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ENHANCING QUALITY AND PRODUCTIVITY OF SESAME THROUGH FOLIAR APPLICATION OF MICRONUTRIENTS MIXTURE

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ABSTRACT

Sesame is often grown on marginal land in rainfed conditions as fallow crop with poor nutrient management leading to micronutrient deficiencies which reduces yield and quality. The study aimed to elucidate the impact of foliar application of micronutrients mixture (MM) with Zn: Fe: Cu: Mn: B: Mo (11.44:2.00:1.27:1.62:5.25:0.27% respectively), for enhancing the quality and productivity in Sesame during summer 2023, at college of agriculture, V. C. Farm, Mandya. The two concentrations (0.1% and 0.2%) were applied either at 25 or 45 days after sowing (DAS) along with Recommended Dose of Fertilizers (RDF) and Farm Yard Manure (FYM). Additional treatments included soil application of $ZnSO_4$ and Borax (5 and 1 kg ha^{-1}, respectively), RDF alone and absolute control. The field experiment comprises of 9 treatments replicated thrice under Randomized Complete Block Design. The two sprays of MM at 0.2% along with RDF+FYM showed significantly higher growth and yield attributes compared to control, including plant height, capsule number and seed yield (883.9 kg ha^{-1}) and quality parameters *viz.*, oil yield (425.4 kg ha^{-1}), crude protein (25.3%) with improved sugars, polyphenols, flavonoids content and enhanced micronutrient content in seeds. This study demonstrates that foliar micronutrient mixture (0.2% at 25 & 45 DAS) is a cost-effective agronomic biofortification strategy for sesame.

***Keywords* :** Sesame; micronutrient mixture; foliar spray; quality; productivity.

Introduction

Sesame (*Sesamum indicum*. L) is the world's one of the oldest oilseed crops, originated in India and belongs to the family Pedaliaceae. Out of 36 wild species of sesame, 19 are found in India and rest are confined to Africa. Most wild species of the genus Sesamum are native to Sub–Saharan Africa, but types including *Sesamum indicum* also formerly found in India. Sesame seed contains 44-58 % oil, 16-25 % protein, 5.8 % water, 3.2 % crude fibre, 18 % carbohydrate and 5.7 % ash, additionally to minerals like Ca, P, and vitamin E, as well as specific amino acids such as tryptophan and methionine (Dhaliwal *et al.*, 2021). It is known as the "Queen of oilseeds" because it contains high-quality polyunsaturated fatty acids such as 47 % oleic and 39 % linoleic acid and, is also known as the "Seeds of immortality". After all, it contains potent antioxidants such as sesamin, sesamol, sesamolin, tocopherols and lignans, which prevent rancidity (Hamideldin and Hussein, 2014).

Oilseed crops are the second-largest category of agricultural production globally, following food grains. Approximately 72% of the oilseed crop area is rainfed and managed by small and marginal farmers with limited fertilizer access, which contributes to low production. Additional challenges include low soil fertility, low-yielding varieties, unbalanced fertilizer use and issues with weeds, pests, and diseases. Micronutrient deficiencies in soils have intensified due to high-yielding varieties, high-analysis fertilizers, increased cropping intensity and insufficient use of organic manures (Shete *et al.,* 2020). Micronutrients, though required in small amounts, are crucial for plant growth and metabolism; their deficiency severely disrupts physiological and biochemical processes (Hanwate *et al.,* 2018). Micronutrient's mixture can enhance plant responses to water and nutrient uptake by providing essential nutrients at various growth stages (Jahan *et al.,* 2019).

Micronutrient deficiencies represent a significant global health challenge, affecting over 3 billion individuals worldwide. Biofortification has emerged as an effective and sustainable strategy to combat these deficiencies, particularly by increasing the micronutrient content of staple crops. In the case of sesame, biofortification aims to enhance its nutritional profile, particularly by essential micronutrients such as iron and zinc, through agronomic approaches. This intervention seeks to improve public health outcomes by providing a more accessible and cost-effective means of addressing nutrient deficiencies. Agronomic fortification of oilseeds, including sesame, offers a promising avenue for enhancing the bioavailability of these vital micronutrients, contributing to the overall fight against malnutrition (Kurt and Demirbas, 2021).

Soil applications of micronutrients can be less effective due to nutrient fixation and leaching. Foliar spraying offers several advantages, including reduced application rates and faster nutrient uptake (El-Fouly *et al.,* 2001). Sesame is often grown on marginal soils with inadequate nutrient management and as a fallow crop leading to nutrient deficiencies, particularly micronutrients. This results in reduced yield and oil content, leading to decreased cultivation. Micronutrient fertilization can address these deficiencies, promoting growth and enzyme function necessary for oil biosynthesis (Narayana *et al.,* 2020). Micronutrient's mixture provides a balanced application of various plant nutrients, tailored to crop needs at different growth stages and suited for site-specific nutrient management. Improving fertilizer use efficiency, often hampered by over-application, can be achieved by integrating multiple nutrients into a single application. Despite evidence of individual micronutrient effects, limited studies exist on the combined foliar application of Zn, Fe, Cu, Mn, B, and Mo in sesame under Indian conditions. Hence, this study aimed to enhances nutrient efficiency and reduces negative effects. Promoting balanced fertilization through appropriate micronutrient mixtures is crucial for improving nutrient use efficiency and increasing crop productivity, which is vital for food and nutritional security.

Material and Methods

The experiment was conducted at College of Agriculture, V.C. Farm, Mandya, UAS Bangalore, during Feb to May 2023, which comes under the Region III and Agro-Climatic Zone VI (Southern Dry Zone) of Karnataka, India, which has 12°34 '03" North latitude and 76°49'08" East longitude with an altitude of 697 metres above mean sea level. It has a subtropical climate with the mean minimum, mean maximum, and average air temperatures of 20, 35 and 27.5°C, respectively. The soil characteristics of agriculture research station is sandy-loam in texture with pH 7.4 and EC 0.14 dSm^{-1}.

Experiment was laid out in a Randomized Complete Block Design (RCBD) with nine treatments were replicated thrice. Sesame variety GKVK - S1 was used. Land was prepared by ploughing and harrowing two times and sown the seeds at the rate of 4 kg ha^{-1} with the spacing of 30*10 cm. Totally 5 irrigations were provided during the crop period. Thinning and gap filling was done at 15 days after sowing (DAS).

