	2023	2024	2023	2024
T1	0.85	0.84	0.98	0.99	0.93	0.97
T2	1.05	1.00	1.17	1.23	1.07	1.13
T3	1.09	1.10	1.25	1.30	1.10	1.12
T4	1.11	1.09	1.31	1.29	1.10	1.12
T5	1.08	1.02	1.16	1.22	1.09	1.12
T6	1.20	1.15	1.29	1.34	1.14	1.19
T7	1.11	1.04	1.16	1.21	1.01	1.09
T8	1.08	1.04	1.17	1.21	1.05	1.11
T9	1.19	1.13	1.16	1.19	1.07	1.10
T10	1.08	1.04	1.16	1.20	1.05	1.07
SEm ($\pm$)	0.06	0.06	0.05	0.05	0.03	0.03
LSD ($p=0.05$)	0.18	0.19	0.15	0.15	0.10	0.10

T1-* Control (Absolute), T2-*100 % RDF (90:40:40 NPK), T3-*75 % RDF +Zeolite (1.5 t ha^{-1}), T4*75 % RDF +Press-mud (15 t ha^{-1}), T5-*75 % RDF +Zeolite (1.5 t ha^{-1}) +Press-mud (15 t ha^{-1}), T6-*75 % RDF +Zeolite (1.5 t ha^{-1}) + Press-mud (15 t ha^{-1}) +Bio-neema (5 kg ha^{-1}), T7-*Nano NPK (19:19:19) +Zeolite (1.5 t ha^{-1}), T8-*Nano NPK (19:19:19) + Press-mud (15 t ha^{-1}), T9-*Nano NPK (19:19:19) + Zeolite (1.5 t ha^{-1}) + Press-mud (15 t ha^{-1}), T10-* Nano NPK (19:19:19) + Zeolite (1.5 t ha^{-1}) +Pressmud (1.5 t ha^{-1}) +Bio-neema (5 kg ha^{-1}). SEm-*Standard Error of Mean, LSD ($p =0.05$)-* Least Significant Difference at 5 % significance level.

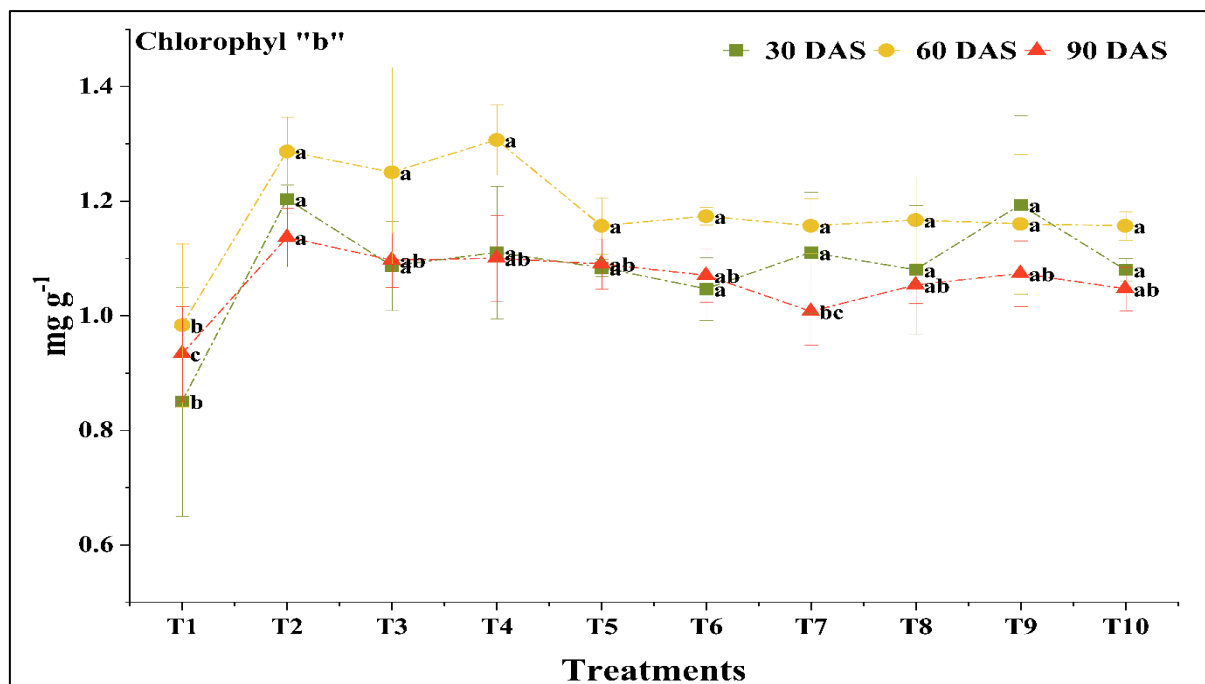


Fig 4.43: Effect of different nutrient management practices on chlorophyll content b in 2023 of sweet sorghum

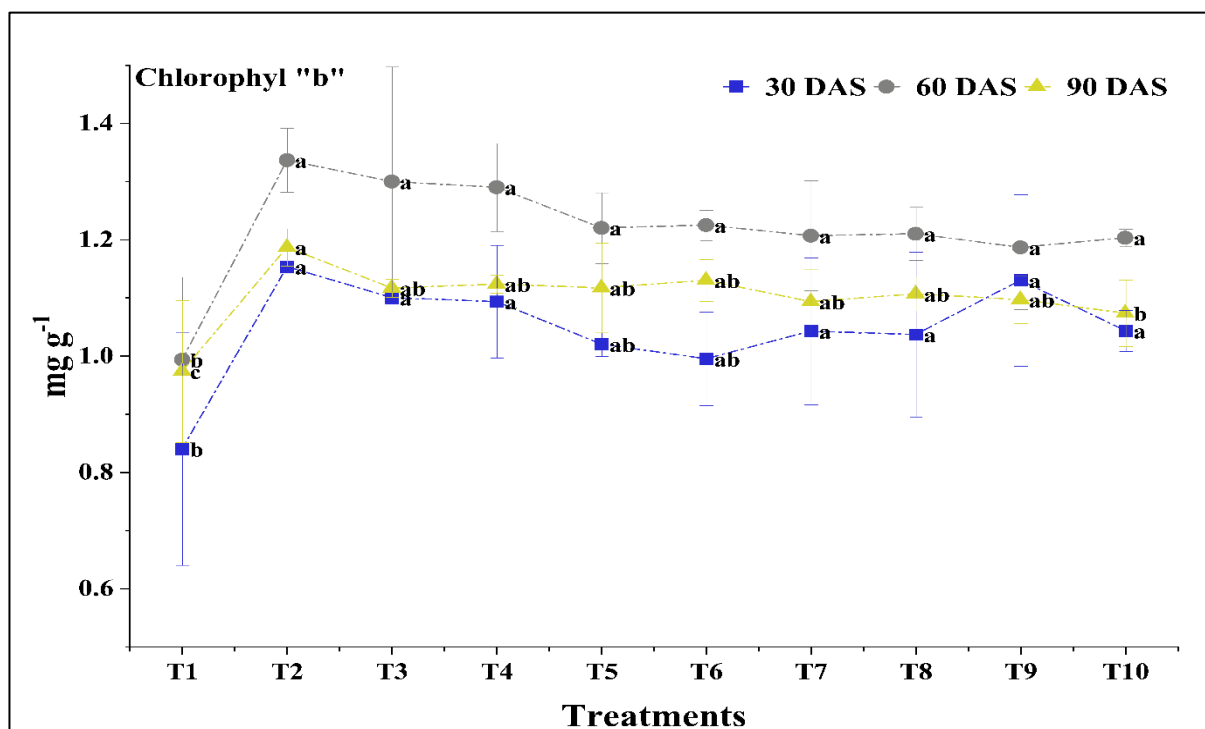


Fig 4.44: Effect of different nutrient management practices on chlorophyll content b in 2024 of sweet sorghum

4.4.3 Protein content in grains (%)

The data indicated that nutrient management strategies significantly increased protein content (%) in sweet sorghum seed during both years (Table 20).

The highest percentage of protein was recorded in T6 (11.27% in 2023 and 11.25% in 2024), which was statistically at par with T2, T3, T4, T5, and T10, respectively, compared to the control (T1), which had the lowest protein percentage recorded (9.06% and 9.02%) in 2023 and 2024. Treatments T7 to T10 showed statistically similar results.

Protein content in sweet sorghum significantly increased, likely due to enhanced nutrient uptake from the soil through the combined use of nutrient sources, particularly nitrogen. Nitrogen is a key component of amino acids, proteins, and nucleotides, and is a constituent of all enzymes (Wu *et al.* 2019). This variety of nitrogen-containing fertilizers provides an ample supply for plant growth and development. However, organic nutrient sources boost microbial activity, overall nutrient uptake, and plant health, thereby enhancing metabolic efficiency and increasing protein synthesis in grains (Chen *et al.* 2017; Sultana *et al.* 2015).

4.4.4 Nitrogen content in grains (%)

The data indicated that nutrient management strategies significantly increased nitrogen content (%) in sweet sorghum seed during both years (Table 20).

Significant differences in nitrogen content were observed among the treatments. The maximum nitrogen content (%) was recorded in T6 (1.80%) in both years, which was statistically equivalent to T5 (1.77% and 1.79%), T3 (1.72% and 1.79%), T4 (1.70% and 1.76%), and T10 (1.65% and 1.64%) in 2023 and 2024. Treatments T7, T8, and T9 also contributed to higher nitrogen content, to a lesser extent. Absolute control (T) resulted in the lowest nitrogen content (%) in both years, at 1.45% and 1.44% in 2023 and 2024, respectively.

The nitrogen content in grain might increase due to the availability of maximum macronutrients (N, P, and K), with nitrogen being the primary macronutrient in the crop. The maximum nitrogen recovery in the crop results from reduced leaching of nitrate and ammoniacal ions and the slow release of ammonium ions from zeolite into the soil (Zheng *et al.* 2018). While organic sources of nutrients, like press-mud and bio-neema, produce mucus and nitrogen excrements, which raise soil nitrogen levels and make it

more accessible for plant uptake. These factors promote greater accumulation and translocation of nitrogen from the source to the sink, leading to the highest nitrogen content in grains (De *et al.* 2021; Prabhavathi and Parama 2019)

4.4.5 Phosphorus content in grains (%)

The data indicated that nutrient management strategies significantly increased phosphorus content (%) in sweet sorghum seed during both years (Table 20).

T6 had the highest phosphorus content in grains, at 0.57% in 2023 and 0.58% in 2024, closely followed by T2, which yielded 0.55% and 0.56%, respectively. T3, T4, T5, T8, and T10 also performed well, though slightly lower than the others. The absolute control plot (T1) showed the lowest productivity in both years, at 0.33% and 0.35% in 2023 and 2024, respectively.

The high content of sweet sorghum grains may result from a synergy between microbial mobilization and reduced phosphorus fixation. While organic amendments stimulate phosphorus-solubilizing microbes (PSM), which secrete organic acids and enzymes to mineralize organic P and solubilize fixed inorganic P, zeolite buffers the soil pH, reducing the chemical reactions that usually lock up P with aluminium, iron, or calcium (Azimnejad *et al.* 2023). This combined approach maximizes the available soil phosphorus, allowing healthy, vigorous plants to efficiently absorb and translocate it into developing grains. These kinds of results are also reported by (Nath *et al.* 2020; Gao *et al.* 2020).

4.4.6 Potassium content in grains (%)

The data indicated that nutrient management strategies significantly increased potassium content (%) in sweet sorghum seed during both years (Table 20).

Potassium content (%) was significantly influenced by the treatment applied. T6 produced the highest potassium content, reaching 0.72% in 2023 and 0.73% in 2024. These values were statistically equivalent to those of T3 and T5, which noted the potassium content (0.71% and 0.70%) and (0.68% and 0.69%) in the same year. Treatments T2, T4, and T10 followed in terms of performance. On the other hand, the absolute control (T1) consistently showed the lowest potassium content, at 0.56% in 2023 and 0.53% in 2024, respectively.

The increased K content in grains may result from a combination of nutrients due to reduced potassium leaching. This is because when zeolites are mixed with

inorganic and organic sources, they help retain nutrients from fertilizers within the root zone, significantly boosting potassium uptake in the stem, leaves, and roots (Louhar, 2020). This potassium then accumulates more in sink parts of the plant, such as the stem and grains (Latifah *et al.* (2017).

Table 4.20 Effect of different nutrient management strategies on nutrient content in the grains of sweet sorghum

Treatments	N%		P %		K%		Protein content %	
	2023	2024	2023	2024	2023	2024	2023	2024
T1	1.45	1.44	0.33	0.35	0.56	0.53	9.06	9.02
T2	1.73	1.74	0.54	0.50	0.62	0.61	10.81	10.90
T3	1.72	1.79	0.54	0.52	0.71	0.70	10.75	11.17
T4	1.70	1.76	0.50	0.53	0.65	0.64	10.63	11.02
T5	1.77	1.79	0.55	0.56	0.68	0.69	11.08	11.21
T6	1.80	1.80	0.57	0.58	0.72	0.73	11.27	11.25
T7	1.63	1.62	0.50	0.48	0.62	0.61	10.21	10.10
T8	1.64	1.63	0.50	0.51	0.58	0.58	10.25	10.21
T9	1.63	1.63	0.48	0.46	0.59	0.58	10.17	10.17
T10	1.65	1.64	0.50	0.51	0.60	0.59	10.31	10.23
SEm (±)	0.05	0.06	0.04	0.04	0.02	0.02	0.34	0.39
LSD (p=0.05)	0.16	0.18	0.13	0.11	0.06	0.05	1.00	1.15

T1-* Control (Absolute), T2-*100 % RDF (90:40:40 NPK), T3-*75 % RDF +Zeolite (1.5 t ha⁻¹), T4*75 % RDF +Press-mud (15 t ha⁻¹), T5-*75 % RDF +Zeolite (1.5 t ha⁻¹) +Press-mud (15 t ha⁻¹), T6-*75 % RDF +Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹) +Bio-neema (5 kg ha⁻¹), T7-*Nano NPK (19:19:19) +Zeolite (1.5 t ha⁻¹), T8-*Nano NPK (19:19:19) + Press-mud (15 t ha⁻¹), T9-*Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹), T10-* Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) +Pressmud (1.5 t ha⁻¹) +Bio-neema (5 kg ha⁻¹). SEm-*Standard Error of Mean, LSD (p =0.05)-* Least Significant Difference at 5 % significance level.

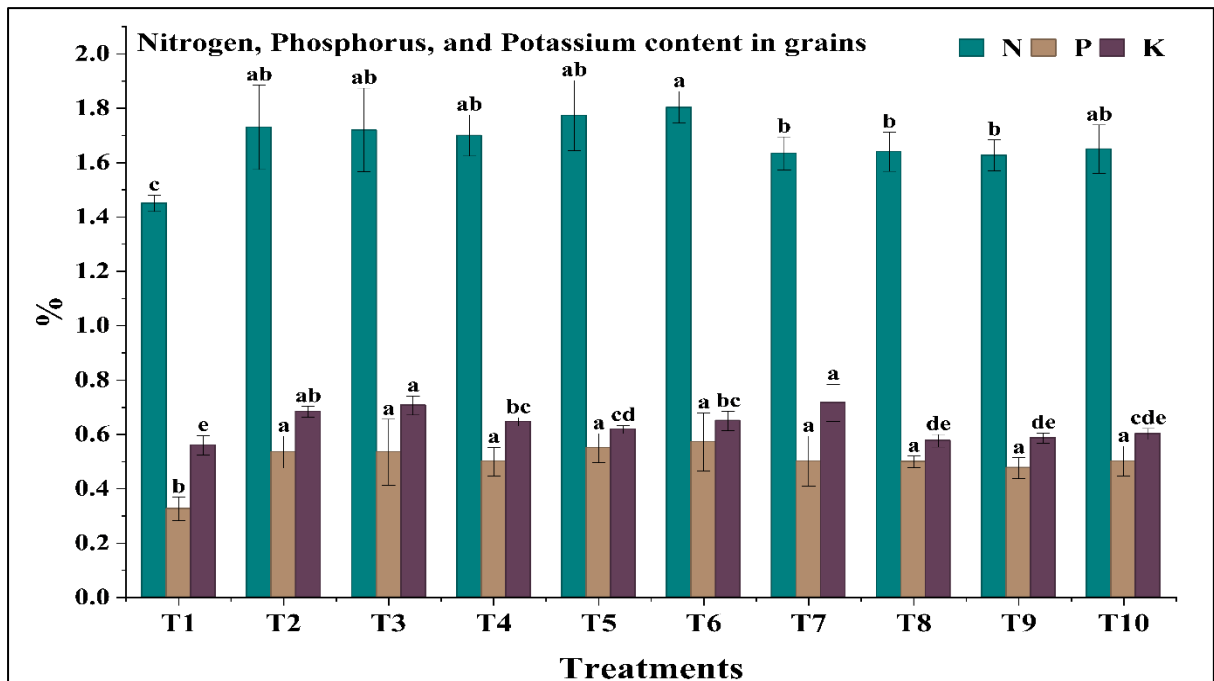


Fig 4.45: Effect of different nutrient management practices on nitrogen, phosphorus, and potassium in 2023 of sweet sorghum

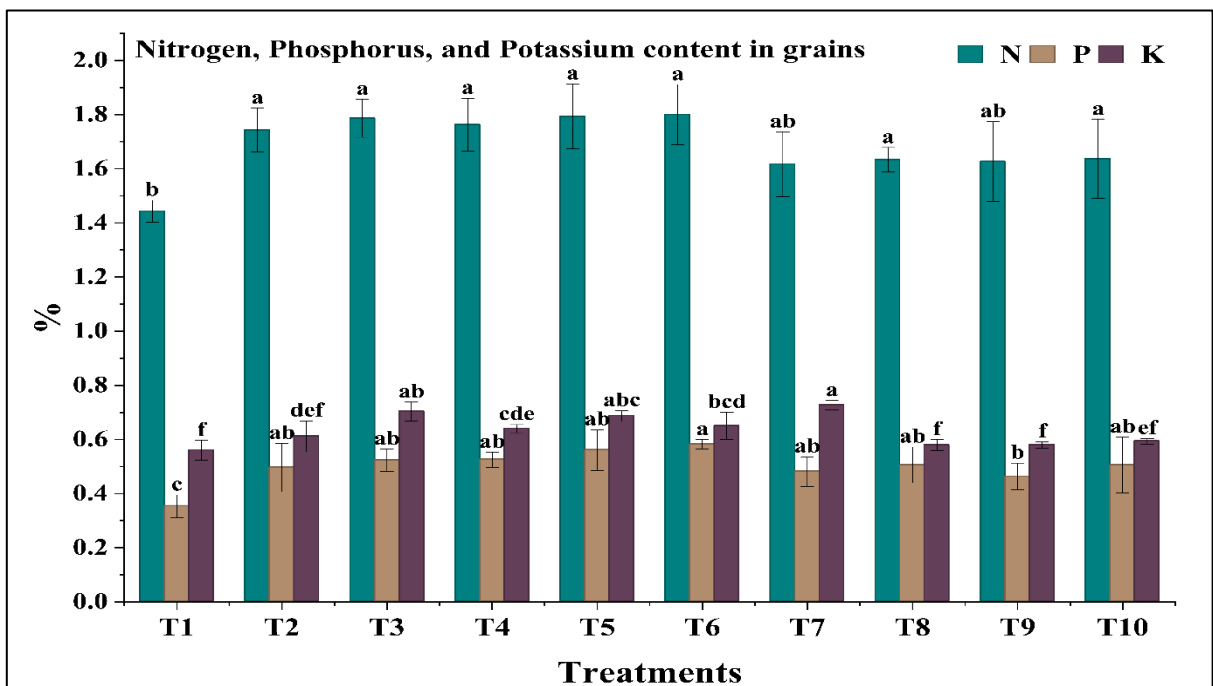


Fig 4.46: Effect of different nutrient management practices on nitrogen, phosphorus, and potassium content in grains 2024 of sweet sorghum

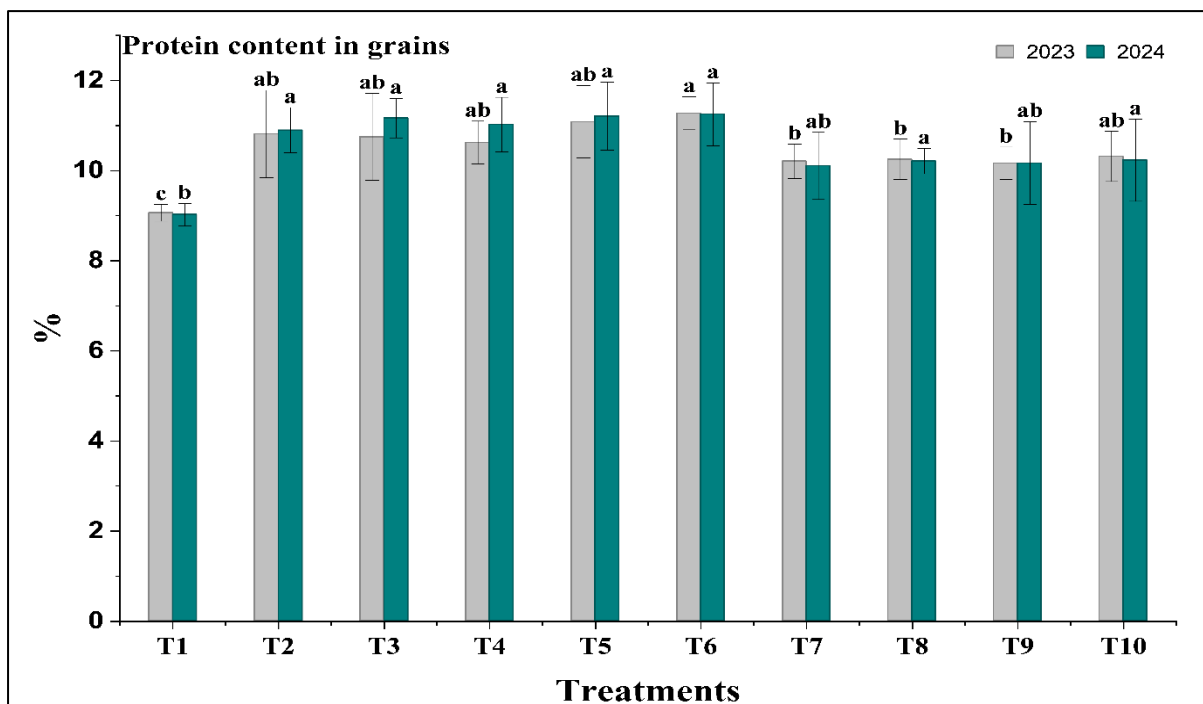


Fig 4.47: Effect of different nutrient management practices on protein content in grains in 2023 and 2024 of sweet sorghum

4.4.7 Nitrogen content in bagasse (%)

The data indicated that nutrient management strategies significantly increased nitrogen content (%) in sweet sorghum bagasse during both years (Table 21).