Treatment details

Sl. No	Treatments
T_1	Absolute Control
T_2	Control (RDF + FYM @ 5 t ha^{-1})
T_3	T_2 + $ZnSO_4$ @ 5 kg ha^{-1} + Borax @ 1 kg ha^{-1}
T_4	T_2 + Foliar application of Micronutrients mixture 0.1 % at 25 DAS
T_5	T_2+ Foliar application of Micronutrients mixture 0.1 % at 45 DAS
T_6	T_2 + Foliar application of Micronutrients mixture 0.2 % at 25 DAS
T_7	T_2 + Foliar application of Micronutrients mixture 0.2 % at 45 DAS
T_8	T_2 + Foliar application of Micronutrients mixture 0.1 % at 25 and 45 DAS
T_9	T_2 + Foliar application of Micronutrients mixture 0.2 % at 25 and 45 DAS

Note: Micronutrients mixture (Fe: 2 %, Zn: 11.44 %, Cu: 1.27 %, Mn: 1.62 %, B: 5.25 %, Mo: 0.27 %); RDF: 37: 25: 25 kg N, P_2O_5, K_2O ha^{-1}.

The micronutrients mixture was prepared in the laboratory containing zinc, iron, copper, manganese, boron and molybdenum salts with the required ratio proportion suitable for crop. The foliar application of micronutrients mixture was carried out with the amount of 200 litres per acre either as single spray or two sprays as per the treatment requirement at the rate of either 0.1 % or 0.2 %.

Five plants from each net plot were selected at random and tagged for the purpose of recording various observations. The harvest index (HI) was calculated by using the formula (Donald, 1962),

$$\text{Harvest index} = \frac{\text{Economic yield}}{\text{Biological yield}} \times 100 \qquad (1)$$

The oil percentage in seed was determined by Soxhlet apparatus by using the formula,

$$\text{Oil content (\%)} = \frac{\text{Weight of oil extracted in grams}}{W_S \text{ weight of seed in grams}} \times 100 \quad (2)$$

Oil yield per hectare was worked out by multiplying oil content and seed yield per hectare. The crude protein content (%), Ash content (%), Iodine value Saponification value was calculated using the formula given by AOAC, 1990. Estimation of total phenols in leaf samples of sesame seeds was done by following Folin-Ciocalteau method suggested by Bray and Thorpe (1954). The total sugars in sesame seeds were estimated following the method suggested by using Somogyi (1952). The flavonoids content in sesame seed was estimated by aluminium chloride colorimetric assay, as described by Zhishen *et al.* (1999). The Benefit cost ratio was calculated by using the formula,

$$B:C = \frac{\text{Gross returns (Rs. ha}^{-1})}{\text{Total cost of cultivation (Rs. ha}^{-1})} \qquad (3)$$

Statistical analysis

The recorded experimental data were subjected to factorial design of analysis of variance (ANOVA) for RCBD as described by Gomez and Gomez (1984). The level of significance used in “F” was P = 0.05. Critical difference (CD) values were calculated for the P = 0.05, whenever the “F” test was found significant.

Results and Discussion

Effect on growth parameters of sesame

The growth parameters *viz.,* plant height (cm) and number of branches and leaves per plant at harvest and chlorophyll content *i.e.,* SPAD (Soil Plant Analysis Development) at 55 DAS exerted significant differences with foliar application (FA) at varied concentration (0.1 and 0.2 %) of micronutrients mixture (MM) and time *i.e.,* 25 and 45 days after sowing (DAS) on sesame.

The single spray of MM at 0.2% either at 25 or 45 DAS was more effective as compared to single spray of MM at the rate of 0.1%. However, two sprays of MM at 25 and 45 DAS either at the rate of 0.1% or 0.2% enhanced the growth parameters of sesame compared to single spray. The growth parameters *viz.,* plant height (114.5 cm), number of leaves (71 per plant), number of capsules (80) at harvest and chlorophyll content (SPAD) at 55 DAS (44.9) were recorded significantly higher with 0.2% at 25 and 45 DAS along with FYM and RDF as compare to absolute control, but statistically on par with FA of MM 0.1 % at 25 and 45 DAS with RDF.

The enhanced growth parameters might be attributed to steady supply of nutrients to the crops. The lower growth parameters were recorded in the control due to losses and fixation of applied nutrients in soil and is a proof that the native supply of nutrients is not just sufficient to support crop growth. Hence, there is a need to supplement nutrients through external sources like foliar application. Supplementary application of micronutrients at important phenological stages of sesame *viz.,* maximum vegetative growth stage from 20 to 40 DAS and reproductively active stage from 40 to 60 DAS, will boost the growth and development.

The increased plant height, number of leaves and number of branches per plant might be due to activation of plant enzymes which are involved in carbohydrate metabolism and growth hormone synthesis, auxin production leading to cell enlargement, increase in cell division, internode elongation and the vigorous root growth of the crop with the supply of Zn (Jahan *et al.,* 2019). Similarly increased metabolic and enzymatic activities with the supply of Fe (Kuldeep *et al.,* 2018), Mn is essential to photosynthesis reactions, enzyme activation and root growth (Mortvedt *et al*., 1999 and Kherawat *et al.,* 2013), enhanced carbohydrate translocation with the supply of Cu (Manivasagaperumal *et al.,* 2011), increased translocation of sugars with the supply of boron (Kulkarni *et al.,* 2002) and greater nitrogenase activity with the supply of Mo (Adesoji *et al.,* 2009). The increase in chlorophyll content may be due to the positive role zinc and iron in chlorophyll synthesis and imparts dark green colour to the plants. Mn, a vital micronutrient in the plant cells, involved in photochemical electron transfer reactions of plants and plays a pivotal role in chlorophyll synthesis (Yruela, 2013). The light harvesting antenna of photosystem II increased chlorophyll content. It is also possible that Cu-induced enzyme might mediate photoreduction of O_2 by PS-I (Syuhada *et al.,* 2014) are the possible reasons for the observed improvement in growth parameters of sesame. The similar results are in line with the findings of Yadav *et al.* (2009) in sesamum, Shanwad *et al.* (2015) in sunflower, Dwivedi *et al.* (2020), Lotha and Dawson (2021), Khuong *et al.* (2022), Kumar et al. (2023).

Effect on yield and yield attributes of sesame

The yield attributes such as number of capsules per plant, number of seeds per capsule, test weight, seed yield per plant, seed yield, haulm yield and harvest index are contributing towards enhancing the yield of sesame. In the present study, varied micronutrients concentrations of foliar nutrition during different intervals have significantly influenced the yield and yield attributes of sesame as compared to without micronutrient foliar application.

The FA of 0.2% MM at 25 and 45 DAS with RDF has recorded significantly higher number of capsules per plant (78.9), number of seeds per capsule (63.8), test weight (3.16 g), seed yield per plant (13.9 g) and seed yield (883.9 kg ha^{-1}), haulm yield (2263.4 kg ha^{-1}) and harvest index (28.1 %) as compared to absolute control (38.6, 46.1, 2.33 g, 8.7 g, 550.3 kg ha^{-1}, 1544.8 kg ha^{-1} and 26.3 % respectively).

An increase in the seed yield of sesame is a manifestation of the growing condition and complementary effect of improved nutrient management leading to enhanced uptake and better translocation in different plants parts, that stimulated better root, haulm and capsule growth with external application of micronutrients, as noticed in present investigation, that might have resulted in higher seed yield. The increase in seed yield due to zinc application that takes part in the metabolism of plant as an activator of several enzymes involved in the formation of glucosinolates, glucosides, sulfhydryl linkage, activation of enzymes and helps in seed formation and development (Taha et al., 2013). The influence of iron fertilization on yield attributes and yield might be due to its role in chlorophyll synthesis, enzyme activity and other metabolic processes.

Boron plays an imperative role in pollen germination, pollen growth and better retention of capsules (Mengel *et al.,* 2001) and helps in fertility improvement and translocation of photosynthates, enhances flower production and retention, pollen tube elongation, and germination, that reduces the pre mature flower dropping and enhance the capsule development in sesame (Khuong *et al.,* 2022). The translocation of photosynthates from vegetative sources towards the reproductive organs which helped the crop to put forth higher test weight. Copper promotes seed production and formation, plays an essential role in chlorophyll formation and Cu is essential for proper enzyme activity and the efficient utilization of applied nutrients resulted in an increase in the yield components. Mn was found to increase stem height and nodes for capsule development in sesame (Jeyabal *et al.,* 1997). The utilization of these essential nutrients by the plants seems to have provided a congenial nutrition for better growth of plants. The numerically higher harvest index is due to increased physiological capacity for mobilization and translocation of photosynthates to organs of economic value and improved seed setting as well as seed filling due to boron application (Maghsud *et al.,* 2014). Foliar application enhances yield of sesame by additional nutrient supply as per crop requirement enhances the yield to an extent of 20 to 25% compared to control. These observations are in conformity with the findings of Hugar and Kurdikeri (2000), Narayana *et al.* (2020), Elayaraja and Jawahar (2021), Kumar *et al.* (2023).

Effect on Quality parameters of sesame

Oil content

The oil content (%) in sesame seeds were recorded higher with the foliar spray of micronutrients. The oil content ranged from 40.03% in the absolute control (T_1) to 48.10% in the treatment with MM at 0.2 % applied at 25 and 45 DAS with RDF (T_9). The treatments where micronutrients were applied either through soil (T_3) or through foliar spray *viz*., T_4, T_5, T_6, T_7, T_8 and T_9, at the rate of 0.1 % or 0.2 % by one or two spray at 25 and 45 DAS combined with RDF + FYM, showed increased oil content compared to the control (T_1).

The observed increase in oil content can be attributed to the role of micronutrients like zinc and iron in enhancing the enzymatic activity that is crucial for the biosynthesis of oil. Zinc and iron are essential for the proper functioning of enzymes involved in the formation of glucosinolates, glucosides, and sulfhydryl linkages, which are key precursors in oil synthesis (Narayana *et al.,* 2020). The supplementation of these micronutrients during critical growth stages such as the vegetative, flowering, and seed-setting phases enhances the enzymatic activities necessary for oil biosynthesis. Moreover, micronutrient application improves photosynthesis and the translocation of assimilates to the seeds, which further supports the increased oil content (Heidarian *et al.,* 2011). Similar findings were reported by Choudhary *et al.* (2017), Bhagwat *et al.* (2018), Gowthami *et al.* (2018), Kumara *et al.* (2019), and Jahan *et al.* (2019), highlighting the positive impact of micronutrients on oil content in sesame seeds.

Oil yield

The oil yield of sesame differed significantly due to the foliar application of micronutrients mixture on sesame. The highest oil yield of 425.4 kg ha^{-1} was recorded in the treatment with 0.2 % FA of MM at 25 and 45 DAS along with RDF + FYM (T_9), which was significantly higher than all other treatments. Further, treatments are statistically on par, which received RDF+FYM as common along with 0.1 % FA of MM at 25 and 45 DAS (T_8: 404.6 kg ha^{-1}) and T_7 (391.6 kg ha^{-1}) and T_6 (385.2 kg ha^{-1}), which received 0.2 % FA of MM at 25 and 45 DAS respectively.

The increased oil yield can be attributed to the improved growth and yield attributes resulting from the supplementary application of micronutrients along with major nutrients. The micronutrients facilitated enhanced photosynthesis, increased enzymatic activity, and improved the translocation of assimilates to the seeds, all of which contributed to higher seed yield and oil content (Heidarian *et al.,* 2011). These results are consistent with previous studies, including those by Lalitha *et al.* (2008), Shaker and Saad (2012), Abdollah (2015), Habimana *et al.* (2016), Gowthami and Anand (2017) and Rachanya *et al.* (2023), who reported that micronutrient application significantly enhances oil yield in oilseed crops, including sesame.

Crude protein

The application of micronutrients significantly influenced the crude protein content of sesame seeds. Among the various treatments, it was observed that treatment T_9, which received 0.2% FA of MM at 25 and 45 (DAS), exhibited the superior protein content (25.3 %). Furthermore, it is on par with T_8, (23.9 %,). In contrast, the absolute control exhibited a lower protein content (18.2 %). This finding underscores the substantial influence of micronutrients application, particularly treatment T_9, in enhancing the protein content of sesame seeds.

Zinc has emerged as an indispensable nutrient for plant growth, which is closely involved in the metabolism of RNA and ribosomal content in plant cells which lead to stimulation of carbohydrates, proteins and the DNA formation and also an essential factor in tryptophan metabolism and consequently affect the auxin content of the plant. Zn activates several enzymes such as breakage of the peptide union in carboxypeptidase, structural role by coordinating the positions of the regulator and catalytic subunits in aspartate trans-carbamylate. Hence, it has a considerable effect on protein synthesis and has a role in catalytic, co-catalytic and structural functions in protein regulation. It plays an important role in nucleic acid and protein synthesis and helps in utilization of phosphorous and nitrogen as well as seed formation and development (Taha *et al.,* 2013).