Significant differences in nitrogen content were observed among all the treatments. The maximum nitrogen content (%) was recorded in T6 (1.13% in 2023 and 1.15% in 2024), which was statistically equivalent to T5 (1.06% and 1.08%) and T4 (1.04% and 1.12%) in 2023 and 2024, respectively. Treatments T7, T8, T9, and T10 also contributed to higher nitrogen content, to a lesser extent. Absolute control (T1) resulted in the lowest nitrogen content (%) in both years, at 0.83% and 0.88% in 2023 and 2024, respectively.

The nitrogen content in bagasse might increase due to the crop's maximum availability of macronutrients (N, P, and K), especially nitrogen. The highest nitrogen recovery in the crop results from reduced leaching of nitrate and ammoniacal ions, along with the slow release of ammonium ions from zeolite into the soil (Khaliq *et al.* 2024). Organic nutrient sources, like press-mud and bio-neema, produce mucus and nitrogen excrements, which boost soil nitrogen levels and enhance its availability for

plant uptake. These factors lead to greater stem accumulation, resulting in the maximum nitrogen content in bagasse (Prabhavathi and Parama, 2019).

4.4.8 Phosphorus content in bagasse (%)

The data indicated that nutrient management strategies significantly increased phosphorus content (%) in sweet sorghum bagasse during both years (Table 21).

T6 had the highest phosphorus content in bagasse, at 0.32% in 2023 and 0.34% in 2024, closely followed by T5, which yielded 0.30% and 0.32%, respectively. T2, T3, T4, and T9 also performed well, but slightly lower than the others. The absolute control plot (T1) showed the lowest nitrogen content in bagasse in both years, at 0.24% and 0.25% in 2023 and 2024, respectively.

The high content of sweet sorghum bagasse may result from a synergy between microbial mobilization and reduced phosphorus fixation. While organic amendments stimulate phosphorus-solubilizing microbes (PSM), which secrete organic acids and enzymes to mineralize organic P and solubilize fixed inorganic P, zeolite buffers the soil pH, minimizing the chemical reactions that typically lock up P with aluminium, iron, or calcium (Mondal *et al.* 2021; Nur Aainaa *et al.* 2018). This combined approach maximizes soil phosphorus availability, enabling healthy, robust plants to absorb and translocate it efficiently (Maqsood *et al.* 2025).

4.4.9 Potassium content in bagasse (%)

The data indicated that nutrient management strategies significantly increased potassium content (%) in sweet sorghum bagasse during both years (Table 21).

Potassium content (%) was significantly influenced by the treatment applied. T6 produced the highest potassium content, reaching 1.63% in 2023 and 1.65% in 2024. These values were closely followed by treatment T3, for which the potassium content was noted (1.62% and 1.60%) in the same year. Treatments T2, T4, and T5 are statistically equivalent in terms of performance. On the other hand, the absolute control (T1) consistently showed the lowest potassium content, at 1.01% in 2023 and 1.00% in 2024, respectively.

The increased potassium content in bagasse might be due to a combination of nutrients, attributed to decreased potassium leaching. This is because when zeolites are combined with inorganic and organic sources, they help retain nutrients from applied fertilizers in the root zone, thereby significantly increasing potassium uptake and

translocation in roots, which then must accumulate more in parts of the plant, such as the stem (Latifah *et al.* 2017; Cairo *et al.* 2017; Budiyo, 2021).

Table 4.21: Effect of different nutrient management strategies on nutrient content in bagasse of sweet sorghum

Treatments	N %		P%		K%	
	2023	2024	2023	2024	2023	2024
T1	0.83	0.88	0.24	0.25	1.01	1.00
T2	1.00	1.05	0.29	0.29	1.42	1.44
T3	1.00	1.01	0.29	0.30	1.62	1.60
T4	1.04	1.12	0.28	0.30	1.43	1.50
T5	1.06	1.08	0.30	0.32	1.45	1.48
T6	1.13	1.15	0.32	0.34	1.63	1.65
T7	0.96	0.99	0.26	0.28	1.40	1.46
T8	0.95	0.97	0.27	0.28	1.43	1.32
T9	0.99	0.95	0.28	0.27	1.44	1.39
T10	0.88	0.99	0.27	0.26	1.41	1.42
SEm ($\pm$)	0.03	0.04	0.01	0.01	0.08	0.07
LSD ($p=0.05$)	0.10	0.13	0.02	0.03	0.23	0.22

T1-* Control (Absolute), T2-*100 % RDF (90:40:40 NPK), T3-*75 % RDF +Zeolite (1.5 t ha^{-1}), T4*75 % RDF +Press-mud (15 t ha^{-1}), T5-*75 % RDF +Zeolite (1.5 t ha^{-1}) +Press-mud (15 t ha^{-1}), T6-*75 % RDF +Zeolite (1.5 t ha^{-1}) + Press-mud (15 t ha^{-1}) +Bio-neema (5 kg ha^{-1}), T7-*Nano NPK (19:19:19) +Zeolite (1.5 t ha^{-1}), T8-*Nano NPK (19:19:19) + Press-mud (15 t ha^{-1}), T9-*Nano NPK (19:19:19) + Zeolite (1.5 t ha^{-1}) + Press-mud (15 t ha^{-1}), T10-* Nano NPK (19:19:19) + Zeolite (1.5 t ha^{-1}) +Pressmud (1.5 t ha^{-1}) +Bio-neema (5 kg ha^{-1}). SEm-*Standard Error of Mean, LSD ($p =0.05$)-* Least Significant Difference at 5 % significance level.

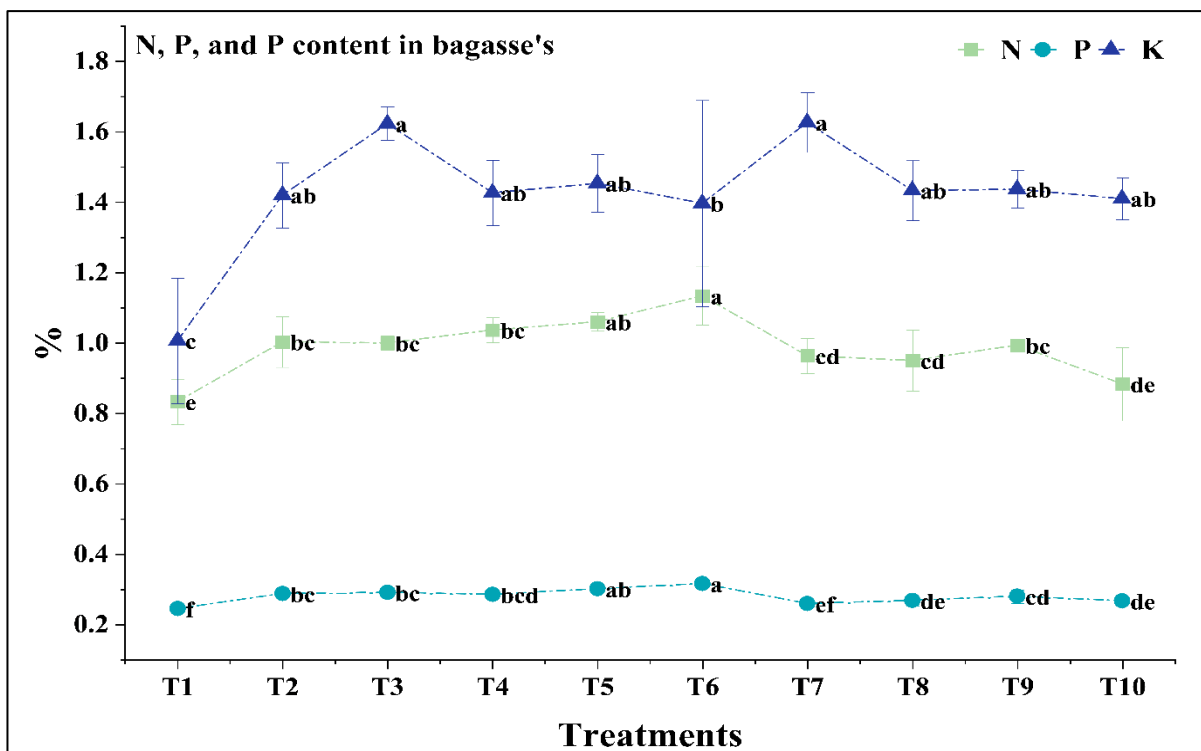


Fig 4.48: Effect of different nutrient management practices on nitrogen, phosphorus, and potassium in bagasse's in 2023 of sweet sorghum

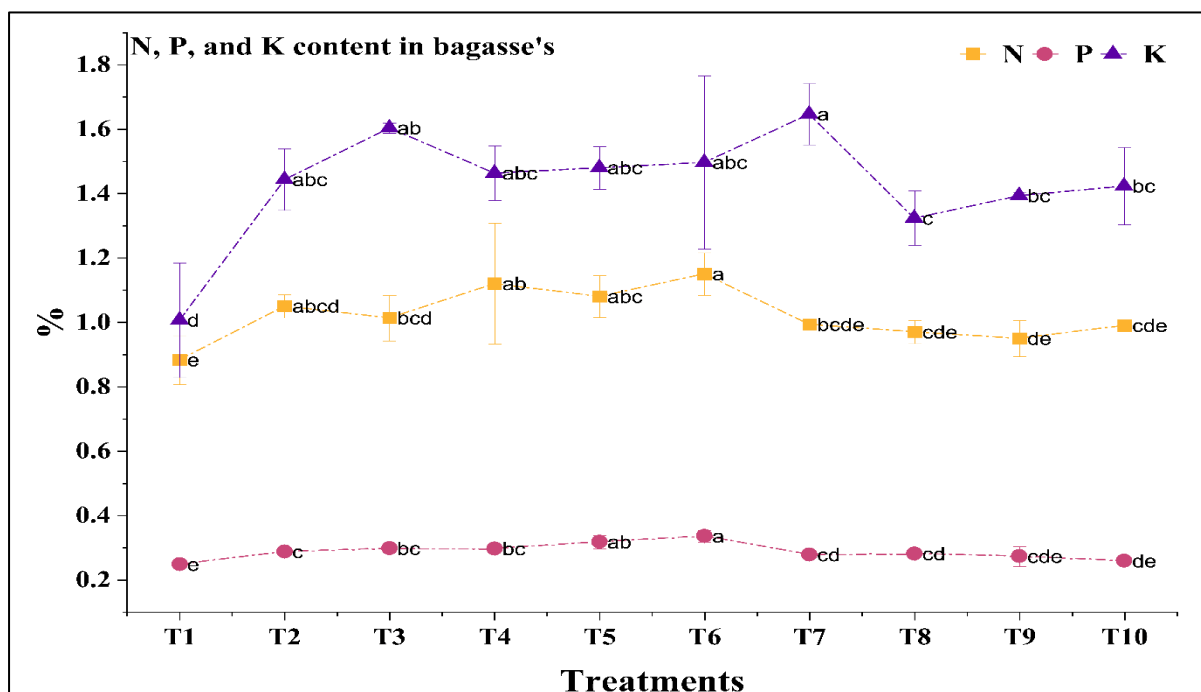


Fig 4.49: Effect of different nutrient management practices on nitrogen, phosphorus, and potassium in bagasse's in 2024 of sweet sorghum

4.4.10 Ash content in grains (%)

The data indicated that nutrient management strategies significantly increased ash content (%) in sweet sorghum grains in both years (Table 22).

T6 had the highest ash content in grains, at 2.13% in 2023 and 2.09% in 2024, closely followed by T4 (2.02% and 2.05%) and T5 (2.05% and 2.00%) in the same years, respectively. T2, T3, and T10 also performed well, though slightly lower than the others. The absolute control plot (T1) showed the lowest grain ash content in both years, at 1.83% and 1.88% in 2023 and 2024, respectively.

The impact of zeolite on the ash content in sweet sorghum grains is significant because it affects nutrient absorption and overall grain quality. Studies indicate that adding zeolite can promote sorghum growth and yield, possibly by altering ash content. The use of zeolite has been shown to increase sorghum yield significantly. Zeolite improves nutrient retention in the soil, making nutrients more available to plants (Nelvia and Wijaya, 2024). This increased nutrient uptake can then influence the ash content in the grains, as higher nutrient levels may lead to a denser grain composition. While applying zeolite alongside organic nutrient sources generally boosts growth and yield, excessive application can cause nutrient imbalances or soil degradation over time, potentially affecting grain quality and ash content (Raza *et al.* 2022).

4.4.11 Lignin content in bagasse (%)

The data indicated that nutrient management strategies significantly increased lignin content (%) in sweet sorghum bagasse during both years (Table 22).

The lignin content was observed non-significant among all the treatments during the both years, but statistically maximum lignin content (%) was observed in T6 (5.98% in 2023 and 5.91% in 2024), which was statistically equivalent to the other treatments in both years. Statistically, the lowest lignin content (%) was observed in the absolute control (T1), with 5.70% and 5.76% in 2023 and 2024, respectively.

The influence of organic and inorganic nutrient sources, along with zeolite amendment, on the lignin composition of sweet sorghum bagasse is significant, especially for bioethanol production and enzymatic hydrolysis. Adsorption efficiency: Naturally occurring zeolites, especially those modified by acid or base activation, have been shown to improve bioethanol concentration during purification, highlighting their effectiveness in treating lignocellulosic substrates (Jasman and Sarifudin, 2024).

Although this combined treatment can promote lignin breakdown and increase bioethanol yields, it is important to remember that focusing too much on reducing lignin may overlook other crucial aspects of biomass processing, such as preserving the structural integrity of hemicellulose and cellulose (Nath *et al.* 2020).

4.4.12 Hemicellulose content in bagasse (%)

The data indicated that nutrient management strategies significantly increased hemicellulose content (%) in sweet sorghum bagasse in both years (Table 22).

Hemicellulose (%) was significantly influenced by the treatment applied. T6 produced the maximum percentage of hemi-cellulose, reaching 26.77% in 2023 and 26.84% in 2024. These values were closely followed by treatment T4 and T5, which noted the potassium content (25.78% and 25.64%), (28.70% and 25.82%) in the same year. Treatments T2, T3, T8, and T10 are statistically equivalent in terms of performance. On the other hand, the absolute control (T1) consistently showed the lowest hemi-cellulose content, at 22.98% in 2023 and 22.86% in 2024, respectively.

Integrated nutrient management has been shown to affect hemicellulose content in bagasse and sweet sorghum grains through various mechanisms. The addition of zeolites, especially within catalytic frameworks, can alter the conversion and extraction processes of hemicellulose from lignocellulosic substrates (Ibrahim *et al.* 2024). This effect is particularly evident in the context of sugarcane press-mud. This effect is especially noticeable in the realm of press-mud, bio-neema, and zeolite combined with inorganic fertilizers, where they improve the hydrolysis of hemicellulose into commercially valuable chemicals, highlighting their role in changing the composition and distribution of hemicellulose-derived products (Albuquerque *et al.* 2024).

4.4.13 Cellulose content in bagasse (%)

The data indicated that nutrient management strategies significantly increased cellulose content (%) in sweet sorghum bagasse during both years (Table 22).

Significant differences in cellulose content were observed among all the treatments. The maximum cellulose content (%) was observed in T6 (29.92% in 2023 and 30.44% in 2024), which was statistically equivalent to the other treatments in both years. Statistically, the lowest cellulose content (%) was observed in the absolute control (T1), with 27.03% and 26.88% in 2023 and 2024, respectively.

In the synthesis of cellulose-based membranes, significant enhancement is achieved through integrated nutrient management practices that augment the membrane's adsorption capabilities. The cellulose content in these membranes is a constant element, while zeolites enhance the composite's functional properties (Ibrahim *et al.* 2024). However, organic sources supply adequate nitrogen and potassium, which strengthen cell wall formation, and botanical protectants support healthier vascular tissues, resulting in thicker, higher cellulose-containing plants (Truong *et al.* 2023).

Table 4.22: Effect of different nutrient management strategies on ash, lignin, hemicellulose, and cellulose content in sweet sorghum

Treatments	Ash %		Lignin %		Hemi-cellulose%		Cellulose%	
	2023	2024	2023	2024	2023	2024	2023	2024
T1	1.83	1.88	5.70	5.76	22.98	22.86	27.03	26.88
T2	1.95	2.02	5.77	5.91	25.42	25.44	29.47	29.75
T3	1.96	2.04	5.96	5.88	25.33	25.17	29.19	29.33
T4	2.02	2.00	5.77	5.84	25.78	25.64	28.72	28.55
T5	2.05	2.05	5.94	5.81	25.70	25.82	28.94	29.11
T6	2.13	2.09	5.98	5.91	26.77	26.84	29.92	30.44
T7	1.95	2.00	5.76	5.86	24.91	24.88	28.82	28.38
T8	1.92	1.96	5.74	5.77	25.20	25.10	28.53	28.95
T9	1.93	1.90	5.88	5.77	24.63	24.51	29.23	29.83
T10	1.99	1.95	5.74	5.91	25.83	25.87	29.14	29.81
SEm (±)	0.05	0.04	0.35	0.30	0.62	0.67	0.97	0.86
LSD (p=0.05)	0.13	0.12	NS	NS	1.83	1.98	2.90	2.55

T1-* Control (Absolute), T2-*100 % RDF (90:40:40 NPK), T3-*75 % RDF +Zeolite (1.5 t ha⁻¹), T4*75 % RDF +Press-mud (15 t ha⁻¹), T5-*75 % RDF +Zeolite (1.5 t ha⁻¹) +Press-mud (15 t ha⁻¹), T6-*75 % RDF +Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹) +Bio-neema (5 kg ha⁻¹), T7-*Nano NPK (19:19:19) +Zeolite (1.5 t ha⁻¹), T8-*Nano NPK (19:19:19) + Press-mud (15 t ha⁻¹), T9-*Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹), T10-* Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) +Pressmud (1.5 t ha⁻¹) +Bio-neema (5 kg ha⁻¹). SEm-*Standard Error of Mean, LSD (p =0.05)-* Least Significant Difference at 5 % significance level.