Manganese activates decarboxylase and dehydrogenase enzymes and is a constituent of complex PS II-protein, superoxide dismutase enzyme (SOD) and phosphatase. (Ibrahim *et al.,* 2016). Further, enhanced phosphorus utilization plays an important role in producing energy for the physiological processes such as synthesis of proteins by formation the ATP. Also, Boron influence on fundamental metabolic reactions like sugar transport, respiration, carbohydrate, RNA, IAA and phenol metabolism or a cascade effect which is known for photo hormones, eventually results in the acceleration of protein synthesis (Parr and Loughman, 1983) and improves nitrate reductase and nitrogenase activities of plants and improves concentrations of seed proteins and oleic acid (Bellaloui *et al.,* 2010).

The synergistic effect of these micronutrients, along with major elements like nitrogen and phosphorus, on biochemical reactions in sesame plants results in improved protein synthesis and higher protein content in the seeds (Soliman *et al.,* 2012). Similar, results were reported by Kader and Mona (2013), Reshma and Nazirkar (2013) and Choudhary *et al.* (2017). also observed increases in protein content in other crops following micronutrient application.

Ash content

The ash content in seeds of control plot was 4.07 %, which was significantly lower than that recorded in treatments received foliar nutrition of micronutrients (T_4 to T_9).

The maximum ash content in seed was recorded in T_9 treatment (6.82 %), which was found on par with other treatments which received micronutrients spray at the rate of 0.1 or 0.2 % either at 25 or 45 DAS. The foliar application of micronutrients on sesame has increased the nutrient concentration in plants has resulted in higher ash content. Similar results are in agreement with the findings of Malewar *et al.* (1993) in groundnut and Naz *et al.* (2022) in pea.

Total sugars

Total sugars in sesame seeds varied significantly with the application of micronutrients mixture. The lower total sugars were noticed in absolute control

(7.80 mg g^{-1} dry weight) and increased superiorly with the application of 0.2 % FA of MM at 25 and 45 DAS (11.10 mg g^{-1} dry weight), followed by T_8, which received 0.1% MM at 25 and 45 DAS, showed an intermediate increase, with total sugars recorded at 10.30 mg g^{-1} dry weight).

The enhanced synthesis of total sugars with the application of micronutrients increased the translocation of sugars with the supply of boron (Devi *et al.,* 2012). Boron promotes production and transport of carbohydrates, necessary for starch accumulation in anther, which may also have contributed to the pollen maturation and carbohydrate (sugars and starch) accumulation in seeds (Ashour and Reda, 1972). Zinc helps in synthesis of carbonic anhydrase, fructose 1-6 biphosphatase, and aldolase enzymes which involved in synthesis and metabolism of carbohydrates, thus improving the soluble carbohydrate contents (Dehnavi *et al.,* 2008), which is in line with the findings of Chatterjee and Khurana (2007), Sohail *et al.* (2020) and Shad *et al.* (2023).

Polyphenols

The polyphenol content in sesame seeds showed significant variation with the application of micronutrient mixture combined with the FYM+RDF. The highest polyphenol content (9.57 mg g^{-1} dry weight) in sesame seeds was recorded in treatment T_9, which received 0.2 % FA of MM at 25 and 45 DAS along with RDF. Treatments T_8, T_7 and T_6 showed similar results, with polyphenol content 8.93, 8.73 and 8.70 mg g^{-1} dry weight, respectively. The lowest polyphenol content was recorded in absolute control (T_1: 7.69 mg g^{-1} dry weight).

Polyphenols are secondary metabolite in plants which act as antioxidant agent and protect biological systems against free radicals. The biosynthesis of soluble phenolics begins with the aromatic amino acid phenylalanine, a product of the shikimate pathway (Castellarin *et al.,* 2012). Boron and copper acts as a cofactor of enzymes and play a significant role in phenol metabolism and also involvement of iron in phenolic acid biosynthesis pathway which increase the phenol content in sesame. The basal supply of urea enhanced the urease enzyme activity which favoured the synthesis of amino acids including phenylalanine, a precursor of phenolic compounds (Zolfaghari *et al.,* 2019).

Phenolic compounds, which are widely distributed in plants and plant products have been indicated to possess antioxidant activity due to their ability to donate a hydrogen atom or an electron so as to form stable radical. The high amounts of phenolic compounds in sesame seed suggest that they could be responsible for the antioxidant potential of this plant. The results of this study align with previous findings by Sohail *et al.* (2020), Naz *et al.* (2022) and Shad *et al.* (2023), that report a significant increase in phenolic content with micronutrient application.

Flavonoids

The application of micronutrient has significantly enhanced the flavonoid content in sesame seeds. The treatment received FA of MM at 0.2 % at 25 and 45 DAS along with RDF and FYM (T_9) has recorded highest flavonoid content (0.497 mg g^{-1} dry weight). However, the treatments from T_8 to T_4 are on par with T_9, which received FA of different concentration (0.1 or 0.2 %) of MM sprayed at once or twice. The lower flavonoid content was found in absolute control (T_1) followed by control (T_2) (0.384 and 0.419 mg g^{-1} dry weight, respectively).

Flavonoids are a diverse group of over 9,000 polyphenolic compounds synthesized by plants through the phenylpropanoid pathway. These compounds include chalcones, flavones, flavanols, flavanones, anthocyanins, and iso-flavonoids and are renowned for their potent antioxidant properties. The increased flavonoids and phenolics in sesame plants neutralize ROS (Reactive oxygen species) effects and form complexes with metals by chelation to reduce phytotoxic effects (Dravie *et al.,* 2020). Micronutrients, phosphorus, potassium and secondary metabolites (polyphenols and flavonoids), these might have promoted the growth and the biosynthesis of oil components and the unsaturated activities, that stimulate the synthesis of polyunsaturated fatty acids, which improves the oil quality (Shad *et al.,* 2023). Zn promotes the biosynthesis of compounds with antioxidant activity like flavonoids and phenols (Geremew *et al.,* 2023). The antioxidants detoxify (ROS), which means metal ions are required as cofactors for antioxidant enzymes, including different forms of SOD, which requiring Cu, Mn and Zn and catalase requires Fe (Zhu *et al.,* 2013). Mn activates several enzymes of the shikimic acid pathway, and subsequent pathways, leading to the biosynthesis of various secondary products such as lignin and flavonoids. Hence, the application of micronutrients enhanced the flavonoids biosynthesis in sesame will helps to improve the quality of sesame. The similar findings are reported by Sohail *et al.* (2020).