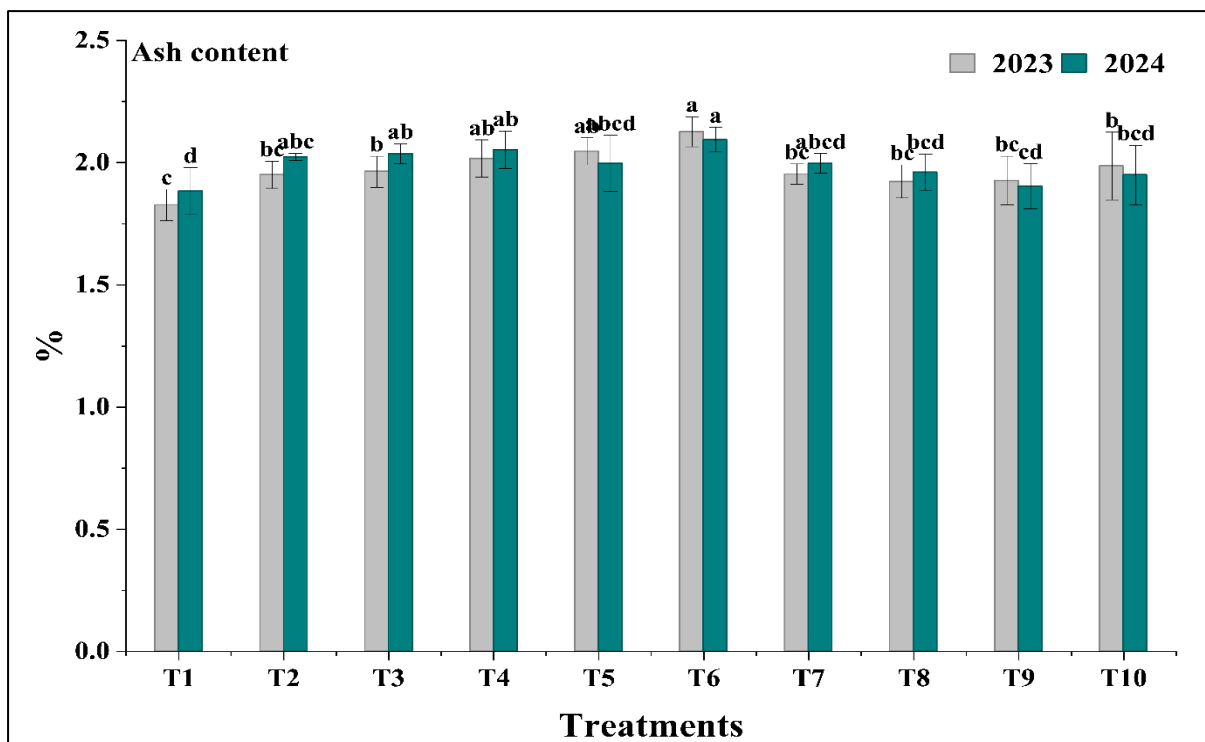


Fig 4.50: Effect of different nutrient management practices on ash content in bagasse's in 2023 and 2024 of sweet sorghum

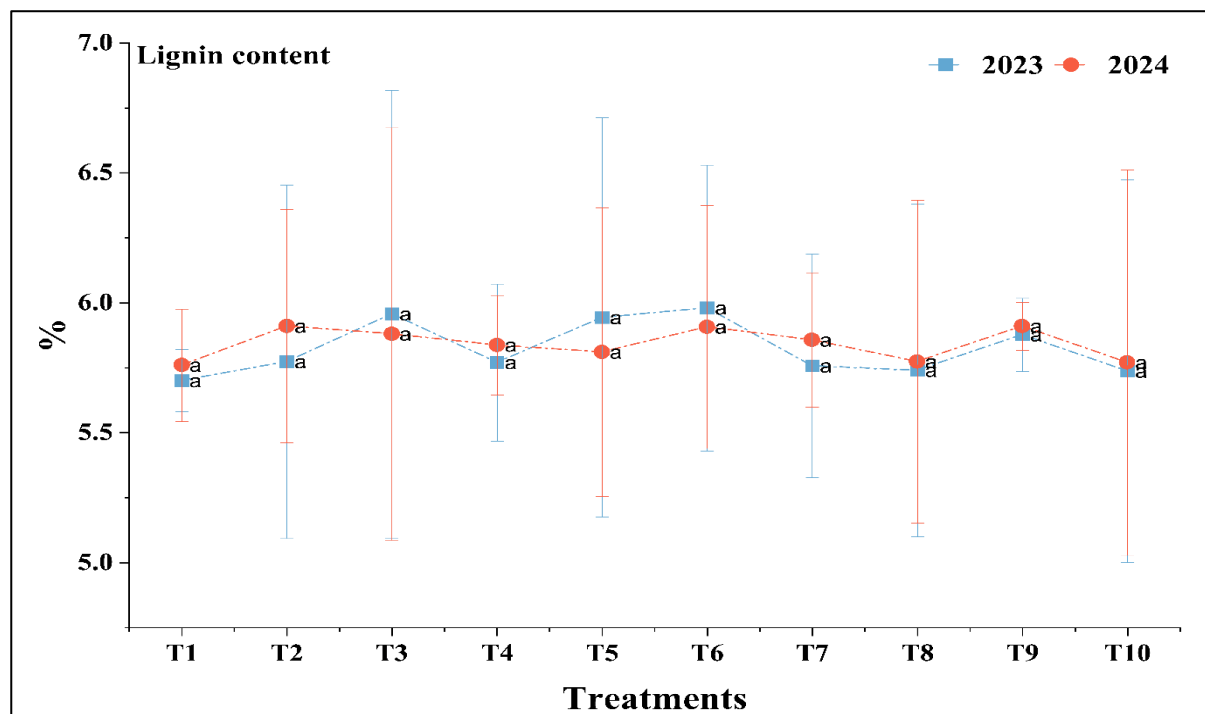


Fig 4.51: Effect of different nutrient management practices on lignin content in bagasse's in 2023 and 2024 of sweet sorghum

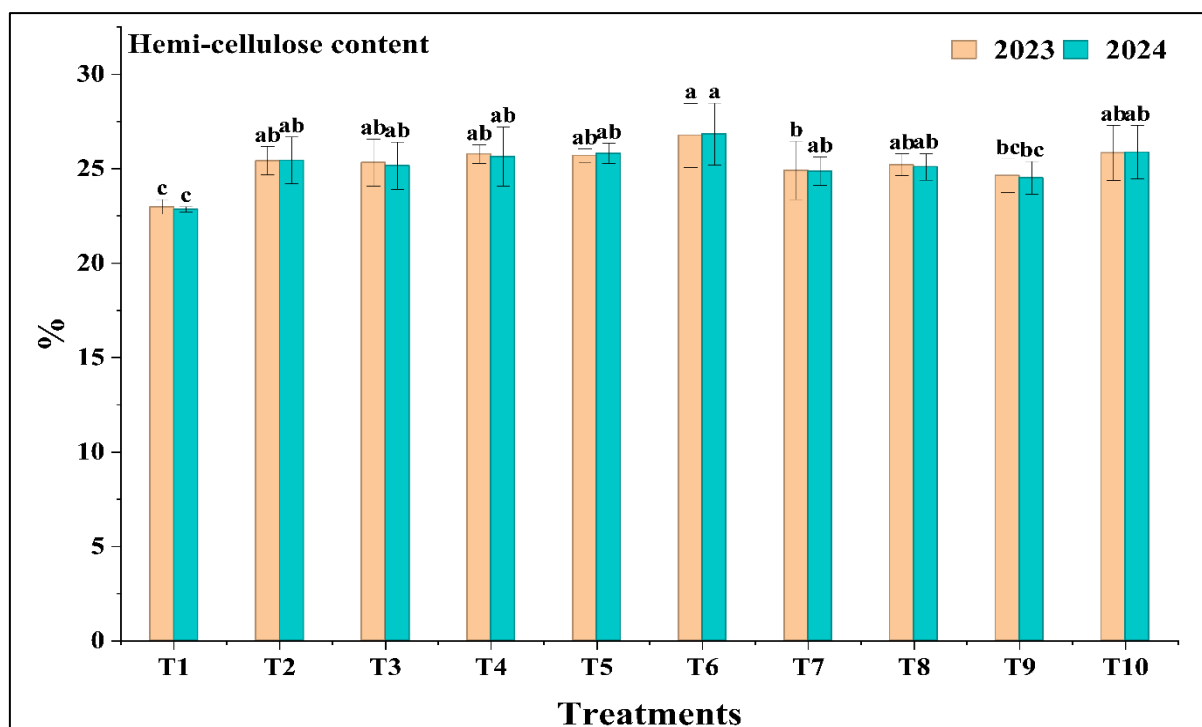


Fig 4.52: Effect of different nutrient management practices on hemi-cellulose content in bagasse's in 2023 and 2024 of sweet sorghum

4.5 Soil health parameters

4.5.1 Soil pH

Different nutrient management practices influence the soil pH data for sweet sorghum after harvest in 2023 and 2024 (Table 23).

The results revealed that the highest soil pH was observed under treatment T6, during both years. Statistically, treatment T6 recorded the highest soil pH after crop harvest, reaching 8.17 and 8.19 in 2023 and 2024, respectively. This value closely followed T3 (8.11 and 8.17) and T10 (8.14 and 8.18) in the same years. Treatments T4, T5, T8, and T9 also slightly influence soil pH. On the other hand, the absolute control (T1) observed the lowest pH, with 7.90 and 8.01 in 2023 and 2024, respectively.

Soil pH after sweet sorghum harvest increased slightly with the application of inorganic fertilizers, press-mud, and bio-neema with zeolite, due to zeolite's high CEC, which helps buffer soil pH by absorbing excess acidity (Zheng *et al.* 2019). While organic sources contribute to microbial activity that releases alkaline compounds, which help improve pH. These combined nutrients maintain a more balanced, stable soil, conducive to better crop growth (Khan *et al.* 2022)

4.5.2 Soil organic carbon (SOC%)

Different nutrient management practices influence soil organic carbon (%) in sweet sorghum after harvest in 2023 and 2024 (Table 23).

The results showed that the T6 treatments influenced the maximum soil organic carbon in both years. The highest soil SOC was recorded in T6 (0.420% in 2023 and 428% in 2024), which was statistically equivalent to T5 (0.410% and 0.425%) in the same years. Treatment T4, T9, and T10 also contribute to higher soil organic carbon, to a lesser extent. The absolute control (T1) showed the lowest soil organic carbon levels, at 0.280% and 0.270% in 2023 and 2024, respectively.

The increase in the organic carbon in the soil after harvest of crop may be due to addition of press-mud, bio-neema and zeolite combined with inorganic fertilizers increased root biomass due to decomposition during the crop growth resulted root biomass which increase number of fauna this helped increased in organic carbon content of soil, and pressmud and bio-neema also good sources of organic which help in to incorporate inorganic matter after mineralization and decomposition (Cataldo *et al.* 2021; Sher *et al.* 2022)

4.5.3 Soil EC (mmhos/cm²)

The data on soil electrical conductivity (mmhos/cm²) of sweet sorghum are influenced by different nutrient management after harvest in 2023 and 2024 (Table 23).

The highest soil electrical conductivity was observed under treatment T2 in both years. The maximum electrical conductivity was noted in T2 (0.324 mmhos/cm² in 2023 and 0.332 mmhos/cm² in 2024), which was statistically at par with T1 (0.311 mmhos/cm² and 0.324 mmhos/cm²) and T4 (0.298 mmhos/cm² and 0.311 mmhos/cm²) in the same year. Treatments T3 and T5 also influenced soil electrical conductivity in both years. The T7 treatment resulted in the lowest electrical conductivity (mmhos/cm²) in years, with 0.272 mmhos/cm² and 0.291 mmhos/cm² in 2023 and 2024, respectively.

A slight increase in electrical conductivity with integrated nutrient management practices might be due to increased total soluble salts, resulting from the release of nutrient cations and anions by zeolite and inorganic fertilizers in the soil solution. Thereby, the decomposition and mineralization of applied press-mud and bio-neema that released salts, which is probably the reason for increased salt content as reflected in soil EC (Sher *et al.* 2022; Kavvadias *et al.* 2023).

Table 4.23 Effect of soil properties after crop harvest through various nutrient management practices

Treatments	Soil pH		SOC (%)		EC (mmhos/cm ²)	
	2023	2024	2023	2024	2023	2024
T1	7.90	8.01	0.280	0.270	0.311	0.324
T2	8.07	8.06	0.313	0.330	0.324	0.332
T3	8.11	8.17	0.363	0.389	0.295	0.298
T4	8.08	8.15	0.391	0.410	0.298	0.311
T5	8.12	8.14	0.410	0.425	0.292	0.314
T6	8.17	8.19	0.420	0.428	0.279	0.326
T7	8.13	8.15	0.328	0.379	0.272	0.291
T8	8.09	8.17	0.330	0.388	0.289	0.305
T9	8.10	8.16	0.357	0.401	0.286	0.309
T10	8.14	8.18	0.380	0.408	0.281	0.312
SEm (±)	0.04	0.03	0.005	0.010	0.10	0.01
LSD (p=0.05)	0.12	0.10	0.015	0.030	0.029	0.030

T1-* Control (Absolute), T2-*100 % RDF (90:40:40 NPK), T3-*75 % RDF + Zeolite (1.5 t ha⁻¹), T4-*75 % RDF + Press-mud (15 t ha⁻¹), T5-*75 % RDF + Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹), T6*75 % RDF + Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹) + Bio-neema (5 kg ha⁻¹), T7-*Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹), T8-*Nano NPK (19:19:19) + Press-mud (15 t ha⁻¹), T9-*Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹), T10-* Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) + Press-mud (1.5 t ha⁻¹) +Bio-neema (5 kg ha⁻¹). SEm-*Standard Error of Mean, LSD (p =0.05)-* Least Significant Difference at 5 % significance level.

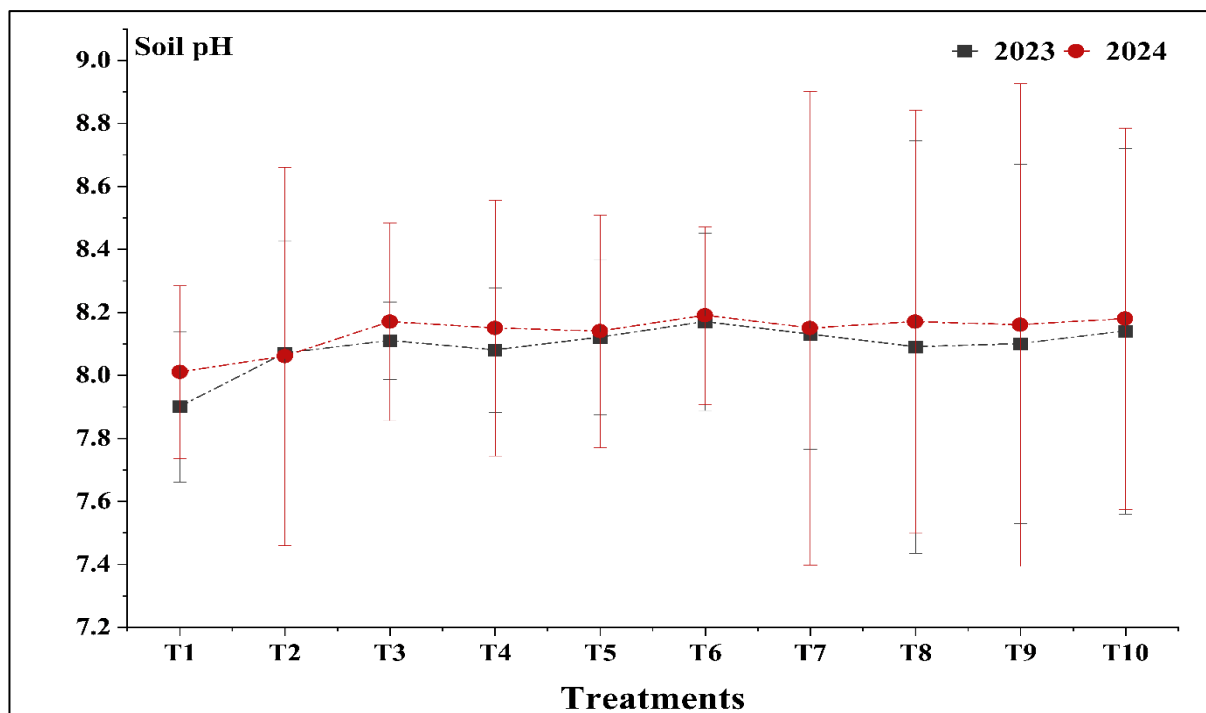


Fig 4.53: Effect of different nutrient management practices on soil pH after harvest of crop in 2023 and 2024

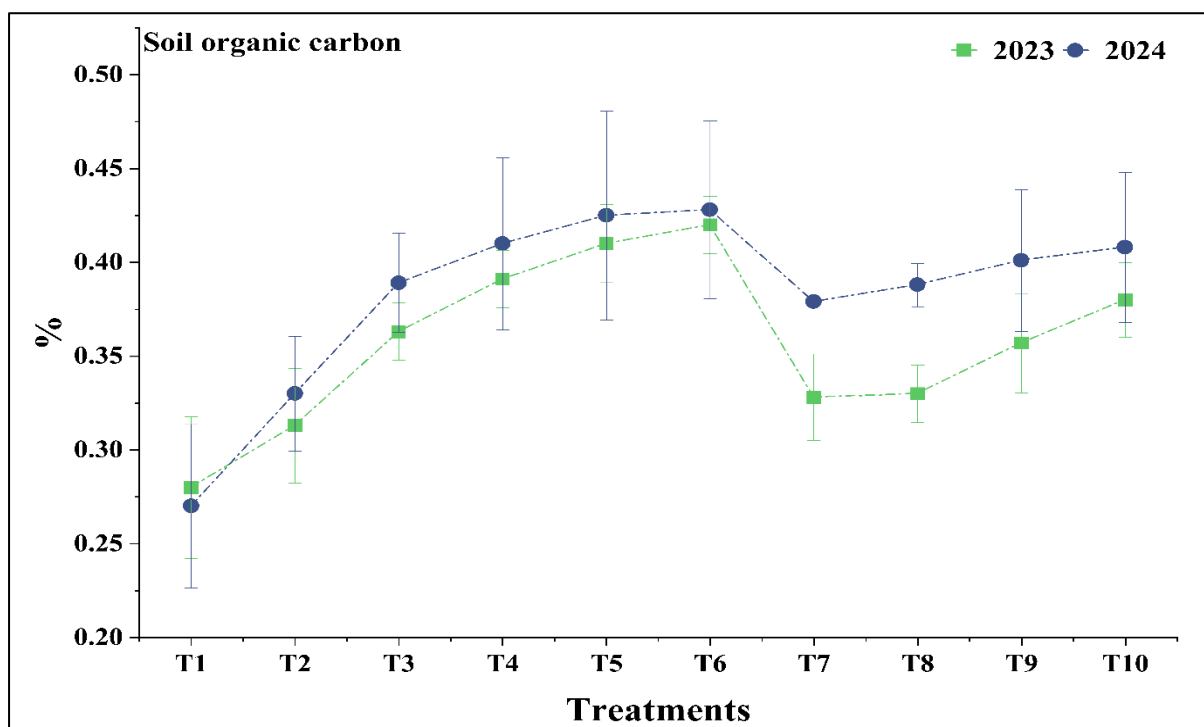


Fig 4.54: Effect of different nutrient management practices on soil organic carbon after harvest of crop in 2023 and 2024

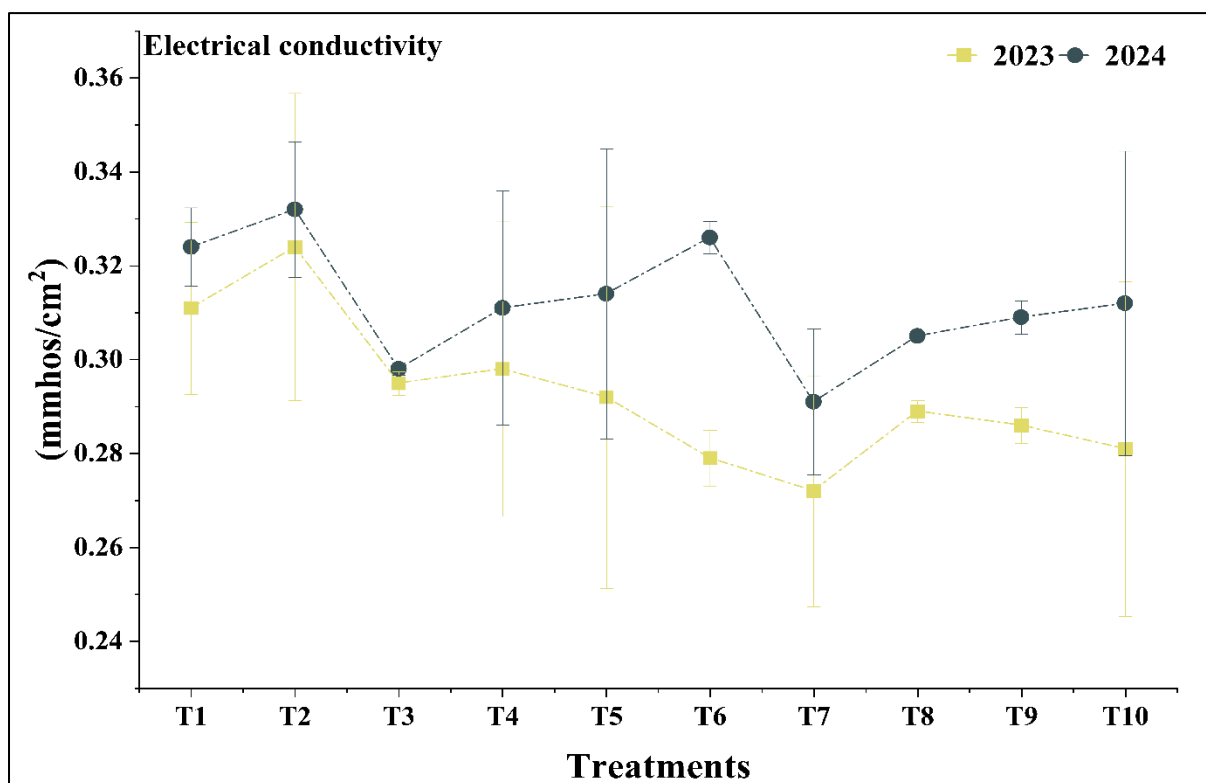


Fig 4.55: Effect of different nutrient management practices on soil electrical conductivity after harvest of crop in 2023 and 2024

4.5.4 Available Nitrogen (kg ha^{-1})

Different nutrient management practices influence soil-available nitrogen (kg ha^{-1}) for sweet sorghum after harvest in 2023 and 2024 (Table 24 and Fig 4.56&57).

The results revealed that the highest soil available nitrogen was influenced under treatment T6 during both years. The maximum available nitrogen was observed in T6 ($235.43 \text{ kg ha}^{-1}$ in 2023 and $247.43 \text{ kg ha}^{-1}$ in 2024), which was statistically equivalent to T2, T3, T4, and T5 in the same year. Treatments T7 to T10 also influenced soil-available nitrogen (kg ha^{-1}) in both years. The treatments' absolute control (T1) had the lowest available nitrogen (kg ha^{-1}) in both years, noted $207.76 \text{ kg ha}^{-1}$ and $198.055 \text{ kg ha}^{-1}$ in 2023 and 2024, respectively.

Available nitrogen after crop harvest was significantly increased by the integrated nutrient approach, especially with zeolite, which reduced nitrification and leaching losses of nitrogen, and the NH_4 released was oxidized by nitrifying bacteria, thereby increasing available nitrogen in the soil (Ravali *et al.* 2020). Organic sources also increased available nitrogen by boosting the abundance of soil microbes important for mineralization and nutrient solubilization (Sheoran *et al.* 2021; Kumar *et al.* 2017)

4.5.5 Available Phosphorus (kg ha⁻¹)

Different nutrient management practices influence soil-available phosphorus (kg ha⁻¹) for sweet sorghum after harvest in 2023 and 2024 (Table 24 and Fig 4.56&57).

The results showed that the T2 treatments influenced the maximum soil available phosphorus in both years. The highest soil available phosphorus was recorded in T2 (25.67 kg ha⁻¹ in 2023 and 27.33 kg ha⁻¹ in 2024), which was statistically equivalent to T6 (24.98 kg ha⁻¹ and 26.65 kg ha⁻¹) and T5 (24.43 kg ha⁻¹ and 26.43 kg ha⁻¹) in the same years. Treatment T3 and T4 also contribute to higher soil available phosphorus, to a lesser extent. Treatments T7 to T10 are statistically similar to each other. The absolute control (T1) showed the lowest soil available phosphorus levels, at 20.27 kg ha⁻¹ and 18.60 kg ha⁻¹ in 2023 and 2024, respectively.

The phosphate anions remain in the soil solution for a longer time, avoiding fixation due to the presence of zeolite, and have the capacity to adsorb phosphorus from chemical fertilizers, thereby reducing phosphorus leaching (Ozbahce *et al.* 2015). While mobilization and chelation of phosphorus due to application of organic matter through press-mud and bio-neema increased the availability of phosphorus in soil (Latifah *et al.* 2017; Sheoran *et al.* 2021)

4.5.6 Available Potassium (kg ha⁻¹)

The data on soil available potassium (kg ha⁻¹) for sweet sorghum are influenced by different nutrient management practices after harvest in 2023 and 2024 (Table 24 and Fig 4.56&57).

The results showed that the T2 treatments influenced the maximum soil-available phosphorus in both years. The highest soil available potassium was recorded in T2 (240.00 kg ha⁻¹ in 2023 and 245.67 kg ha⁻¹ in 2024), which was statistically equivalent to T6 (239.69 kg ha⁻¹ and 245.05 kg ha⁻¹) and T5 (239.06 kg ha⁻¹ and 244.06 kg ha⁻¹) in the same years. Treatment T3 and T4 also contribute to higher soil available potassium, to a lesser extent. Treatments T7 to T10 are statistically similar to each other. The absolute control (T1) showed the lowest soil available potassium levels, at 221.53 kg ha⁻¹ and 217.53 kg ha⁻¹ in 2023 and 2024, respectively.

The available potassium content of soil after sweet sorghum harvest increased with the application of 75% RDF, zeolite, press-mud, and bio-neema, which may be

attributed to initial adsorption of K^+ ions (Nur Aainaa *et al.* 2018). The adsorbed K^+ ions were later released into the soil solution by exchange, and microbes mineralized organic sources (Arulazhagan *et al.* 2024; Roshan and Verma, 2015).

Table 4.24 Effect of soil properties after crop harvest through various nutrient management practices

Treatments	Available N ($kg\ ha^{-1}$)		Available P ($kg\ ha^{-1}$)		Available K ($kg\ ha^{-1}$)	
	2023	2024	2023	2024	2023	2024
T1	207.76	198.55	20.27	18.60	221.53	217.53
T2	234.12	241.79	25.67	27.33	240.00	245.67
T3	232.48	243.81	23.99	25.66	239.56	243.90
T4	234.08	243.08	23.65	27.32	238.85	243.02
T5	234.24	245.83	24.43	26.43	239.06	244.06
T6	235.43	247.43	24.98	26.65	239.69	245.05
T7	223.74	220.41	22.64	23.31	221.75	220.42
T8	226.84	221.51	21.75	23.42	224.25	221.33
T9	227.08	222.75	21.03	22.36	223.59	221.59
T10	228.67	223.00	21.87	23.21	223.16	221.67
SEm ($\pm$)	1.69	2.14	0.90	0.94	1.97	1.54
LSD ($p=0.05$)	5.03	6.36	2.66	2.80	5.85	4.58

T1-* Control (Absolute), T2-*100 % RDF (90:40:40 NPK), T3-*75 % RDF +Zeolite ($1.5\ t\ ha^{-1}$), T4*75 % RDF +Press-mud ($15\ t\ ha^{-1}$), T5-*75 % RDF +Zeolite ($1.5\ t\ ha^{-1}$) +Press-mud ($15\ t\ ha^{-1}$), T6-*75 % RDF +Zeolite ($1.5\ t\ ha^{-1}$) + Press-mud ($15\ t\ ha^{-1}$) +Bio-neema ($5\ kg\ ha^{-1}$), T7-*Nano NPK (19:19:19) +Zeolite ($1.5\ t\ ha^{-1}$), T8-*Nano NPK (19:19:19) + Press-mud ($15\ t\ ha^{-1}$), T9-*Nano NPK (19:19:19) + Zeolite ($1.5\ t\ ha^{-1}$) + Press-mud ($15\ t\ ha^{-1}$), T10-* Nano NPK (19:19:19) + Zeolite ($1.5\ t\ ha^{-1}$) +Pressmud ($1.5\ t\ ha^{-1}$) +Bio-neema ($5\ kg\ ha^{-1}$). SEm-*Standard Error of Mean, LSD ($p =0.05$)-* Least Significant Difference at 5 % significance level.

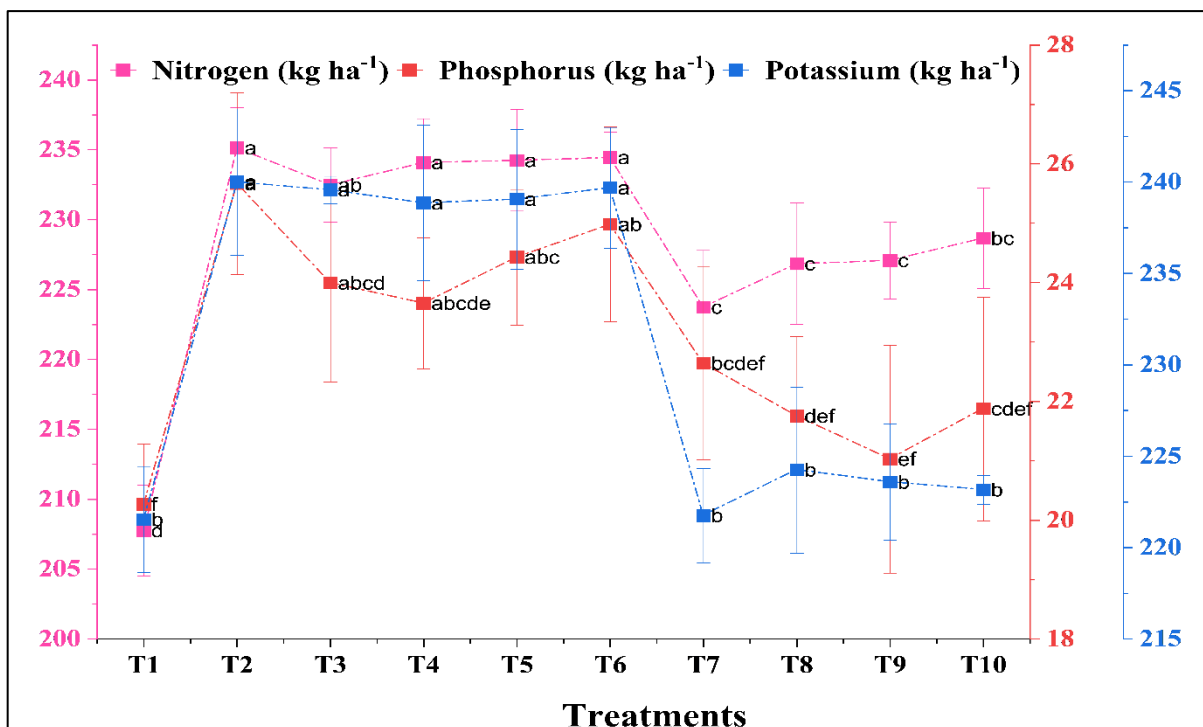


Fig 4.56: Effect of different nutrient management practices on available nitrogen, phosphorus, and potassium in soil in 2023 of sweet sorghum

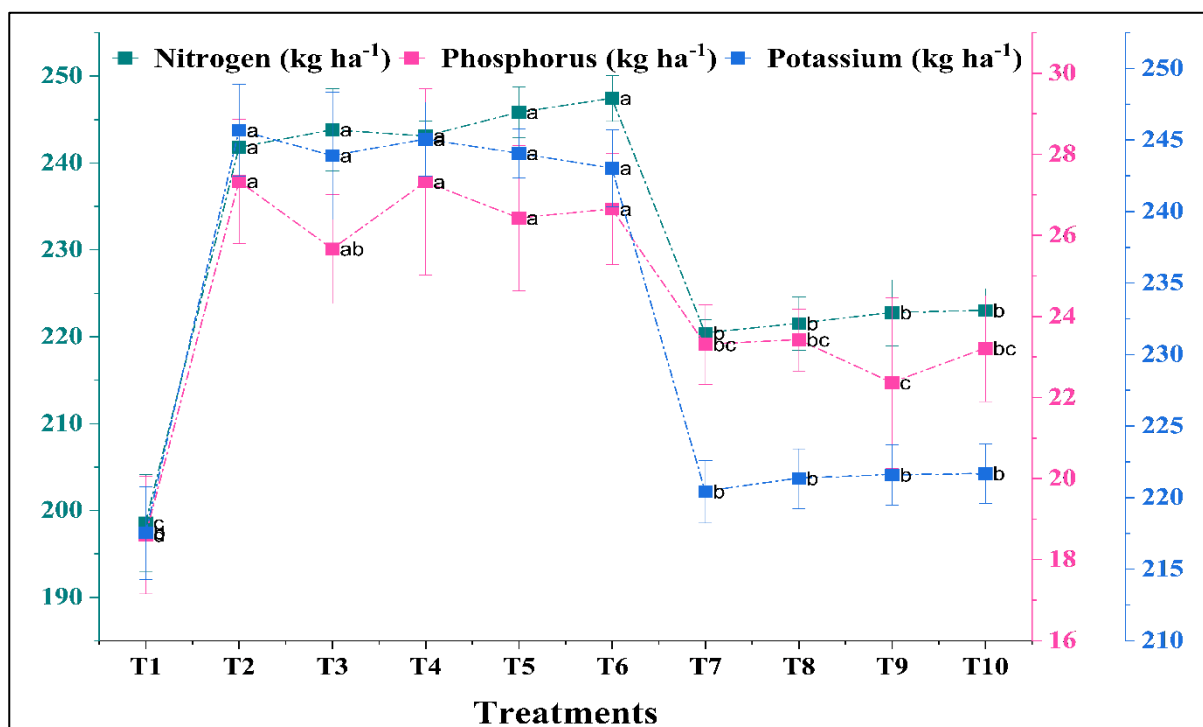


Fig 4.57: Effect of different nutrient management practices on available nitrogen, phosphorus, and potassium in soil in 2024 of sweet sorghum

4.5.7 Microbial count (cfu g⁻¹ 10⁴)

Different nutrient management treatments affect microbial counts in sweet sorghum soil at 90 days after sowing in 2023 and 2024 (Table 25 and Fig 4.58).

The data indicated that nutrient management practices significantly affected soil microbial counts. Among the treatments, T₆ consistently achieved well, recording the highest microbial count, reaching 6.43 (cfu g⁻¹ 10⁴) in 2023 and 7.26 (cfu g⁻¹ 10⁴) in 2024, compared to the control T₁, which had the lowest microbial count at 3.38 (cfu g⁻¹ 10⁴) and 3.71 (cfu g⁻¹ 10⁴). However, treatment T₆ was statistically on par with T₂, T₃, T₄, and T₅, and T₉ in 2023 and 2024.

The microbial population was significantly influenced by the combined use of organic and inorganic nutrient sources, along with zeolite amendment in soil, to provide essential organic carbon as a direct food source and to improve soil structure. However, zeolite stabilizes the environment by regulating nutrient and moisture release, leveraging its high CEC to prevent toxicity and create stable microenvironments (Cataldo *et al.* 2021). These sources ensure a supply of organic carbon and stable nutrients, along with the optimal conditions necessary to sustain and increase the microbial population (Silva *et al.* 2024; Dotaniya *et al.* 2025).

4.5.8 Ureases activity (µg NH₄-N g⁻¹ soil h⁻¹)

The data indicated that nutrient management practices significantly influenced urease activity at 90 days after sowing of sweet sorghum (Table 25 and Fig 4.59).

The maximum ureases activity was recorded in T₆ (128.79 µg NH₄-N g⁻¹ soil h⁻¹ in 2023 and 140.16 µg NH₄-N g⁻¹ soil h⁻¹ in 2024) statistically at par with T₅ (126.97 µg NH₄-N g⁻¹ soil h⁻¹ and 138.26 µg NH₄-N g⁻¹ soil h⁻¹), followed by T₂, T₃, and T₄. Treatment T₇ to T₁₀ showed statistically similar results in 2023 and 2024. Absolute control (T₁) resulted in the lowest urease activity, observed in both years, with values of 104.96 µg NH₄-N g⁻¹ soil h⁻¹ and 108.48 µg NH₄-N g⁻¹ soil h⁻¹.

The significant increase in urease activity under press-mud, bio-neema, and zeolite combined with inorganic fertilizers may be due to the provision of organic carbon for microbial growth, which is essential for urease enzyme production. Inorganic fertilizers act as specific substrates for urease enzymes (Mondal *et al.* 2021). Meanwhile, zeolite functions as a nutrient and moisture reservoir, with its high CEC, to regulate nutrient and moisture levels during the mineralization of organic carbon,

preventing stress and toxicity that could inhibit urease activity (Eifediyi *et al.* 2017; Ram *et al.* 2024).

4.5.9 Dehydrogenase activity ($\mu\text{g TPF g}^{-1} \text{ soil h}^{-1}$)

The data indicated that nutrient management practices significantly influenced dehydrogenase activity at 90 days after sowing in sweet sorghum (Table 25 and Fig 4.60).

The maximum dehydrogenase activity was recorded in T5 ($136.75 \mu\text{g TPF g}^{-1} \text{ soil h}^{-1}$ in 2023 and $139.15 \mu\text{g TPF g}^{-1} \text{ soil h}^{-1}$ in 2024), which was statistically at par with T4, T6, T8, T9, and T₁₀, followed by T₂ and T₃ in 2023 and 2024. Absolute control (T1) resulted in the lowest dehydrogenase activity, recorded at $114.09 \mu\text{g TPF g}^{-1} \text{ soil h}^{-1}$ and $112.24 \mu\text{g TPF g}^{-1} \text{ soil h}^{-1}$ in both years.

Dehydrogenase activity was positively observed under integrated nutrient management practices might be due to contributed organic colloids with a high CEC, which is allowing to hold and exchange essential ions like NH_4^+ , K^+ , Ca^{2+} and Mg^{2+} more efficiently and lead to increase microbial biomass, which releases organic acids that mobile nutrients and enhance ion-exchange surface around the rhizosphere, along with enhancing microbial respiration and redox reactions (Cairo *et al.* 2017). This nutrient composition provides a consistent supply of readily available ions and nutrients, thereby increasing microbial metabolic activity and improving microhabitat conditions, thereby stimulating dehydrogenase activity (Bashir *et al.* 2021).