Saponification value

Saponification value is a measure of the alkali reactive groups in fats and oils and is useful in predicting the type of glycerides in a sample. The glycerides containing short chain fatty acids have higher saponification value. The higher saponification value indicates the short alkyl chain in the fatty acids of triglycerides. The lower saponification value also implies that average molecular weight of the fatty acids constituting the fats in the seed oils were greater than that for conventional oils. According to codex standard for named vegetable oils the reported saponification value was 186 to 199 mg g^{-1} KOH of oil in sesame.

The saponification value of sesame oil has not influenced significantly with micronutrients application at varied rate during different crop growth stages (vegetative and flowering and pod initiation stage) at 25 and 45 days after sowing. The saponification number of sesame oil is decreased satisfactorily by 5.55 % with the application of micronutrient mixture @ 0.2 % at 25 and 45 DAS (T_9: 187.01 mg g^{-1}) when compare to no application of nutrient sources (T_1: 197.40 mg g^{-1}) and control (T_2: 196.14 mg g^{-1}), which are non-significant among the different treatments. The slight reduction in saponification value in the treatment with micronutrient application suggests that the fatty acid profile of the sesame oil may have been slightly altered, possibly indicating the presence of longer alkyl chains in the triglycerides.

Iodine value

Iodine value is the number of grams of iodine required to saturate 100 g oil. Iodine value indicates the presence of unsaturated fatty acid of oils but does not define the specific fatty acids. Iodine value analysis provides near theoretical values, except in the case of conjugated double bonds or when the double bond is near a carboxyl group. In codex standard for iodine value for vegetable oils is 104 to 120 g per 100 g.

The sesame oil iodine value did not differ significantly due to the application micronutrients on sesame. However, the numerically higher iodine value of sesame oil was recorded in T_9 (111.68 g per 100g), which was decreased by 6.27 % in control (T_2: 104.67 g per 100g). The lower iodine value is found in absolute control (103.25 g per 100g). The sesame oil had a clear yellow colour, without any haziness. The high iodine value obtained in the control treatment, suggests the presence of unsaturated fatty acids. This value indicates the degree of unsaturation in the fatty acids of triacylglycerol and can be used to quantify the amount of double bonds present in the oil. These double bonds signify the oil's susceptibility to oxidation, which in turn influences the peroxide value of the oil. The peroxide value is an indication of the oil's ability to become rancid due to oxygen absorption during storage or processing. This observation suggests an increase in the stability and shelf life of oils, reducing the risk of the rancidity process. Furthermore, since this oil has a high iodine number, it implies that the majority of fatty acids are unsaturated, making consumption of unsaturated fatty acids (USFA) a healthier lifestyle choice.

Even though, the saponification value and iodine number are non-significant among the treatments, the reduction in the saponification value of sesame oil can be attributed to several factors. The presence of sulphur within sulphate salts of micronutrients plays a pivotal role in the synthesis of fatty acids. There is a higher proportion of unsaturated fatty acids relative to saturated ones in the oil. Additionally, this composition contributes to a reduction in oil rancidity and an increase in the concentration of long-chain fatty acids within the oil. A study conducted by Ravi *et al.,* 2008, supports the idea that sulphur fertilization enhances oil quality by exerting a suppressive effect on the saponification value, acid value, and increase in iodine number. Similar findings were also documented by Krishnamurthi and Mathan in 1996 in the context of sunflower oil. The decline in lipid concentration within chloroplasts can be ascribed to Mn involvement in the biosynthesis of fatty acids, carotenoids, and related compounds, ultimately resulting in a reduction in the saponification value of the oil.

The alterations in lipid composition that favour an increase in unsaturated fatty acids are induced by the presence of copper (Cu). This phenomenon is associated with modifications in the polypeptides of Photosystem II (PS II). These changes extend to the fatty acid composition within the thylakoid membranes and the PS-II complex. It is plausible that the functions of copper in the desaturation of long-chain fatty acids contribute to the production of shorter-chain fatty acids. Zn deficiency, as observed by Welch *et al.,* 1982, is characterized by the leakage of low-molecular-weight solutes, a reduction in phospholipid concentration and a decrease in the degree of unsaturation of fatty acids within membrane lipids. Potassium (K) exerts its influence on biochemical pathways in plants, ultimately leading to an increase in the unsaponifiable matter, which has a beneficial impact on the stability of oil. Application of zinc and phosphorus to cotton plants has been demonstrated to elevate the acid value, saponification value, and iodine values (Sawan *et al.,* 2006).

Effect of foliar application of micronutrients mixture for nutrients content in sesame

Sesame is one of the rich food sources in terms of minerals such as Fe, Zn, and Mg. The foliar application of micronutrients mixture at twice (25 and 45 DAS) either at 0.1 or 0.2 % has significantly enhanced the micronutrients *viz.,* Zn (57.26 mg kg^{-1}) Fe (149.80 mg kg^{-1}), Mn (39.92 mg kg^{-1}) Cu (43.20 mg kg^{-1}) and B (39.2 mg kg^{-1}) content in sesame. The micronutrient content was decreased as the concentration and interval was reduced.

The supplementary application of nutrients enhanced the growth and development increased the micronutrients content in sesame. Zinc has synergistic effect with nitrogen; hence the Zn uptake is promoted in plants. Zinc is cofactor of more than 300 enzymes and involved in carbohydrate metabolism, photosynthesis, conversion of sugars to starch, protein metabolism, auxin metabolism, pollen formation, integrity of biological membranes and resistance to infection by certain pathogens (Adônis *et al.,* 2018). The combined application of FYM which chelated as phytosiderophore-Fe complexes in soil and made easier availability to root surfaces and absorption by root cells enhance the Fe transport and also due to absorption of iron from foliar application of micronutrient mixture which contained Fe (Havlin *et al.,* 2016). Zn localized in protein bodies as globoid crystals (phytate) which acts as a sink for Zn and Fe in seeds. Fe acts as a cofactor for approximately 140 enzymes that catalyse unique biochemical reactions and 90% of Fe in leaves occurs with lipoprotein in chloroplast and mitochondria membranes and Fe store in a seed as ferritin compound and also phytate has a high binding affinity to Fe, which increase the Fe accumulation in seeds (Broadley *et al.,* 2012).

Manganese acts as co-factor, activating about 35 different enzymes involved in catalyse, oxidation-reduction, decarboxylation and hydrolytic reactions. Mn is essential to electron transfer through chlorophyll and acts as an activator of Mn-SOD, manganese is involved in membrane protection against oxidative damage through the detoxification of reactive oxygen species and activates RNA polymerase helps to protein synthesis. Mn binds firmly to lamellae of chloroplast, possibly to the outer surface of thylakoid membranes, affecting the chloroplast structure and photosynthesis, thus Mn accumulation was increased (Marschner, 2011). Copper is important metal constituent of hundred different forms of protein bound to plastocyanin in chloroplast to perform photosynthetic reactions. The Cu co-factor in super oxide dismutase (SOD), Ascorbate oxidase, Diamine oxidases, Polyphenol oxidases, Cytochrome-c-oxidase and involved in electron transfer, peroxidases, which oxidize monophenols to diphenols and multi-Cu proteins, which act as oxidases. Moreover, Cu has a high affinity for peptide and sulfhydryl groups, cysteine-rich proteins, as well as also for carboxylic and phenolic groups. The Cu-containing proteins bound to plastocyanin and Cu atom is involved in the mechanism of detoxification of reactive oxygen species (CuZnSOD) generated during abiotic and biotic stress (Broadley *et al.,* 2012). The higher content of Fe, Mn and Zn elevated the Cu concentration by forming complex with enzymes. Hence, this which triggers the Cu concertation in sesame plant parts. Similar results are also found by Guruprasad *et al.* (2009) in groundnut, Rajath *et al.,* 2019 in sunflower and Kumara *et al.,* 2019 in safflower.

Boron involved in sugar transport, cell wall synthesis, lignification, cell wall structure, carbohydrate metabolism, RNA metabolism, respiration, indole acetic acid (IAA) metabolism, phenol metabolism. B is complexed as cis-diol esters in the cell walls associated with cell wall pectin. B required for cross linking to pectin rhamnogalacturonan-II is highly active in pollen tubes and helps in reproductive tissue development and fertilization. B provides cross-links between cell wall polysaccharides that gives a flexible structure to the cell wall (Broadley *et al.,* 2012). Hence, the supplementary application increases the B content. The above findings are in agreement with the findings of Kader and Mona (2013), Rajath *et al.* (2019) and Kumara *et al.* (2019).

Effect of foliar application of micronutrients mixture on economics of sesame cultivation

The economic analysis conducted for the sesame cultivation revealed distinct variations in the cost of cultivation and subsequent returns based on the treatments applied. Economic analysis was conducted by taking into account the costs associated with agronomic practices, fertilizers, and plant protection chemicals that were applicable during the crop cultivation period. The cost incurred and profit derived are calculated. The economic analysis conducted for the sesame cultivation revealed distinct variations in the cost of cultivation and subsequent returns based on the treatments applied. The total cost of cultivation for the control treatment (T_1), which did not receive any fertilizers or micronutrient applications, was Rs. 26,934. With the addition of RDF and FYM (T_2), the cost increased to Rs. 36,951, reflecting an average additional expenditure of Rs. 10,000.

When micronutrient mixtures (MM) were applied as foliar sprays, the cost of cultivation further increased. The cost for a single spray (either at 25 or 45 DAS) of MM at 0.1% was Rs. 37,928, and for 0.2%, it was Rs. 38,514. The highest cost was observed in treatments where two sprays of MM were applied, amounting to Rs. 39,101 for 0.1% and Rs. 39,452 for 0.2%. Despite the increase in cost, the treatments with foliar application of MM resulted in significantly higher gross returns and net returns. The highest gross return of Rs. 1,06,069 and net return of Rs. 66,617 was recorded for the treatment (T_9) that received 0.2% FA of MM at 25 and 45 DAS, along with RDF and FYM. This treatment also recorded the highest benefit-cost (B:C) ratio of 2.69. The second-highest returns were observed in T_8, which received two sprays of 0.1% MM, with gross returns of Rs. 1,03,189 and net returns of Rs. 64,088, and a B:C ratio of 2.64. In contrast, the control treatment (T_1) resulted in the lowest gross returns (Rs. 66,031) and net returns (Rs. 39,097), with a B:C ratio of 2.34. The treatment that received RDF and FYM without any micronutrient application (T_2) also had a relatively low B:C ratio (2.34).

The higher B:C ratios observed with treatments receiving micronutrients can be attributed to the enhanced nutrient management throughout the crop period. The supplementary application of micronutrients improved growth and yield characteristics, thereby increasing the overall yield and net returns. Despite the higher cost of cultivation associated with micronutrient application, the increased returns clearly justify the investment, demonstrating the economic viability of micronutrient supplementation. This result is consistent with the findings of Lotha and Dawson (2021), Ram *et al.* (2021), and Idhole *et al.* (2022), who also reported significant improvements in the profitability of crops with the application of micronutrients, leading to higher yields and enhanced economic returns.

Conclusion

The supplementation of micronutrients for enhanced crop growth and development and also improvement in micronutrients concentration can be impacted by the interplay between micronutrients and macronutrients. The utilization of a micronutrients blend facilitates the administration of a diverse array of essential plant nutrients in precise proportions, customized to meet the distinct requirements of a crop during various growth stages. Interactions of micronutrients with macronutrients can influence the effectiveness of quality improvement in crops. This results in increased micronutrient concentrations in the edible parts of the crop. Thus also helps in biofortification of the essential oil seeds which improves the dietary nutrition also. The micronutrients mixture provides the wide range of plant nutrients (Zn, Fe, Mn, Cu, B) in the proportion and to suit the specific requirements of a crop in different stages of growth. Foliar spray of MM at 0.2% twice at 25 and 45 DAS increased yield by 23% over RDF+FYM with enhanced quality and recorded highest B:C ratio (2.69).

Table 1: Effect of foliar application of micronutrients mixture on growth parameters of sesame

Treatment	Plant height (cm)	No. of Branches plant^{-1}	No. of Leaves plant^{-1}	Chlorophyll content (SPAD)
T_1: Absolute Control	85.9	3.1	32	30.8
T_2: Control (RDF + FYM @ 5 t ha^{-1})	93.9	4.0	40	34.6
T_3: T_2 + $ZnSO_4$ @ 5 kg ha^{-1} + Borax @ 1 kg ha^{-1}	99.8	4.2	45	35.2
T_4: T_2 + Foliar application of Micronutrients Mixture 0.1 % at 25 Days After Sowing	101.2	4.6	54	36.4
T_5: T_2+ Foliar application of Micronutrients Mixture 0.1 % at 45 DAS	103.8	4.6	56	37.8
T_6: T_2 + Foliar application of Micronutrients Mixture 0.2 % at 25 DAS	104.2	4.9	59	38.4
T_7: T_2 + Foliar application of Micronutrients Mixture 0.2 % at 45 DAS	107.3	5.1	60	39.1
T_8: T_2 + Foliar application of Micronutrients Mixture 0.1 % at 25 and 45 DAS	112.3	5.6	63	41.7
T_9: T_2 + Foliar application of Micronutrients Mixture 0.2 % at 25 and 45 DAS	120.9	6.2	71	44.9
S.Em±	**4.31**	**0.20**	**2.2**	**1.19**
CD @ 5%	**12.91**	**0.59**	**6.62**	**3.57**