Table 4.25: Effect of different microbial properties through integrated nutrient properties in sweet sorghum

Treatments	Microbial count (cfu g ⁻¹ 10 ⁴) at 90 DAS		Ureases activity ($\mu\text{g NH}_4\text{-N g}^{-1} \text{ soil h}^{-1}$) at 90 DAS		Dehydrogenase activity ($\mu\text{g TPF g}^{-1} \text{ soil h}^{-1}$) 90 DAS	
	2023	2024	2023	2024	2023	2024
T1	3.38	3.71	104.96	108.48	114.09	112.24
T2	5.60	6.15	116.64	127.36	124.64	128.74
T3	5.65	6.47	124.30	135.43	127.42	128.07
T4	5.68	6.33	123.38	134.50	133.37	135.08
T5	6.01	7.00	126.97	138.26	136.75	139.15

T6	6.43	7.26	128.79	140.16	134.61	137.57
T7	4.81	5.33	117.83	128.78	130.41	129.71
T8	5.30	5.95	121.14	132.12	135.48	136.93
T9	5.53	6.08	121.59	132.58	132.66	134.35
T10	5.23	6.27	123.39	133.06	133.53	134.74
SEm ($\pm$)	0.34	0.36	1.42	1.07	1.55	1.56
LSD ($p=0.05$)	1.00	1.08	4.22	3.18	4.61	4.63

T1-* Control (Absolute), T2-*100 % RDF (90:40:40 NPK), T3-*75 % RDF +Zeolite (1.5 t ha^{-1}), T4*75 % RDF +Press-mud (15 t ha^{-1}), T5-*75 % RDF +Zeolite (1.5 t ha^{-1}) +Press-mud (15 t ha^{-1}), T6-*75 % RDF +Zeolite (1.5 t ha^{-1}) + Press-mud (15 t ha^{-1}) +Bio-neema (5 kg ha^{-1}), T7-*Nano NPK (19:19:19) +Zeolite (1.5 t ha^{-1}), T8-*Nano NPK (19:19:19) + Press-mud (15 t ha^{-1}), T9-*Nano NPK (19:19:19) + Zeolite (1.5 t ha^{-1}) + Press-mud (15 t ha^{-1}), T10-* Nano NPK (19:19:19) + Zeolite (1.5 t ha^{-1}) +Pressmud (1.5 t ha^{-1}) +Bio-neema (5 kg ha^{-1}). SEm-*Standard Error of Mean, LSD ($p =0.05$)-* Least Significant Difference at 5 % significance level.

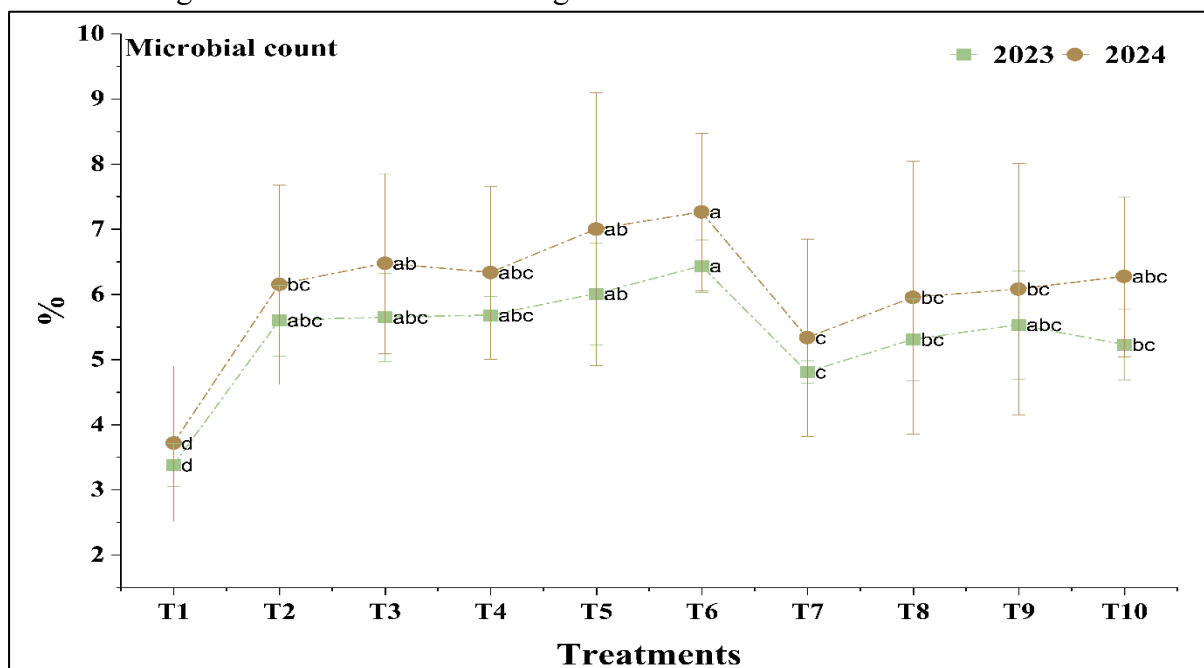


Fig 4.58: Effect of different nutrient management practices on microbial population in soil in 2023 and 2024 of sweet sorghum

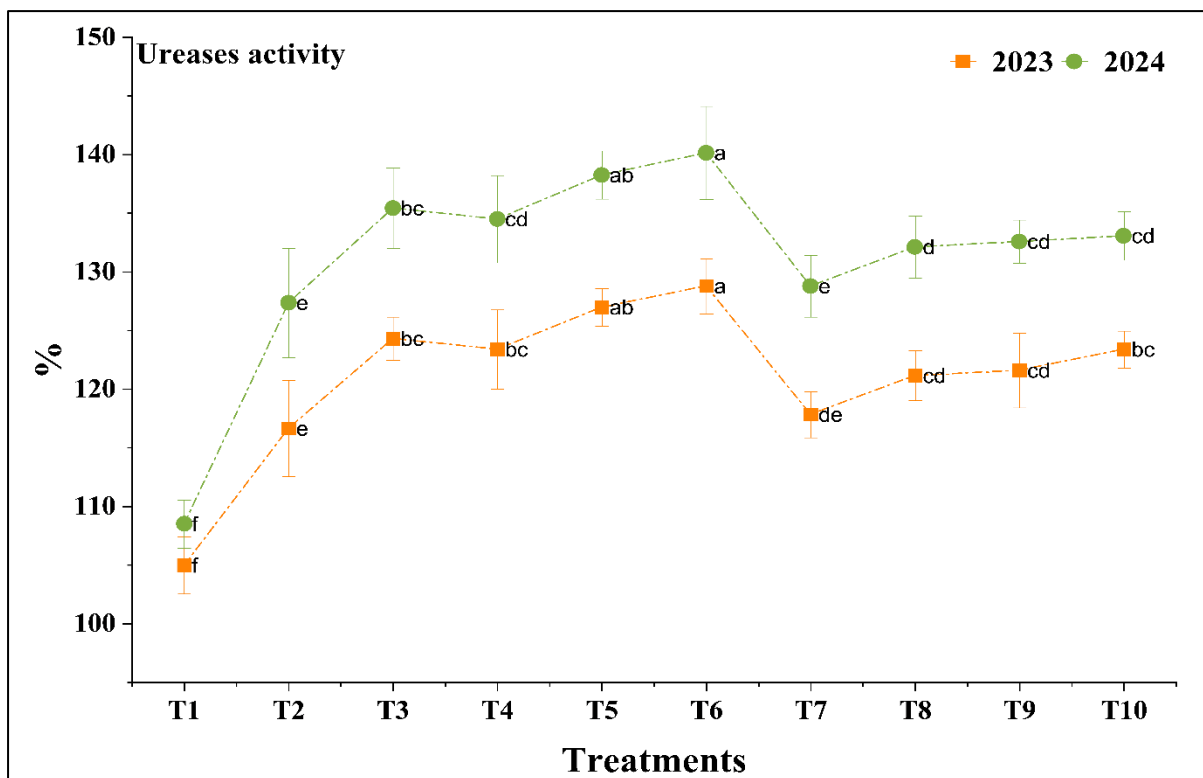


Fig 4.59: Effect of different nutrient management practices on Ureases activity in soil in 2023 and 2024 of sweet sorghum

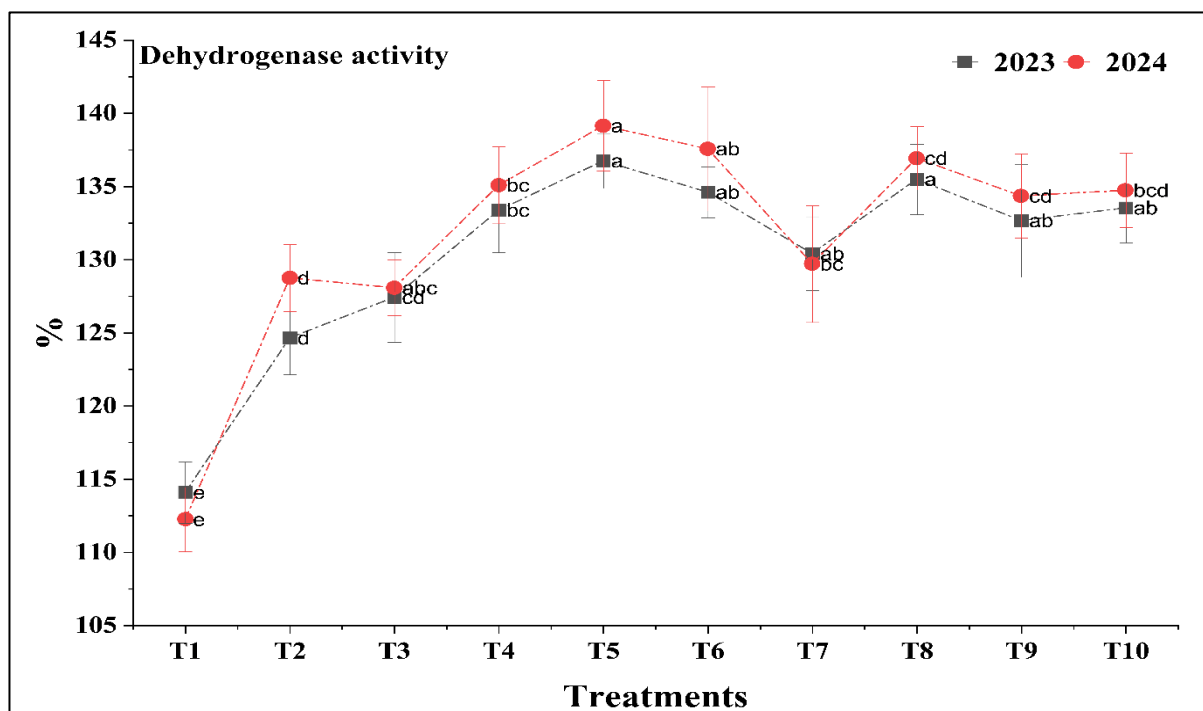


Fig 4.60: Effect of different nutrient management practices on dehydrogenase activity in soil in 2023 and 2024 of sweet sorghum

4.6 Analytical analysis

4.6.1 FTIR

Changes in the structure and composition of sorghum extract across T1 to T4 treatments, as observed from FTIR spectra, are presented (Fig. 4.61).

In general, FTIR peaks are described in wavenumbers (cm^{-1}) with characteristic stretches such as broad O-H (alcohols, water) at $\sim 3200\text{--}3600\text{ cm}^{-1}$, C=O (carbonyls) at $\sim 1650\text{--}1800\text{ cm}^{-1}$, C-H at $\sim 2800\text{--}3000\text{ cm}^{-1}$, C-O at $\sim 1000\text{--}1300\text{ cm}^{-1}$, and C-N, S=O in the intermediate range between $\sim 1500\text{--}1700\text{ cm}^{-1}$. Peak signals detected in the spectrum of T1 include 1069.57 cm^{-1} (C-O stretch of primary alcohols), 2201.77 cm^{-1} (N=C=S stretch of isothiocyanate), and 2345.88 cm^{-1} (O=C=O, possibly CO_2 product), and substantiated the presence of primary alcohol originating from sugars, bioactive and/or degradative isothiocyanates, and early fermentation products of CO_2 . Exhibits peaks at 1110.61 cm^{-1} (alcohol), 1285.32 cm^{-1} (Spectrum T2, C-O stretching of the secondary alcohol), 1657.48 cm^{-1} (COO/CO stretching of ester or acid), and (C=C stretching of alkenes), indicating enzymatic conversion or gentle treatment of the product for phenolic/ester production (Cao *et al.*, 2012). Spectrum T3 shows 1314.38 cm^{-1} and 1942.20 cm^{-1} (C=C=C stretching, allied to allenes), 1541.83 cm^{-1} (O-H bending) and (C=C bending, alkenes), which imply an oxidative degradation of polyunsaturated compounds, as a result of heat or UV, and structural rearrangement, but with the persistence of alcohol sign. 1746 cm^{-1} (N=O stretching, nitro compound), 2199.72 cm^{-1} stretching (alkynes), and 2788.88 cm^{-1} (C $\equiv$ C (O-H stretch) of Spectrum T4 indicate that it may be due to advanced microbial fermentation. Also, exposure to a nitrogenous environment led to the production of unusual groups such as nitro and alkyne moieties, possibly arising from the protein or amino acid metabolism. The coatings of spectra shown in combination are indicative of the successive transformation from fresh extract high in sugar (T1), with little further changes, to enzymatically or acid hydrolysed (T2), thermally or oxidatively stressed (T3), to nitrogen enriched or highly fermented states (T4), reflecting the increasingly degree of chemical modification over a range of treatments and storage.

These findings suggest that we should adapt the way we think about soil management to include biologically rich, multi-component methods that can sustain high soil fertility and agricultural productivity over time. FTIR analysis of the structural

biomolecules in the sorghum extract also shows that T6 and other combined treatments significantly influence the biochemical makeup of the stalk. For instance, the presence of C=C and O-H functional groups in T6 indicates that metabolic changes are more advanced, suggesting a more efficient fermentation process that may yield more ethanol. The big O-H band (3298.56 cm^{-1}) and C=C band (1632.35 cm^{-1}) indicate the presence of polymeric alcohols and unsaturated compounds, which are the building blocks for microbial fermentation. T6 had the highest ethanol production of 2457.35 L ha^{-1} , indicating that the biochemical preparation for the conversion process was more effective. When you look at T6 next to T1 and T7, it is clear how vital changing chemical groups is for making ethanol. T1 exhibited simple carbohydrate structures, including a C-O stretch at 1069.57 cm^{-1} , indicating that the sugars were not digested. Similarly, (38) investigated the FTIR-ATR spectra of ethanol-water mixtures and found that the vibrational bands changed significantly as the water content increased. For example, the H-O-H bending vibration shifted 18.9 cm^{-1} to the red, and the β -CH 3 cm^{-1} group's asymmetric C-H stretching shifted 9.0 to the blue. These changes suggest that cyclic hydrogen-bonded networks are forming between water and ethanol molecules. High-level B3LYP/aug-cc-pVQZ quantum chemical calculations and MMFF94s molecular simulations backed up the experimental results. They showed that hydrogen-bonded clusters were present, especially in systems with up to 30 water molecules. This meant that hydrogen bonding led to significant structural changes. T6 featured more complicated and reactive structures, such as conjugated alkenes and cross-linked polysaccharides. These made it easier for microbes to access the sugar and release it. On the other hand, T7 showed spectral features of benzene rings and oxidised compounds, which might indicate that the substrates that could be fermented were deteriorating and losing their fermentability (Patel et al., 2025).

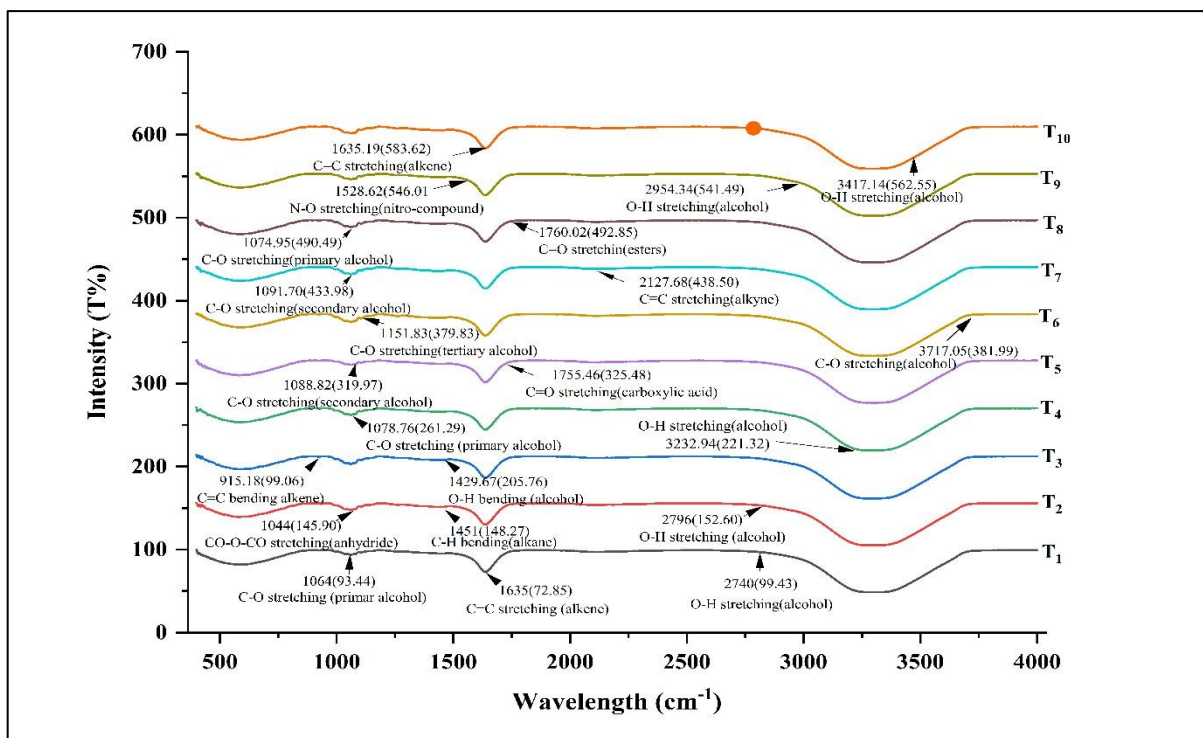


Fig 4.61: FTIR of extract

4.6.2 TGA analysis of sweet sorghum seed powder

The thermogravimetric and derivative thermogravimetric curves (TGA/DTG) of sample T1 (initial weight: 8.945 mg) exhibit two typical decomposition steps, providing basic information about the thermal stability and composition (Fig. 4.62).

The first small weight-loss step occurs at 48.82 °C, with a mass decrease from 8.945 mg to 8.752 mg (approximately 2.1%), corresponding to the release of lattice water molecules. This results from surface-adsorbed moisture or physically bound volatiles, which comprise a small percentage of the trapped ingredients. The primary decomposition begins sharply at 294.15°C (sample mass: 7.780 mg), marked by a rapid decrease, as indicated by a peak at 320 °C on the DTG curve, with a maximum derivative weight loss rate of approximately 1.2 mg/min. In this region, the mass drops from 7.78 mg to 1.0 mg (around 88–89% weight loss), due to the decomposition and vaporization of organic material. At higher temperatures, the degradation rate slows significantly between 350 and 550°C, leaving a stable residue of 1.0 mg at 600°C (about 11% of the original weight), likely inorganic ash, carbon char, or other heatresistant components. Compared with other samples, the onset of significant degradation at 294

°C indicates that T1 exhibits weak thermal stability, surviving structurally only just below 300 °C before undergoing rapid pyrolytic decomposition. The large percentage of mass loss during the primary step indicates a predominantly organic material, while the 11% residue suggests an inorganic, non-volatile content. The DTG curve also shows a single dominant degradation stage with a narrow, sharp peak, indicating a uniform thermal breakdown process. Overall, these results demonstrate that T1 is highly stable at low to moderate temperatures but undergoes intense decomposition between 294 and 350 °C, making it suitable only for applications below 290 °C unless stabilized or modified. The thermal stability and decomposition behaviours of T6 were analysed using thermogravimetric analysis (TGA). The DTG curves show a multistep weight loss, indicating that the polymer comprises multiple components with a robust, well-structured composition even when heated gradually. The TGA data, starting from an initial weight of 8.967 mg, reveals the first mass loss beginning at 48. 50°C, with the sample weighing 8.363 mg. This minor loss is attributed to the desorption of physically adsorbed water or to solvent evaporation, confirming the material's hygroscopic nature without damaging its structure. The most significant thermal event occurs at 293. 54°C (mass at onset: 7,305 mg), marking the primary decomposition of T6. This higher onset temperature indicates the strong thermal stability of its main molecular structure. The rapid breakdown, as evidenced by a well-defined peak with a minimum value of 1.252 in the DTG data, suggests an explosive single-step decomposition that occurs at a critical temperature. This process is likely related to the pyrolysis of organic components, the cleavage of labile functional groups, or disintegration reactions within the polymer backbone. Beyond this main event, the TGA curve shows continued mild mass loss up to 599. 9°C, indicating multistage carbonization or degradation from more thermally stable structures. The remaining residue provides valuable information on the inorganic content or char yield, which may relate to flame-retardant properties or the presence of inorganic fillers. The high primary decomposition temperature of 293.54. 54°C highlights T6's favourable thermal stability and suitability for use in flexible electronics or high-performance polymer composites that require long-term stability at elevated temperatures. The sharp, energetic break during decomposition suggests a controlled energy release profile, which could be advantageous for energetic materials or catalysts. The initial low-temperature mass loss, associated with moisture, is essential

for process and storage stability in pharmaceuticals or bio-based polymers. The multistep degradation and char formation have direct implications for designing T6-based materials with tailored flame-retardant properties or as precursors for carbonaceous materials. In conclusion, the TGA results indicate that T6 exhibits high thermal stability, with decomposition occurring in multiple stages. The process begins with moisture removal, followed by main degradation at around 300°C, and leaves behind thermally stable residues (Akash and Rehman, 2025).