Table 2: Effect of foliar application of micronutrients mixture on yield parameters and yield of sesame

Treatment	No. of Capsules plant^{-1}	No. of Seeds capsule^{-1}	Test weight (g)	Seed yield plant^{-1} (g)	Seed yield (kg ha^{-1})	Haulm yield (kg ha^{-1})	Harvest index (HI) (%)
T_1: Absolute Control	38.6	46.1	2.33	8.7	550.3	1544.8	26.3
T_2: Control (RDF + FYM @ 5 t ha^{-1})	53.6	54.4	2.68	9.9	720.8	1947.1	27.0
T_3: T_2 + $ZnSO_4$ @ 5 kg ha^{-1} + Borax @ 1 kg ha^{-1}	59.0	56.4	2.81	10.4	782.8	2119.9	26.9
T_4: T_2 + Foliar application of Micronutrients Mixture 0.1 % at 25 Days After Sowing	63.1	58.7	2.84	10.6	797.5	2144.9	27.1
T_5: T_2+ Foliar application of Micronutrients Mixture 0.1 % at 45 DAS	63.5	59.7	2.85	10.9	808.9	2149.9	27.3
T_6: T_2 + Foliar application of Micronutrients Mixture 0.2 % at 25 DAS	65.7	59.9	2.89	11.1	821.9	2189.3	27.2
T_7: T_2 + Foliar application of Micronutrients Mixture 0.2 % at 45 DAS	66.3	59.9	2.91	11.3	834.4	2227.1	27.2
T_8: T_2 + Foliar application of Micronutrients Mixture 0.1 % at 25 and 45 DAS	70.9	61.3	2.93	12.5	859.9	2239.8	27.7
T_9: T_2 + Foliar application of Micronutrients Mixture 0.2 % at 25 and 45 DAS	78.9	63.8	3.16	13.9	883.9	2263.4	28.1
S.Em±	**1.74**	**2.48**	**0.12**	**0.47**	**33.01**	**88.72**	**1.22**
CD @ 5%	**5.22**	**7.42**	**0.36**	**1.42**	**98.9**	**265.9**	**NS**

Table 3: Effect of micronutrients mixture foliar application on quality parameters of sesame

Treatment	Oil content (%)	Oil yield (Kg ha^{-1})	Crude Protein (%)	Ash Content (%)	Saponi-fication value (mg g^{-1})	Iodine value (g/ 100g)
T_1: Absolute Control	40.0	220.3	18.2	4.07	197.40	111.68
T_2: Control (RDF + FYM @ 5 t ha^{-1})	42.1	304.6	20.7	5.42	196.14	109.84
T_3: T_2 + $ZnSO_4$ @ 5 kg ha^{-1} + Borax @ 1 kg ha^{-1}	45.6	357.0	21.2	5.93	192.30	107.33
T_4: T_2 + Foliar application of Micronutrients Mixture 0.1 % at 25 Days After Sowing	46.6	371.5	21.4	6.12	190.39	106.62
T_5: T_2+ Foliar application of Micronutrients Mixture 0.1 % at 45 DAS	46.6	379.0	21.6	6.15	189.55	106.15
T_6: T_2 + Foliar application of Micronutrients Mixture 0.2 % at 25 DAS	46.9	385.2	22.3	6.34	188.80	105.73
T_7: T_2 + Foliar application of Micronutrients Mixture 0.2 % at 45 DAS	46.9	391.6	22.4	6.38	188.47	105.54
T_8: T_2 + Foliar application of Micronutrients Mixture 0.1 % at 25 and 45 DAS	47.1	404.6	23.9	6.40	187.60	104.00
T_9: T_2 + Foliar application of Micronutrients Mixture 0.2 % at 25 and 45 DAS	48.1	425.4	25.3	6.82	187.01	104.54
S.Em±	**1.98**	**14.85**	**0.95**	**0.25**	**7.45**	**5.75**
CD @ 5%	**NS**	**44.53**	**2.84**	**0.75**	**NS**	**NS**

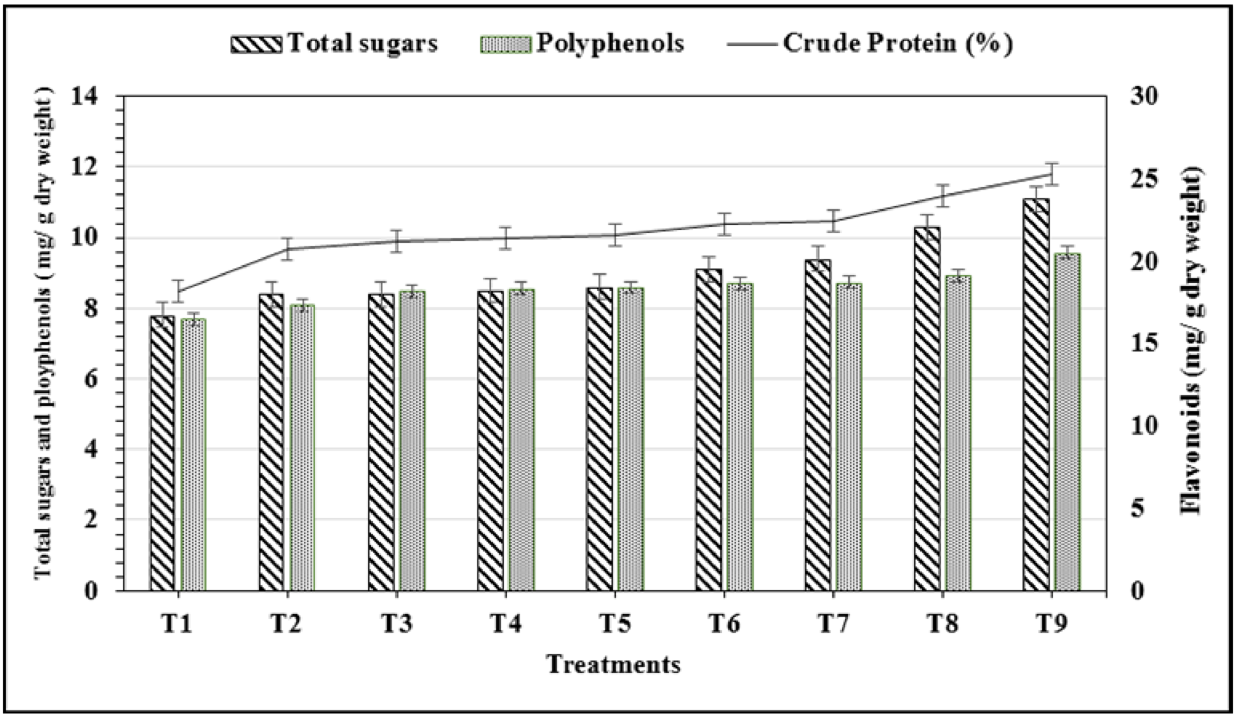

Fig. 1: Effect of micronutrients mixture foliar application on total sugars, polyphenols, flavonoids content of sesame