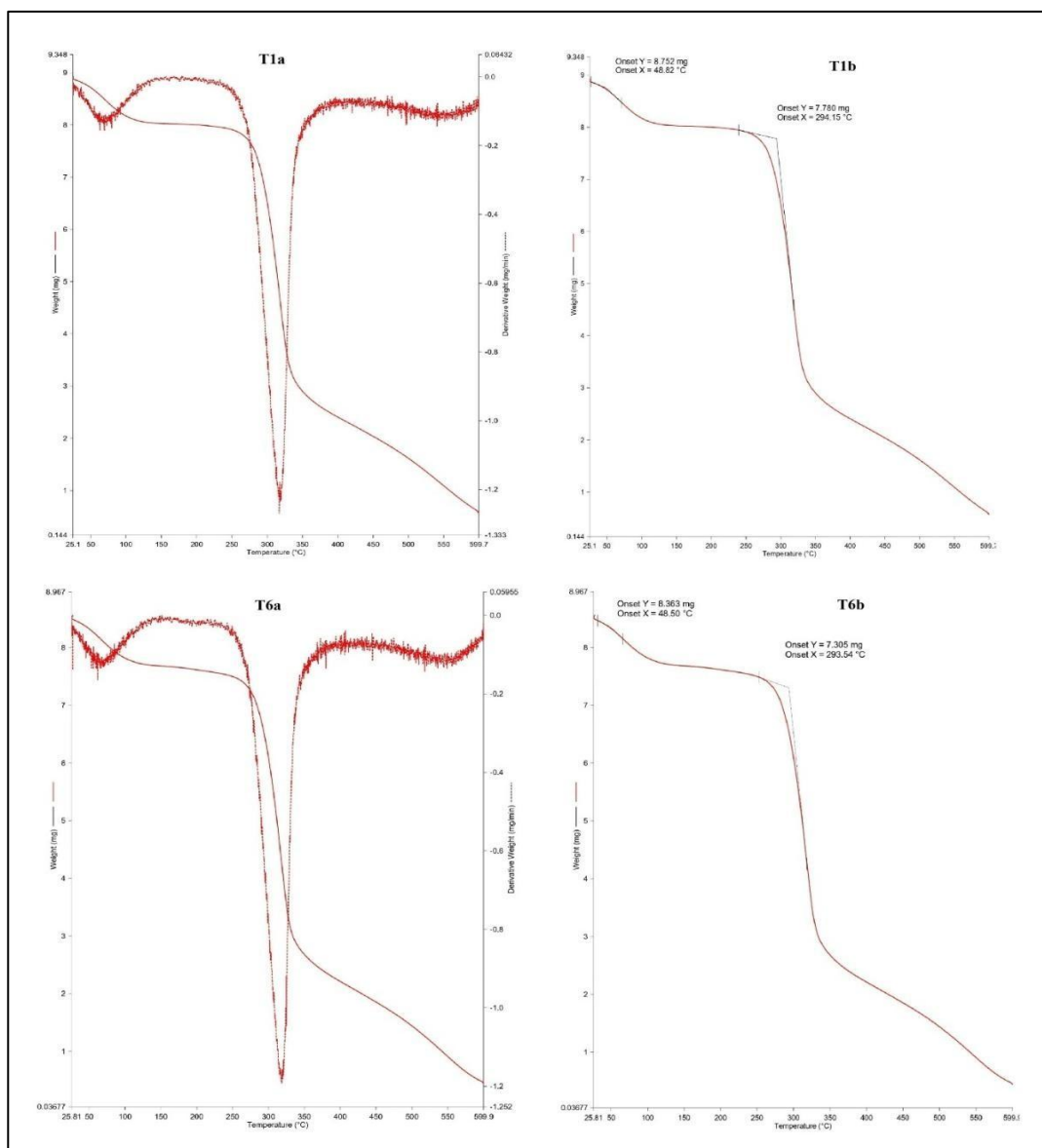


Fig. 4.62: Thermal Decomposition Kinetics of Sweet Sorghum Seeds by TGA

4.6.3 EDX analysis of sweet sorghum seed powder

The energy-dispersive X-ray (EDX) test showed that sample T6 has a complicated elemental profile including C, O, N, Mg, Si, P, S, Cl, K, Ca, Ti, Mn, Fe, Cu, Zn, Se, Pb, Mo, Ni, and B (Fig. 4.63).

This mixture of different materials suggests that there is a composite matrix that serves several purposes and contains both organic and inorganic materials. On the other hand, sample T1 (Control) showed a simpler, less intense spectrum, with carbon and oxygen as the most common components and only trace amounts of other elements. This means the organic base material is cleaner and contains fewer extraneous minerals or additives. Elemental mapping showed that the two samples differed significantly. T6 has components spread across a wide area, with C and O evenly distributed, and the remaining elements grouped or distributed in gradients. These patterns show areas where minerals are added or removed, most likely due to mineral inclusions or the intentional addition of functional additives. T1, on the other hand, had a highly even distribution of all the parts that were found. The absence of elemental clumps or gradients supports the idea that T1 is a cleaner, more uniform material. The fact that Mo and Ni are separate locations in T6 indicates the presence of nanoparticles or small particles within the material. These traits suggest that functional enhancements could improve the material's catalytic activity, conductivity, or mechanical properties. T1 didn't have any of these unique elemental inclusions, which supports the idea that it was a compositionally simpler material with little use beyond its fundamental organic structure.

The organic matrix in T6 appears to work better with the inorganic parts embedded in it, which might make the whole thing last longer and perform better. The matrix in T1, on the other hand, is mostly organic and doesn't interact with inorganic materials very much. This makes it more consistent and homogeneous, but it does not work as well. This demonstrates that T6 has additional potential uses, but its complicated composition may make it hard to handle and reproduce. Lastly, the differences in structure and content between T1 and T6 are probably owing to the use of various synthesis methods. The complexity of T6 indicates that it was produced in multiple steps, including the planned addition of nanoparticles and mineral phases

(Patel *et al.* 2025). On the other hand, T1 is most likely the result of a one-step synthesis done under controlled conditions to get.

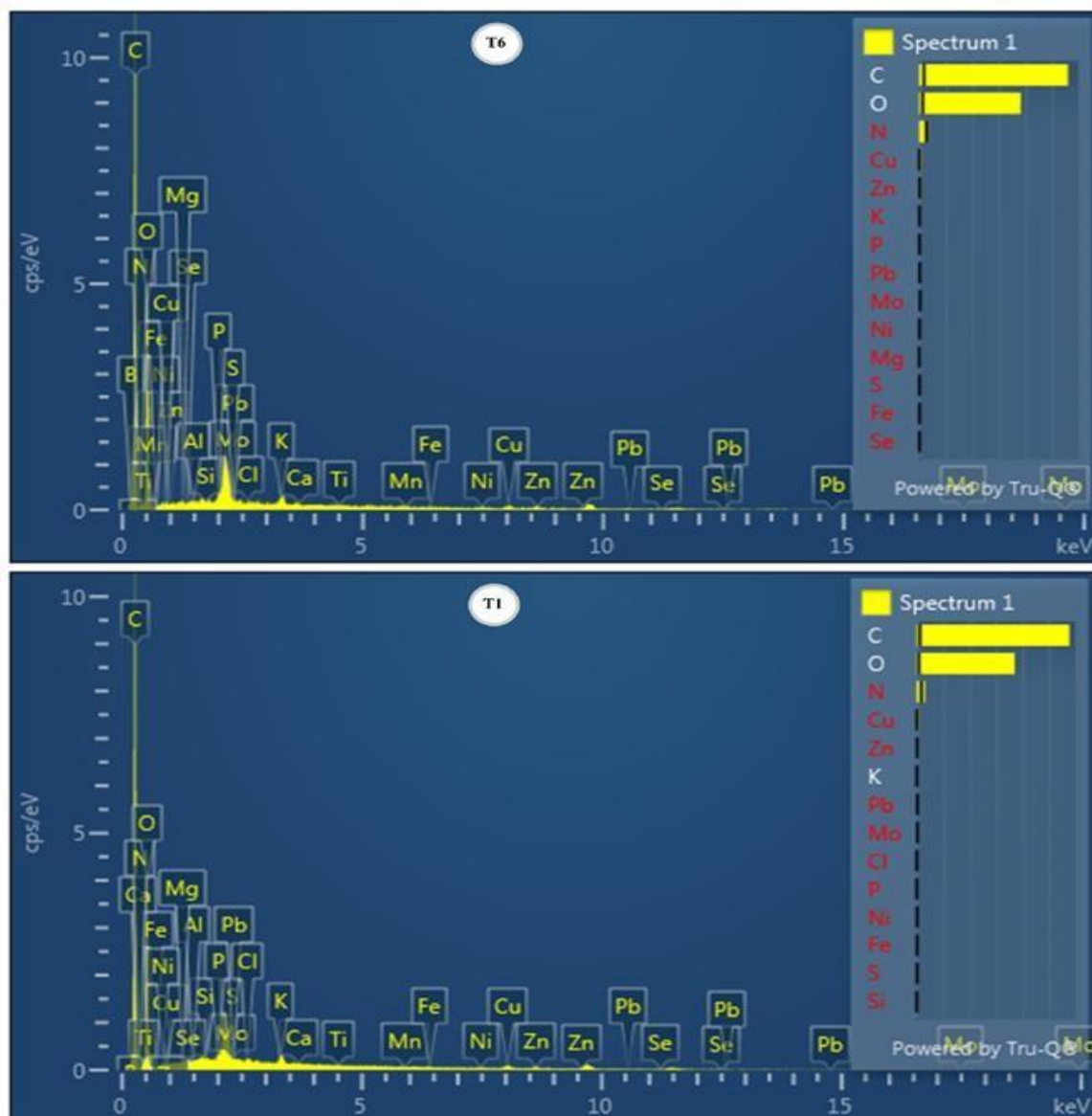


Fig. 4.63: Influence of treatment on nutritional quality analysis by EDX spectrum.

4.7 Economics

The data on economics, including cost of cultivation, gross return, net return and benefit cost (B:C) ratio, were influenced by different nutrient management treatments during 2023 and 2024.

4.7.1. Cost of cultivation of grain production (₹ ha⁻¹)

The data on cultivation costs (₹ ha⁻¹) are influenced by different nutrient management strategies for grain producing sweet sorghum in 2023 and 2024 (Tables 26 and 27).

The cost of cultivation showed a significant different between the treatments; the highest price was recorded through the application 75% RDF + zeolite (1.5 t ha⁻¹) + press-mud (15 t ha⁻¹) + bio-neema (5 kg ha⁻¹) (T6) (49702.11 ₹ ha⁻¹ in both year), reflecting costliest cultivation; while the lowest cost of cultivation was noted in the absolute control (T1), with cultivation expenses (34925.00 ₹ ha⁻¹), respectively.

Among the different nutrient management practices through integrated approach in sweet sorghum in the T6 (75% RDF + zeolite 1.5 t ha⁻¹ + press-mud 15 t ha⁻¹ + bio-neema 5 kg ha⁻¹) highlights might be due maximum total cost of cultivation primarily because of the inclusion of zeolite, which is a relatively costly material that requires a bulk application rate; this factor dramatically raise both the direct material cost and associated labour for spreading. In addition of standard fixed and variable expenses like land preparation, fertilizer, irrigation, insecticide, land value, and labour ultimately reflecting the highest initial cost (Ryan *et al.* 2018; Ram *et al.* 2017).

4.7.2 Gross return of grain production (₹ ha⁻¹)

The data on gross return (₹ ha⁻¹) are influenced by different nutrient management practices for grain production in 2023 and 2024 (Table 26)

The gross return for grain production exhibited a substantial range across different nutrient management practices, where the maximum gross return was noted in T6 (97,880.40 ₹ ha⁻¹ in 2023 and 1,04,568.42 ₹ ha⁻¹ in 2024), showed the greatest profitable scenario; however, the minimal gross return was recorded T1, reaching (44,742.60 ₹ ha⁻¹ in 2023 and 46,014.15 ₹ ha⁻¹ in 2024).

The highest gross return was recorded through the application of (75% RDF + zeolite 1.5 t ha⁻¹ + press-mud 15 t ha⁻¹ + bio-neema 5 kg ha⁻¹) (T6) might be due to higher yield of grains might be due to improvement soil fertility, nutrient availability

and plan growth. Pressmud supplies organic matter and essential nutrients, while zeolite enhances nutrient retention and reduces leaching losses. Bio-neema helps in controlling soil-borne pests and improves root health. The combined effect of these inputs with RDF enhances nutrient use efficiency, resulting in better crop growth, higher grain yield, and ultimately higher gross returns (Ryan *et al.* 2018; Ram *et al.* 2017).

4.7.3 Net return of grain production (₹ ha⁻¹)

The data on net return (₹ ha⁻¹) are influenced by different nutrient management practices for grain production in 2023 and 2024 (Table 26)

The net return for grain production varied substantially across different nutrient management practices. An analysis of financial conclusion showed a significant divergence in net return. The highest net return was observed through the application of 75% RDF + zeolite 1.5 t ha⁻¹ + press-mud 15 t ha⁻¹ + bio-neema 5 kg ha⁻¹ (T6) (48178.29 ₹ ha⁻¹ in 2023 and 54866.31 ₹ ha⁻¹ in 2024). Conversely, the minimum net return was recorded in T1 (absolute control) 9817.60 ₹ ha⁻¹ in 2023 and 11089.15 ₹ ha⁻¹ in 2024.

The highest net return was noted in T6 in both years as compared to rest of treatment. It might be better grain yield of sweet sorghum with spend minimal cost through combination nutrient management (Ram *et al.*, 2017).

4.7.4 Benefit cost ratio (B:C ratio)

The B: C ratio for grain production showed a substantial difference in returns per rupee invested. The maximum benefit-cost ratio was recorded in T2 (2.14 in 2023 and 2.34 in 2024), while the minimum benefit-cost ratio was recorded in T9 and T1 in 2023 and 1.28 in 2024, respectively.

The maximum benefit cost ratio was recorded in T2 (100% RDF) might be due to the minimal cost and minimal gross return of under this nutrient management practices in sweet sorghum, while minimal benefit cost was recorded in T9 (Ryan *et al.* 2018; Ram *et al.* 2017)

Table 4.26: Effect of cost of cultivation through different nutrient management practices in grain production of sweet sorghum in 2023-24

Treatments	Cost of cultivation (₹ ha ⁻¹)		Gross return (₹ ha ⁻¹)		Net return (₹ ha ⁻¹)		B: C ratio	
	2023	2024	2023	2024	2023	2024	2023	2024
T1	34925.00	34925.00	44742.60	46014.15	9817.60	11089.15	1.28	1.32
T2	39656.75	39656.75	84778.80	92938.47	45122.05	53281.72	2.14	2.34
T3	43902.11	43902.11	81662.40	88960.69	37760.29	45058.58	1.86	2.03
T4	43452.11	43452.11	76256.40	83600.80	32804.29	40148.69	1.75	1.92
T5	47952.11	47952.11	93651.00	102377.27	45698.89	54425.16	1.95	2.13
T6	49702.11	49702.11	97880.40	104568.42	48178.29	54866.31	1.97	2.10
T7	41845.00	41875.00	53000.01	59632.99	11155.01	17757.99	1.27	1.42
T8	41395.00	41425.00	55448.61	63442.22	14053.61	22017.22	1.34	1.53
T9	45895.00	45925.00	56286.00	60678.00	10391.00	14753.00	1.23	1.32
T10	47645.00	47675.00	58299.99	66307.57	10654.99	18632.57	1.22	1.39

T1-* Control (Absolute), T2-*100 % RDF (90:40:40 NPK), T3-*75 % RDF +Zeolite (1.5 t ha⁻¹), T4-*75 % RDF +Press-mud (15 t ha⁻¹), T5-*75 % RDF +Zeolite (1.5 t ha⁻¹) +Press-mud (15 t ha⁻¹), T6-*75 % RDF +Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹) +Bio-neema (5 kg ha⁻¹), T7-*Nano NPK (19:19:19) +Zeolite (1.5 t ha⁻¹), T8-*Nano NPK (19:19:19) + Press-mud (15 t ha⁻¹), T9-*Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹), T10-* Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) +Press-mud (1.5 t ha⁻¹) +Bio-neema (5 kg ha⁻¹). SEm*Standard Error of Mean, LSD (p =0.05)-* Least Significant Difference at 5 % significance level.

4.7.5 Cost of cultivation of ethanol production (₹ ha⁻¹)

The data on cultivation costs (₹ ha⁻¹) are influenced by different nutrient management strategies for producing ethanol from sweet sorghum in 2023 and 2024 (Table 27).

The cost of cultivation showed a significant different between the treatments; the highest price was recorded through the application 75% RDF + zeolite (1.5 t ha⁻¹) + press-mud (15 t ha⁻¹) + bio-neema (5 kg ha⁻¹) (T6) (125687.71 ₹ ha⁻¹ in 2023 and 131359.71 ₹ ha⁻¹ in 2024), reflecting costliest cultivation; while the lowest cost of

cultivation was noted in the absolute control (T1), with cultivation expenses (50,216.47 ₹ ha⁻¹ in 2023 and 48,315.20 ₹ ha⁻¹ in 2024),

Among the different nutrient management practices through integrated approach in sweet sorghum in the T6 (75% RDF + zeolite 1.5 t ha⁻¹ + press-mud 15 t ha⁻¹ + bio-neema 5 kg ha⁻¹) highlights might be due maximum total cost of cultivation primarily because of the inclusion of zeolite, which is a relatively costly material that requires a bulk application rate; this factor dramatically raise both the direct material cost and associated labour for spreading. In addition of standard fixed and variable expenses like land preparation, fertilizer, irrigation, insecticide, land value labour and ethanol processing cost, ultimately reflecting the highest initial cost need to achieve the maximum potential economic return necessary for profitable ethanol production (Ryan *et al.* 2018; Ram *et al.* 2017).

4.7.6 Gross return of ethanol production (₹ ha⁻¹)

The data on gross return (₹ ha⁻¹) are influenced by different nutrient management practices for ethanol production in 2023 and 2024 (Table 27).

The gross return for grain production exhibited a substantial range across different nutrient management practices, where the highest gross return was noted in T6 (17,881,3.29 ₹ ha⁻¹ in 2023 and 197999.11 ₹ ha⁻¹ in 2024), showed the greatest profitable scenario; however, the minimal gross return was recorded T1, reaching (55845.62 ₹ ha⁻¹ in 2023 and 53498.25 ₹ ha⁻¹ in 2024).

The highest gross return was recorded through the application of (75% RDF + zeolite 1.5 t ha⁻¹ + press-mud 15 t ha⁻¹ + bio-neema 5 kg ha⁻¹) (T6) might be due to higher yield of sweet stalk, which is used to making ethanol. This nutrient combination showed higher efficient and potential to promotion form the point of view of economic efficiency (Ryan *et al.* 2018; Ram *et al.* 2017).

4.7.7 Net return of ethanol production (₹ ha⁻¹)

The data on net return (₹ ha⁻¹) are influenced by different nutrient management practices for ethanol production in 2023 and 2024 (Table 27).

The net return for grain production varied substantially across different nutrient management practices. An analysis of financial conclusion showed a significant divergence in net return. The highest net return was observed through the application of 75% RDF + zeolite 1.5 t ha⁻¹ + press-mud 15 t ha⁻¹ + bio-neema 5 kg ha⁻¹ (T6)

(53125.58 ₹ ha⁻¹ in 2023 and 66639.40 ₹ ha⁻¹). Conversely, the minimum net return was recorded in T1 (absolute control) 5629.15 ₹ ha⁻¹ in 2023 and 5183.05 ₹ ha⁻¹ in 2024, respectively.

The highest net return was noted in T2 in both years compared to rest of treatment. It might be higher yield of sweet stalk was recorded nutrient management through RDF (Ryan *et al.* 2018; Ram *et al.* 2017).

4.7.8 Benefit cost ratio of ethanol (B:C ratio)

The B: C ratio for ethanol production showed a substantial difference in returns per rupee invested. The maximum benefit-cost ratio was recorded in T2 (1.51 in 2023 and 1.59 in 2024), while the minimum benefit-cost ratio was recorded in T9 and T1 in both years.

The maximum benefit cost ratio was recorded in T2 (100% RDF) might be due to the minimal cost and maximum gross return of under this nutrient management practices in sweet sorghum, while minimal benefit cost was recorded in absolute control (T10) (Ryan *et al.* 2018; Ram *et al.* 2017).

Table 4.27: Effect of cost of cultivation through different nutrient management practices in ethanol production through sweet sorghum in 2023-24

Treatments	Cost of cultivation		Gross return (₹ ha ⁻¹)		Net return (₹ ha ⁻¹)		B: C ratio	
	2023	2024	2023	2024	2023	2024	2023	2024
T1	50216.47	48315.20	55845.62	53498.25	5629.15	5183.05	1.11	1.11
T2	102022.55	105702.45	154081.42	168379.79	52058.87	62677.34	1.51	1.59
T3	100965.46	106048.71	142050.80	158227.83	41085.34	52179.12	1.41	1.49
T4	102368.31	104818.71	146562.52	157061.31	44194.21	52242.60	1.43	1.50
T5	114603.11	121717.11	161269.03	182331.05	46665.92	60613.94	1.41	1.50
T6	125687.71	131359.71	178813.29	197999.11	53125.58	66639.40	1.42	1.51
T7	67129.27	68277.00	77308.16	83070.83	10178.89	14793.83	1.15	1.22
T8	68936.51	68276.30	81439.96	83646.66	12503.46	15370.36	1.18	1.23
T9	72177.51	76558.90	78822.63	91079.92	6645.12	14521.02	1.09	1.19
T10	75314.92	78811.60	80966.41	91369.04	5651.49	12557.44	1.08	1.16

T1-* Control (Absolute), T2-*100 % RDF (90:40:40 NPK), T3-*75 % RDF +Zeolite (1.5 t ha⁻¹), T4*75 % RDF +Press-mud (15 t ha⁻¹), T5-*75 % RDF +Zeolite (1.5 t ha⁻¹) +Press-mud (15 t ha⁻¹), T6-*75 % RDF +Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹) +Bio-neema (5 kg ha⁻¹), T7-*Nano NPK (19:19:19) +Zeolite (1.5 t ha⁻¹), T8-*Nano NPK (19:19:19) + Press-mud (15 t ha⁻¹), T9-*Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹), T10-* Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) +Pressmud (1.5 t ha⁻¹) +Bio-neema (5 kg ha⁻¹). SEm-*Standard Error of Mean, LSD (p =0.05)-* Least Significant Difference at 5 % significance level.

4.7.9 Cost of cultivation of sugar production (₹ ha⁻¹)

The data on cultivation costs (₹ ha⁻¹) are influenced by different nutrient management strategies for producing sugar from sweet sorghum in 2023 and 2024 (Table 28).

The cost of cultivation showed a significant different between the treatments; the highest price was recorded through the application 75% RDF + zeolite (1.5 t ha⁻¹) + press-mud (15 t ha⁻¹) + bio-neema (5 kg ha⁻¹) (T6) (68335.11 ₹ ha⁻¹ in 2023 and 68347.11 ₹ ha⁻¹ in 2024), reflecting costliest cultivation; while the lowest cost of cultivation was noted in the absolute control (T1), with cultivation expenses (39063.00 ₹ ha⁻¹ in 2023 and 38943.00 ₹ ha⁻¹ in 2024), respectively.

Among the different nutrient management practices through integrated approach in sweet sorghum in the T6 (75% RDF + zeolite 1.5 t ha⁻¹ + press-mud 15 t ha⁻¹ + bio-neema 5 kg ha⁻¹) highlights might be due maximum total cost of cultivation primarily because of the inclusion of zeolite, which is a relatively costly material that requires a bulk application rate; this factor dramatically raise both the direct material cost and associated labour for spreading. In addition of standard fixed and variable expenses like land preparation, fertilizer, irrigation, insecticide, land value labour and sugar processing cost, ultimately reflecting the highest initial cost need to achieve the maximum potential economic return necessary for profitable ethanol production (Ryan *et al.* 2018; Ram *et al.* 2017).

4.7.10 Gross return of sugar production (₹ ha⁻¹)

The data on gross return (₹ ha⁻¹) are influenced by different nutrient management practices for sugar production in 2023 and 2024 (Table 28).

The gross return for grain production exhibited a substantial range across different nutrient management practices, where the highest gross return was noted in T6 (229242.23 ₹ ha⁻¹ in 2023 and 243565.29 ₹ ha⁻¹ in 2024), showed the greatest

profitable scenario; however, the minimal gross return was recorded T1, reaching (67202.98 ₹ ha⁻¹ in 2023 and 61926.42 ₹ ha⁻¹ in 2024).

The highest gross return was recorded through the application of (75% RDF + zeolite 1.5 t ha⁻¹ + press-mud 15 t ha⁻¹ + bio-neema 5 kg ha⁻¹) (T6) might be due to higher yield of sweet stalk, which is used to making sugar. This nutrient combination showed higher efficient and potential to promotion form the point of view of economic efficiency (Ryan *et al.* 2018; Ram *et al.* 2017).

4.7.11 Net return of sugar production (₹ ha⁻¹)

The data on net return (₹ ha⁻¹) are influenced by different nutrient management practices for sugar production in 2023 and 2024 (Table 28).

The net return for grain production varied substantially across different nutrient management practices. An analysis of financial conclusion showed a significant divergence in net return. The highest net return was observed through the application of 75% RDF + zeolite (1.5 t ha⁻¹) + press-mud (15 t ha⁻¹) + bio-neema (5 kg ha⁻¹) (T6) (160919.12 ₹ ha⁻¹ in 2023 and 175218.18 ₹ ha⁻¹ in 2024). Conversely, the minimum net return was recorded through in absolute control (28139.98 ₹ ha⁻¹ in 2023 and 22983.42 ₹ ha⁻¹ in 2024) (T1).

The highest net return was noted in T6 in both years compared to rest of treatment. It might be higher yield of sweet stalk, which is used for sugar production was recorded through this combination nutrient management (Ryan *et al.* 2018; Ram *et al.* 2017).

4.7.12 Benefit cost ratio (B:C ratio)

The B: C ratio for sugar production showed a substantial difference in returns per rupee invested. The maximum benefit-cost ratio was recorded in T2 (3.54 in 2023 and 3.71 in 2024), while the minimum benefit-cost ratio was recorded in T1 (1.72 in 2023 and 1.59 in 2024).

The maximum benefit cost ratio was recorded in T2 (100% RDF) might be due to the minimal cost and maximum gross return of under this nutrient management practices in sweet sorghum, while minimal benefit cost was recorded in absolute control (T1) (Ryan *et al.* 2018; Ram *et al.* 2017).

Table 4.28: Effect of cost of cultivation through different nutrient management practices in sugar production through sweet sorghum in 2023-24

Treatments	Cost of cultivation		Gross return (₹ ha ⁻¹)		Net return (₹ ha ⁻¹)		B: C ratio	
	2023	2024	2023	2024	2023	2024	2023	2024
T1	39063.00	38943.00	67202.98	61926.42	28139.98	22983.42	1.72	1.59
T2	55297.75	55313.75	195634.56	205052.59	140336.81	149738.84	3.54	3.71
T3	58288.11	58377.11	180387.98	192967.15	122099.87	134590.04	3.09	3.31
T4	58358.11	58301.11	186002.43	191357.79	127644.32	133056.68	3.19	3.28
T5	64497.11	64675.11	205848.08	223452.74	141350.97	158777.63	3.19	3.46
T6	68335.11	68347.11	229254.23	243565.29	160919.12	175218.18	3.35	3.56
T7	48565.00	48677.00	94941.04	98699.42	46376.04	50022.42	1.95	2.03
T8	48518.00	48659.00	100638.82	99189.12	52120.82	50530.12	2.07	2.04
T9	52733.00	53034.00	98050.20	108836.92	45317.20	55802.92	1.86	2.05
T10	54855.00	55020.00	100448.81	109475.10	45593.81	54455.10	1.83	1.99

T1-* Control (Absolute), T2-*100 % RDF (90:40:40 NPK), T3-*75 % RDF +Zeolite (1.5 t ha⁻¹), T4*75 % RDF +Press-mud (15 t ha⁻¹), T5-*75 % RDF +Zeolite (1.5 t ha⁻¹) +Press-mud (15 t ha⁻¹), T6-*75 % RDF +Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹) +Bio-neema (5 kg ha⁻¹), T7-*Nano NPK (19:19:19) +Zeolite (1.5 t ha⁻¹), T8-*Nano NPK (19:19:19) + Press-mud (15 t ha⁻¹), T9-*Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) + Press-mud (15 t ha⁻¹), T10-* Nano NPK (19:19:19) + Zeolite (1.5 t ha⁻¹) +Pressmud (1.5 t ha⁻¹) +Bio-neema (5 kg ha⁻¹). SEm-*Standard Error of Mean, LSD (p =0.05)-* Least Significant Difference at 5 % significance level.

Summary and Conclusion

A field experiment entitled “Investigating the synergistic impact on press-mud, zeolite, bio-neema, and Nano NPK on the growth, productivity, and quality of Sweet Sorghum (*Sorghum bicolor* (L.) Moench)” was conducted during the Kharif season of 2023 and 2024 at the Agricultural Research Farm, School of Agriculture, Lovely Professional University, Phagwara, Punjab. The experimental plot had a sandy loam texture and a slightly alkaline soil pH of 7.90. The soil contained 0.28% organic carbon (SOC) and had available nitrogen, phosphorus, and potassium at 239.30, 23.3, and 249.70 kg ha⁻¹. The field experiment was conducted in a randomized block design with ten treatment combinations, replicated three times. Inorganic fertilizer was applied at 100% and 75% RDF, with or without press-mud, zeolite, and bio-neema, along with nano NPK foliar application. The key findings of this investigation are outlined in this chapter under the following headings and subheadings.

5.1 Morphological traits of sweet sorghum

- ✚ Sweet sorghum during the second year of the research showed improved growth, with greater maximum plant height, increased dry matter accumulation, higher crop growth rate (CGR), and higher relative growth rate (RGR) compared to the first year.
- ✚ Among the various nutrient management practices in sweet sorghum, significantly higher morphological traits such as the number of internodes, internode length (cm), stem thickness (mm), and fresh and dry matter accumulation (g) were observed with 75% of the recommended dose of fertilizer (RDF) combined with press mud (15 t ha⁻¹), zeolite (1.5 t ha⁻¹), and bio-neem (5 kg ha⁻¹).
- ✚ However, plant height, the number of leaves per plant, leaf area, and leaf area index were measured after applying 100% of the recommended dose of fertilizer (RDF) at 30 and 60 days after sowing, which might be due to the initial availability of essential nutrients from inorganic sources.
- ✚ The growth indices such as crop growth rate (CGR), relative growth rate (RGR), and chlorophyll index (SPAD value) were significantly higher under the T6 treatment

(75% recommended dose of fertilizer (RDF) + press-mud at 15 t ha⁻¹, zeolite at 1.5 t ha⁻¹, and bio-neema at 5 kg ha⁻¹).

- ✚ Among the nutrient management strategies in sweet sorghum, treatments with 75% of the recommended dose of fertilizer (RDF) combined with press-mud (15 t ha⁻¹), zeolite (1.5 t ha⁻¹), and bio-neema (5 kg ha⁻¹) showed significantly better results in morphological traits. These outcomes were statistically comparable to those obtained with 75% RDF plus press-mud and zeolite, followed by 100% RDF.
- ✚ While the nano NPK with press mud, zeolite, and bio-neem without RDF slightly improved morphological traits compared to the absolute control.

5.2 Yield traits of sweet sorghum

- ✚ The yield-attributing characters of sweet sorghum, such as weight of grains per ear head (g), length of ear head (cm), number of panicles per ear head, number of grains per ear head, test weight, and grain yield, were significantly and better recorded under integrated nutrient management practices.
- ✚ The maximum yield characteristics were observed in T6 (75% recommended dose of fertilizer (RDF) + press-mud (15 t ha⁻¹), zeolite (1.5 t ha⁻¹), and bio-neema (5 kg ha⁻¹), which was statistically on par with T5 (75% recommended dose of fertilizer (RDF) + press-mud (15 t ha⁻¹), zeolite (1.5 t ha⁻¹)), followed by T2, T3, and T4.
- ✚ In integrated nutrient management strategies, the highest or superiorly attributed result was observed in T6. Additionally, nano-NPK increased yield attributes, but compared to T6 (75% recommended dose of fertilizer (RDF) + press-mud (15 t ha⁻¹), zeolite (1.5 t ha⁻¹), and bio-neema (5 kg ha⁻¹)), a slight yet significant increase was observed over the absolute control.

5.3 Sugar and ethanol traits of sweet sorghum

- ✚ The sugar and ethanol-related characteristics of sweet sorghum, such as fresh stalk (t ha⁻¹), juice extraction (%), juice yield (l ha⁻¹), potential ethanol yield (l ha⁻¹), brix ratio (%), TSS (%), sugar yield (t ha⁻¹), extract/juice pH, reducing sugar (%), non-reducing sugar (%), and total sugar index (%) were significantly observed under integrated nutrient management practices.
- ✚ T6 performance consistently outperforms and provides vital nutrients that generate optimal sugar and ethanol-related parameters.

- 75% recommended dose of fertilisers + Zeolite (1.5 t ha^{-1}), 75% recommended dose of fertilisers + Press-mud (15 t ha^{-1}), and 75% recommended dose of fertilisers + Zeolite (1.5 t ha^{-1}) + Press-mud (15 t ha^{-1}) showed the second highest treatment, which helped produce maximum sugar and ethanol attribute characters.
- The maximum sugar and ethanol attributes were observed in T6 (75% recommended dose of fertilizer (RDF) + press-mud (15 t ha^{-1}), zeolite (1.5 t ha^{-1}), and bio-neema (5 kg ha^{-1})), which was statistically on par with T5 (75% recommended dose of fertilizer (RDF) + press-mud (15 t ha^{-1}), zeolite (1.5 t ha^{-1})), followed by T2, T3, and T4.
- However, the lowest sugar and ethanol-related attributes were recorded in the absolute control due to low availability of essential nutrients or minimal sources of nutrients available to the plant. At the same time, T7 to T10 also shared the enhanced characteristics.

5.4 Quality traits of sweet sorghum

- The quality-contributing characteristics of sweet sorghum, such as chlorophyll a & b, protein content in grains, nitrogen, phosphorus, potassium, ash, lignin, hemicellulose, and cellulose in bagasse, are significantly observed through combined nutrient management strategies.
- The highest quality attributes were observed with the application of 75% recommended dose of fertilizer (RDF) + press-mud (15 t ha^{-1}), zeolite (1.5 t ha^{-1}), and bio-neema (5 kg ha^{-1}) (T6), which was comparable to T5 ((75% recommended dose of fertilizer (RDF) + press-mud (15 t ha^{-1}), zeolite (1.5 t ha^{-1})), followed by T2, T3, and T4.
- While press-mud and zeolite, with or without bio-neema, along with spray nano NPK, also enhance the quality attributes of sweet sorghum, a minimal improvement in quality was observed under the absolute control (T1).

5.5 Soil health traits

5.5.1 Soil physical property

- In integrated nutrient management for sweet sorghum, there was a slight increase in soil pH compared to the 100% recommended dose and the absolute control.

- ✚ The maximum soil pH was observed in T6 (75% recommended dose of fertilizer (RDF) + press-mud (15 t ha⁻¹), zeolite (1.5 t ha⁻¹), and bio-neema (5 kg ha⁻¹)), while the lowest pH was recorded in T1 (absolute control).
- ✚ In electrical conductivity (EC), notable changes occurred under combined nutrient management practices in sweet sorghum.
- ✚ The highest electrical conductivity was observed in T2 (100% recommended dose of fertilizers), while the second highest was noted in T1 (absolute control).
- ✚ The lowest electrical conductivity was recorded in T6 (75% recommended dose of fertilizer (RDF) + press-mud (15 t ha⁻¹), zeolite (1.5 t ha⁻¹), and bio-neema (5 kg ha⁻¹)).

5.5.2 Available nutrient

- ✚ Available nutrients such as nitrogen, phosphorus, potash, and organic carbon content in soil

are significantly affected by combined nutrient management practices in sweet sorghum.

- ✚ The highest nitrogen and organic carbon content was observed in T6 (75% recommended dose of fertilizer (RDF) + press-mud (15 t ha⁻¹), zeolite (1.5 t ha⁻¹), and bio-neema (5 kg ha⁻¹)).
- ✚ The highest levels of phosphorus and potassium were observed in T2 (100% RDF), while the lowest nitrogen, phosphorus, potassium, and organic carbon content was found in T1 (absolute control).

5.5.3 Biological properties

- ✚ The biological properties of soil, such as microbial count, urease activity, and dehydrogenase activity, were significantly affected by different nutrient management practices in sweet sorghum.
- ✚ Among the nutrient management treatments in sweet sorghum with 75% recommended dose of fertilizer (RDF) + press-mud (15 t ha⁻¹), zeolite (1.5 t ha⁻¹), and bio-neema (5 kg ha⁻¹), the highest microbial count and urease activity were recorded, which was statistically on par with the treatment involving 75% RDF + press-mud (15 t ha⁻¹) and zeolite (1.5 t ha⁻¹).
- ✚ However, the maximum dehydrogenase activity was observed with the application of (75% recommended dose of fertilizer (RDF) + press-mud (15 t ha⁻¹), zeolite (1.5

t ha⁻¹), and was statistically similar to the activity recorded in T6 (75% recommended dose of fertilizer (RDF) + press-mud (15 t ha⁻¹), zeolite (1.5 t ha⁻¹), and bio-neema (5 kg ha⁻¹). The lowest microbial count, urease activity, and dehydrogenase activity were noted in T1 (absolute control).

5.6 Economics

- ✚ The economic aspects, such as cost of cultivation, gross return, net return, and benefit-cost ratio, were observed across different nutrient management practices in sweet sorghum.
- ✚ Among nutrient management practices, the highest cost of cultivation, gross return, were observed with the application of 75% recommended dose of fertilizer (RDF) + press mud (15 t ha⁻¹), zeolite (1.5 t ha⁻¹), and bio-neema (5 kg ha⁻¹) (T6), but net return was recorded in T2 (100% RDF) for the grain and ethanol production; while for sugar producing the maximum net return was recorded in T6 (75% recommended dose of fertilizer (RDF) + press mud (15 t ha⁻¹), zeolite (1.5 t ha⁻¹), and bio-neema (5 kg ha⁻¹).
- ✚ The maximum benefit-cost ratio was observed with the application of 100% RDF, due to the minimal cultivation cost and higher gross return compared to T6.