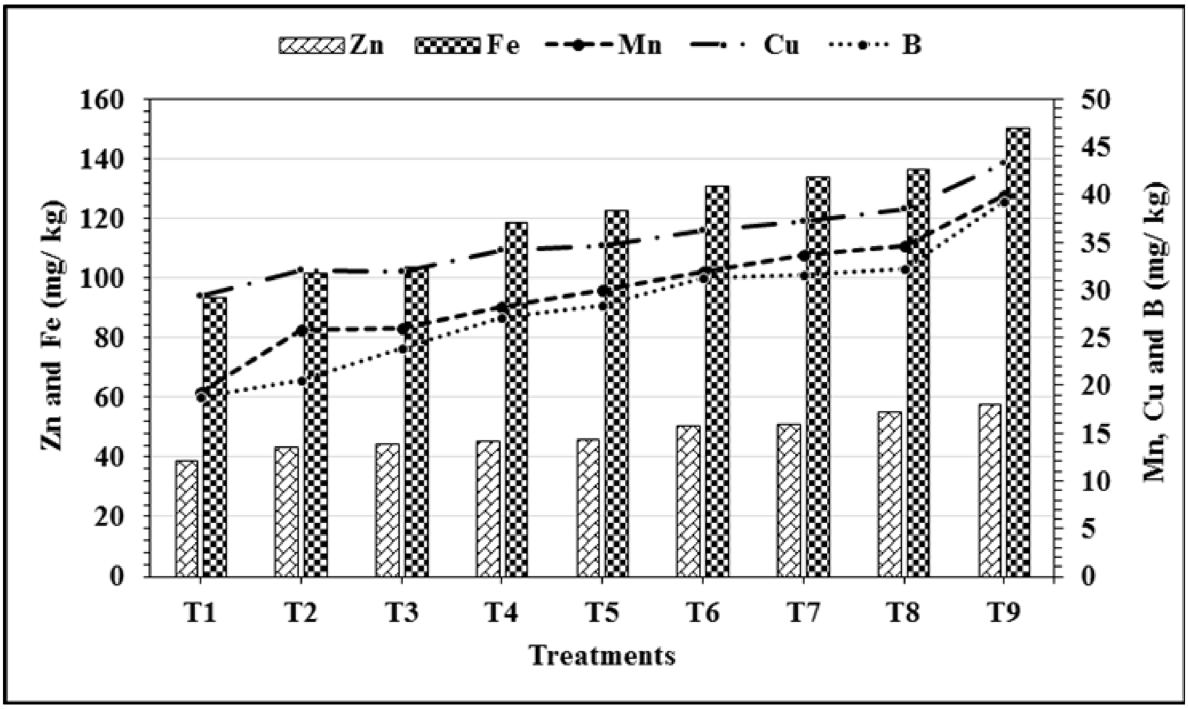

Fig. 2: Effect of micronutrients mixture foliar application on micronutrients content of sesame seed

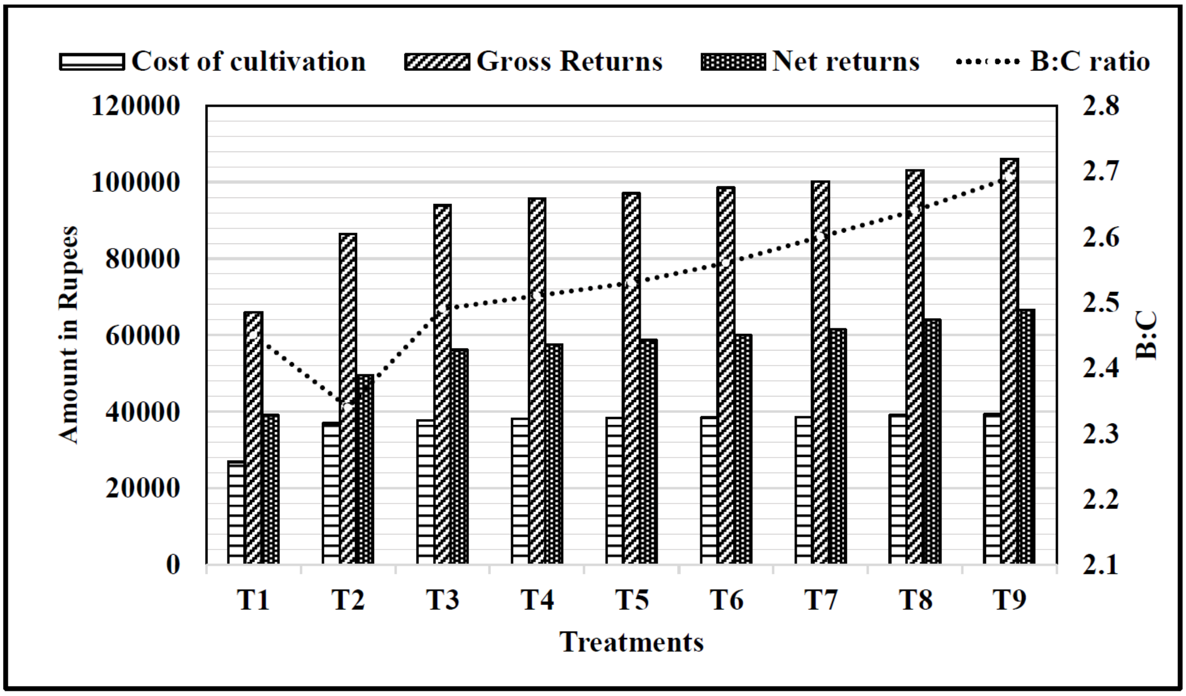

Fig. 3: Economics of sesame cultivation as influenced by the foliar application of micronutrients mixture

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