Conclusion

- ✚ The nutrient management in integrated manner including 75% recommended dose of fertilizers (RDF) + press-mud (15t ha⁻¹) + zeolite (1.5t t ha⁻¹) + bio-neema (5 kg t ha⁻¹) significantly improved the growth attributes, yield components, and overall productivity of sweet sorghum compared to other treatments.
- ✚ Application of individual and combined nutrient sources such as press-mud, zeolite, bioneem, and inorganic fertilizers contributed to improved crop performance by enhancing soil organic matter content, stimulating microbial activity, and supplying essential nutrients in a slow and sustained manner, thereby supporting better plant growth.
- ✚ The integrated use of organic amendments, bio-inputs, and chemical fertilizers improved soil fertility status and nutrient uptake, resulting in better crop performance and sustainability of the production system.

- ✚ Economically, the treatment 75% RDF + press-mud (15 t ha⁻¹) + zeolite (1.5 t ha⁻¹) + bio-neema (5 kg ha⁻¹) proved to be the most profitable nutrient management strategy in sweet sorghum.

Future Direction

- ✚ **Development of sustainable bioethanol production systems:** Future research should focus on optimizing integrated nutrient management strategies to maximize stalk biomass, fermentable sugar content, and ethanol yield from sweet sorghum while reducing dependence on chemical fertilizers.
- ✚ **Enhancing nutrient use efficiency:** Further studies are needed to quantify the long-term effects of press-mud, zeolite, bio-neema, and nano NPK on nutrient use efficiency, fertilizer recovery, and nutrient cycling under different agro-climatic conditions.
- ✚ **Climate-resilient bioenergy production:** As sweet sorghum is tolerant to drought and marginal soils, future investigations should evaluate the effectiveness of integrated nutrient management under climate change-induced stresses, including drought, salinity, and high temperatures, to ensure stable biofuel production.
- ✚ **Soil health and carbon sequestration:** Long-term experiments should evaluate the impact of press-mud, zeolite, and bio-neema on soil organic carbon, microbial diversity, enzyme activity, and carbon sequestration, contributing to sustainable soil management.
- ✚ **Integration with precision agriculture:** Future studies should combine integrated nutrient management with precision nutrient application technologies, remote sensing, and drone-based monitoring to improve nutrient use efficiency and reduce production costs.
- ✚ **Nano-fertilizer optimization:** Further research is required to optimize the dose, timing, and method of Nano NPK application and to evaluate its interaction with organic amendments for improving crop productivity and minimizing nutrient losses.
- ✚ **Economic and life-cycle assessment:** Comprehensive studies should assess the economic feasibility, energy balance, greenhouse gas emissions, and life-cycle sustainability of sweet sorghum-based ethanol production under integrated nutrient management practices.

- ✚ **Industrial-scale validation:** Multi-location and large-scale field trials should be conducted to validate the most promising nutrient management strategy for commercial cultivation of sweet sorghum as a renewable biofuel feedstock.
- ✚ **Policy and commercialization:** Future research should generate evidence to support policies promoting sweet sorghum as a sustainable bioenergy crop, encouraging adoption of integrated nutrient management practices that improve productivity while reducing environmental impacts.

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Optimization and conformational study to increase nutrients and biofuel content in the extract of sorghum's plant augmented by nano NPK and zeolite

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ARTICLE INFO

Keywords:

Integrated soil amendments
Extract quality optimization
Confirmatory analysis
Multivariate analysis
Nutritional and biofuel production

ABSTRACT

This research addresses the use of nano-NPK, zeolite, press mud, and bio-neema together to make sweet sorghum (*Sorghum bicolor* L.) more nutrient-efficient and better for producing biofuels. We conducted a field experiment with 10 different optimized treatment combinations to assess their impact on the plants' growth, function, and chemistry. Treatment T6 (75 % RDF + zeolite + press mud + bio-neema) performed better than all other treatments compared to the control (T1). It increased plant biomass, extract yield (29,505.11 L ha⁻¹), and possible ethanol production. FTIR-ATR analysis confirmed changes in the extract's composition, demonstrating that it could convert more biochemically, including ethanol. However, EDX spectra and elemental mapping showed that T6 had a complex, nutrient-rich matrix, which meant that it could absorb nutrients well. Principal Component Analysis (PCA) showed that T6's shape was better at 30 and 60 days after planting. The findings show that adding nano-mineral-organic amendments not only reduces the demand for chemical fertilizers but also improves the structure of sorghum extract, making it more nutritious and easier to ferment. This optimization and structural strategy lay the groundwork for making sorghum a better dual-purpose crop for biofuel and food in places where resources are limited.

1. Introduction

The growing demand for renewable energy and nutrient-dense food has fueled interest in multipurpose crops that can address both energy and nutritional security, particularly in import-dependent areas [1,2]. Sweet sorghum (*Sorghum bicolor* L.), the sixth most significant cereal, is valued as a dual-purpose crop due to its capacity to thrive in dry, low-input environments and its high energy and nutritional content. Its stalks contain 12–20 % brix and 50–75 % fermentable sugars (sucrose, glucose, and fructose), making them excellent for bioethanol production, whilst grains contain 9–11 % protein, 70–72 % carbs, essential amino acids, B-complex vitamins, and minerals [3,4]. Despite attempts to enhance through biostimulants, irrigation, and fertilizer control, results remain uneven across agro-climatic conditions [5]. This emphasises the critical need for targeted research to improve sugar accumulation and biomass yield, thereby boosting renewable energy production and food security in resource-constrained areas. Previous

efforts to increasing sorghum yield included chemical fertilizers, irrigation changes, and biostimulants. However, long-term reliance on such approaches frequently results in environmental issues such as soil acidification, nutrient leaching, and greenhouse gas emissions, while failing to maintain microbial diversity or nutrient retention. Conventional treatments typically improve yield only temporarily and rarely improve extract quality or fermentation potential. In contrast, the current work is unique in that it combines nano-NPK, zeolite, press mud, and bio-neema into a single nutrient management system. This combination was intended to reduce chemical fertilizer use while also improving soil microbial and physicochemical health, as well as increasing sweet sorghum's nutritional and bioethanol potential an aspect that had not previously been investigated.

Nanotechnology and organic soil additions have made progress recently that may help overcome these problems. Nano NPK fertilizers help plants take in more nutrients, speed up enzyme activity, and make more chlorophyll. This makes photosynthesis happen more quickly, and

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<https://doi.org/10.1016/j.biombioe.2025.108343>

Received 15 July 2025; Received in revised form 21 August 2025; Accepted 1 September 2025

Available online 5 September 2025

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Strigolactones as Central Integrators of Plant Development and Multistress Resilience

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Received: 15 October 2025 / Accepted: 23 December 2025

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Abstract

Strigolactones (SLs) were initially identified as signals in root exudates that activate symbiotic fungi in the rhizosphere. However, they have since been recognized as a class of master regulators that control plant architecture, nutrient uptake, and plant responses to abiotic stresses. Plastid-derived canonical and non-canonical SLs are synthesized from carotenoid precursors and are modified in the endoplasmic reticulum. They are then recognized by the α/β -hydrolase receptor *D14*, which leads to the proteasomal degradation of ‘repressors’ *SMXL/D53s* via *SCF/MAX2*, ultimately reprogramming transcription. This core signaling module interacts dynamically with the abscisic acid, ethylene, auxin, and Karrikin pathways to regulate stomatal conductance, root system architecture, antioxidant defenses, and osmolyte accumulation. Under conditions of drought, high salinity, extreme temperatures, and heavy metal stress, SLs enhance stress tolerance by upregulating antioxidant enzymes (*SOD*, *CAT*, and *APX*), heat shock proteins (*HSP70/90*), cold-regulated genes, and metal-chelating mechanisms. Simultaneously, they facilitate resource allocation by suppressing shoot branching and promoting primary root growth. SLs are also key players in mutualistic symbioses with arbuscular mycorrhizal fungi (AMF) and likely *rhizobia*, linking the plant’s nutrient status to the recruitment of relevant microbial partners. Recent evidence also suggests a role for SLs in systemic signaling and in the regulation of circadian stress responses. Here, we compile this information to suggest that, beyond functioning as a developmental hormone, SLs are central components of a plant-wide resilience network. We propose that targeted manipulation of SL biosynthesis or signaling genes offers a promising approach to developing climate-resilient crops with improved nutrient use efficiency and reduced reliance on chemical inputs, both of which are crucial for ensuring sustainable food security in a changing environment.

Keywords Strigolactones · Salinity · Transporters · 9-cis- β -carotene · Biosynthetic genes

Abbreviations

4DO	4-deoxyorobanchol
ABA	Absciscic Acid
ABRE	ABSCISIC ACID RESPONSIVE ELEMENT
ABFs	ABA-responsive element binding factors

AMF	Arbuscular Mycorrhizal Fungi
ANAC019/055	Arabidopsis NAC domain-containing protein 19/55
ANS	Anthocyanidin Synthase
APX	Ascorbate Peroxidase
ARF7/19	Auxin Response Factor 7/19
ARRs	Arabidopsis Response Regulators
AREBs	ABA-Responsive Element Binding proteins
AtMYBS1	Arabidopsis thaliana MYB-like transcription factor S1
BICYC P7E41	a specific enzyme or gene name, not explicitly defined
CA-SLs	Canonical Strigolactones, from context
CAT	Catalase

Communicated by Birinchi Kumar Sarma.

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Molecular Nexus Between Salinity Stress and Plants Necessitates Re-Thinking of Sustainable Agronomic Practices and Resilience Strategies

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Received: 24 October 2025 / Accepted: 3 April 2026

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Abstract

Salinity is a significant global problem influencing soil quality, water availability and agricultural productivity. Emphasizing creative biotechnology interventions, ecologically friendly soil amendments and precision farming methods, this article thoroughly reviews the most recent advancements in salinity management. It examines and re-evaluates how plants tolerate salinity stress, including genetic modifications, root-structure adaptations, and microbial-assisted therapeutic methods. The prospect of rethinking the process might open new avenues for effectively reducing plant salinity stress. Ion transporters, osmoprotectants, and hormone regulation are sophisticated mechanisms that plants have evolved to identify and mitigate salinity stress. *HKTs* and *NHXs* control the Na^+ and Cl^- compartmentalization, thus avoiding cytotoxicity. Genes including *GA2ox*, *MYB*, and *WRKY* affect stress responses and development, enhancing salinity tolerance. While phytohormones such as Jasmonic acid (JA) and salicylic acid (SA) influence stress-induced adaptation responses, osmolytes, including proline and polyamines, play a crucial role in maintaining cellular homeostasis. Oxidative damage is partially prevented by antioxidant enzymes such as catalase (CAT) and superoxide dismutase (SOD). Precision farming techniques, microbial inoculants and genetic engineering offer promising opportunities to enhance crop resistance in saline environments, ensuring long-term agricultural productivity and sustainability. This article provides a comprehensive roadmap for addressing salinity issues by combining cutting-edge research, current advancements and integrative approaches.

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Systems-Level Decoding of Root-to-Shoot Microbiome Dynamics via Integrated Multi-Omics and Network Analysis

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Received: 6 November 2025 / Accepted: 18 June 2026

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Abstract

The rhizosphere–phyllosphere continuum constitutes a multifaceted biological interface that integrates root- and leaf-associated microbiomes into a single, functionally cohesive phytobiome capable of maintaining systemic homeostasis and stress resilience. This review delineates how distinct microbial taxa inhabiting plant tissues, along with the associated biochemical signaling networks, including volatile organic compounds (VOCs), phytohormones, extracellular vesicles (EVs), and small RNAs (sRNAs), collectively underpin the molecular and physiological interconnectivity that links the belowground and aerial compartments of the plant. Using a combination of bibliometric analysis and multi-omics integration, this work synthesizes global research trends, thematic advancements, and mechanistic insights into the crosstalk between the rhizosphere and phyllosphere. The integration of metagenomic, metabolomic, and transcriptomic datasets enables a comprehensive reconstruction of microbial interaction networks, revealing how these communities coordinate nutrient fluxes, regulate plant defense responses, and mediate adaptive strategies under diverse environmental conditions. Additionally, the use of synthetic microbial communities (SynComs) and computational network modeling supports these findings by experimentally confirming the regulatory interdependencies among microbial groups. These methods provide mechanistic evidence of how engineered microbial consortia can be optimized to enhance crop productivity, accelerate nutrient cycling, and improve plant resilience against both abiotic and biotic stressors. Overall, this synthesis presents a systems-level framework that links microbial ecology, molecular signaling, and network biology. It highlights the emerging approach of microbiome-informed crop engineering, where ecological and molecular insights converge to promote sustainable agriculture and the long-term stability of agroecosystems.

Communicated by Ajaya Kumar Trivedi

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Impact of Various Nutrient Management Technique on Growth, Yield and Quality Attributes of Sweet Sorghum (*Sorghum bicolor* L.)

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ABSTRACT

Background: These studies aim to determine the influences of various organic and inorganic nutrient sources on the growth, yield and quality attributes of sweet sorghum within the Indo-Gangetic region.

Methods: The experiment utilized a randomized block design with ten treatments replicated three times. These treatments included various nutrient management strategies: two different doses of inorganic fertilizers (100% and 75% of the recommended dose) applied with or without zeolite, press-mud and bio-neema, as well as three foliar applications of nano NPK.

Result: Among the nutrient management strategies, the application of 75% of the recommended dose of fertilizers (RDF) along with zeolite, press-mud and bio-neema showed a superior and significant improvement. This strategy enhanced growth attributes such as plant height by 23.73% and dry matter accumulation by 42.25%. It also improved yield attributes, including ear head length by 31.34%, grain yield by 53.25% and test weight by 30.67%. Furthermore, this treatment increased the Brix ratio by 37.67% and the juice extraction percentage by 39.04% compared to the control. This study underscores the crucial role of strategic nutrient management in sweet sorghum cultivation, demonstrating the most promising outcomes for enhancing growth, yield and quality.

Key words: Bio-neema, Brix ratio, Juice extraction, Press-mud, Sweet sorghum, Zeolite.

INTRODUCTION

Sweet sorghum, specifically the species (*Sorghum bicolor* L.) has considerable potential as a bioethanol feedstock due to its juice richness and high biomass yield. Globally, sweet sorghum stands as the fifth most widely cultivated cereal grain, after wheat, rice, maize and barley, as reported by Namooobe *et al.* (2014). This versatile crop can be readily cultivated in areas with arid, semi-arid and salt-tolerant climates. In challenging conditions, it efficiently converts sunlight into high concentrations of carbohydrates and sugars and is commonly used for ethanol production (Zhang and Vesselinov, 2014). This crop exhibits distinctive traits, notably its grain yield and versatility in stem utilization, encompassing applications such as sugar production, alcohol, syrup, jaggery, roofing materials, fencing and paper manufacturing. About 70-80% of the biomass in sweet sorghum comes from its stalk, which is also the main part of the plant where its juice is stored. Characteristics of sweet sorghum include its quickly growing nature, adaptability and resistance to non-living environmental stressors like flooding, high salt levels, or lack of water (Arumugam *et al.*, 2025). Nitrogen is vital for plant development; therefore, sweet sorghum is a superior crop that reacts positively to nitrogen fertilizers, demonstrating a high level of nitrogen use efficiency compared to other cereal crops. A sufficient nutrient supply is crucial for maintaining steady growth, foliage development, internode expansion, plant stature and the buildup of dense components, like total dissolved solids (measured by the Brix ratio), spike length and the quantity of grains per spike

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How to cite this article: Patel, M., Gill, R., Kumar, P., Singh, R. and Singh, U.K. (2025). Impact of Various Nutrient Management Technique on Growth, Yield and Quality Attributes of Sweet Sorghum (*Sorghum bicolor* L.). Agricultural Science Digest. 1-5.

Submitted: 18-02-2025 **Accepted:** 15-04-2025 **Online:**

(Ajeigbe *et al.*, 2018). The application of nano fertilizers can improve plant nutrient uptake and promote soil health and productivity for an extended period (Umesh *et al.* 2024). Therefore, they can navigate and travel more freely inside plants. They also contribute to minimizing nutrient waste, which benefits the soil, water, environment and tiny organisms in the soil. Research by Kopittke *et al.* (2019) discovered that applying nano fertilizers to leaves led to a rise in the nitrogen levels in the plants following the application (Roy *et al.*, 2019). The small particles, measuring 25-50 nanometers in width, enable the plants to retain essential nutrients and offer a greater surface area through which they can absorb these nutrients, according to Singh *et al.* (2025). Consequently, nano-NPK fertilizers can decrease nutrient loss as the nutrients are directly absorbed by the plant. In contrast, conventional phosphorus



FTIR-based Agronomic Validation for Impact of Zeolite, Press-Mud, Nano NPK and Bio-neema on Sweet Sorghum Stalk Juice Quality

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10.18805/ag.D-6367

ABSTRACT

Background: The application of these amendments significantly influenced the biochemical composition of the juice, as evidenced by FTIR spectral resolution corresponding to the mid-infrared region of 4000-400 cm⁻¹ with 4 cm⁻¹ from 32 scans per sample and representing essential organic compounds.

Methods: The field experiment was conducted during the *kharif* in 2023-24 at research farm Lovely Professional University, using a randomized block design with ten treatments and three replications. These treatments included several nutrient management practices such as: two different doses of inorganic fertilizers (75 and 100% recommended dose of fertilizers) and with or without zeolite, press-mud and bio-neema, as well as three foliar applications of nano NPK.

Result: The FTIR spectral Sample T6 results present a strong C=C stretching band at 1632.35 cm⁻¹, representing the conjugated alkenes commonly produced during unsaturated compounds' thermal degradation or photochemical rearrangements. A wide O-H stretching band at 3298.56 cm⁻¹ which is associated with the O-H stretching band at 3737.99 cm⁻¹ of the secondary OH group, is evidence of the existence of intermolecular bonded polymeric alcohols and possible hydrogen bonding in the thermally modified polysaccharides.

Key words: Ethanol, FTIR, No poverty, Organic compound, Quality, Sugar, Zero hunger.

INTRODUCTION

Sweet sorghum [*Sorghum bicolor* (L.) Moench], is known as "heart of the desert" and "camel crop". Sorghum, the 5th most significant cereal crop in the world, produces multiple products depending on its variety, such as grain sorghum, which is used for human food. Sorghum stalks are used to produce syrup, alcohol and bioethanol, which might be due to the high amount of sugar accumulation in the stem (Sasy and Abu-Elail, 2021).

Sorghum is the 3rd largest producer in the world, producing 5.27 million tonnes and shares 8% of the world production after the United States and Nigeria. Leading producing state in India, including Maharashtra (37%), Karnataka (22%), Tamil Nadu (10%), Rajasthan (8%) and Madhya Pradesh (7%) (According to International Production Assessment Division "IPDA", 2024). Sweet sorghum contains (Sucrose, fructose, glucose) in stalk and juice percentage share 50-75% of total biomass production and in seed 9-11% protein, 1.2-1.5% minerals, 1.6 fat and 70-72% carbohydrate (Rachman *et al.*, 2025). Sweet sorghum juice has emerged as a vital resource in recent decades, offering significant benefits for human health and environmental sustainability (Amaravel *et al.*, 2023). Juice is a nutritious beverage that provides a natural energy source, supports digestive health and boosts immunity due to its antioxidant properties. Its low glycemic index makes it a healthier alternative to refined sugars, appealing to health-conscious consumers (Olugbemi *et al.*, 2018). Sweet sorghum serves as a dual-purpose crop for food and bioethanol

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How to cite this article: Patel, M., Kumar, P., Devi, M.I., Dey, S.R. and Choudhury, D. (2026). FTIR-based Agronomic Validation for Impact of Zeolite, Press-Mud, Nano NPK and Bio-neema on Sweet Sorghum Stalk Juice Quality. *Agricultural Science Digest*. 1-8. doi: 10.18805/ag.D-6367.

Submitted: 10-05-2025 **Accepted:** 02-07-2026 **Online:** 25-08-2026

production, supporting renewable energy, reducing greenhouse gas emissions and enhancing food security (Patel *et al.*, 2025). Its juice is a sustainable and health-friendly option, with total sugar content ranging from 12-20% as measured by a Brix refractometer (Reddy *et al.*, 2023). Zeolite improves nutrient retention through high cation-exchange capacity, press-mud enriches soil structure and microbial activity and bio-neem acts as both bio-pesticide and bio-fertilizer to enhance nutrient use efficiency.