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Sulphur and manures nutrition in oilseeds: Crop demand, physiology, phenology, deficiency symptoms and management

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Abstract

Oilseed crops are also known to be very demanding in terms of sulfur and are important in nutritional and physiological processes of this element. Sulfur is also needed to produce sulfurous compounds like sulfur-containing antifungal proteins cysteine and glucosinolates, which provide resistance against diseases and stimulate the good health of the plants. The lack of sulfur in the oilseeds like rapeseed lowers its antimicrobial capability, susceptibility to illness, and the concentrations of defensive secondary metabolites, thus adversely influencing crop production. Sulfur physiologically is needed to maximise the uptake and remobilisation of both nitrogen and sulfur during the vegetative period of growth that promotes biomass accumulation and overall development. The plants may be able to counter the lack of sulfur on a short-term basis by recycles of the endogenous sulfur, but not with enough levels to cover the shortage. Phenologically, accurate information on the crop growth stages, which are similar to the safflower, is used to plan the nutrient management to ensure optimal growth and produce. Thus, the coordination of the sulfur use and the developmental needs of the crop according to the phenology of the crop is crucial. The common effects of sulfur deficiency in oil seed crops include stunted growth, chlorosis, and poor quality of seeds and as such, the need to ensure a balanced sulfur nutrition program. These signs are indicative warning signs of insufficient status of sulfur and should be corrected. Therefore, the management techniques are based on the synergistic nature of appropriate sulfur fertilisation by either mineral or organic manures in combination with other nutrient amendments. This plan increases the friability of soils, nutrient availability, and stress and productivity tolerance in crops. The combination method of fertilisation also maintains the best physiological and phenological performance of oil crop plants. Making use of manure does not only provide sulfur but also enhances the microbial activities and the content of organic matter of soil. This kind of improvement encourages an increase in the efficiency of nutrient cycling and enhances the growth of crops in the different agro-climatic zones. Overall, the combination of sulfur nutrition and manure control is also essential to the needs of oilseeds, proper maturation and physiological control, mitigation of the symptoms of deficiency, and maintenance of production.

Keywords: Sulfur nutrition in oilseeds, Nutrient management strategies, Sulfur deficiency symptoms, Oilseed crop productivity, Integrated fertilization approaches

Introduction

Sulphur (S) is a crucial element that cannot be overlooked in the development and growth of oil seed crops because it is the primary constituent in structural biomolecules, metabolic background, and resistance to stress in plants. Its role has never been given much importance in history but with the growing attention to the fact that the soil lacks sufficient levels of sulphur and the growing demands to produce more products the ignorance about malnutrition has been revealed as the necessity of sulphur in crop farming, crop quality and crop resistance to abiotic stress. Sufficient nutrition to sulphur maintains physiological roles, including protein production, enzymatic activity and antioxidative defense, which affect plant development and production (Zenda *et al.*, 2021) ^[1]. The phenological cycle of the oil seed crops indicates that certain sulphur needs are involved especially in the initial stage of their growth when the uptake and assimilation of sulphur determine the growth of the leaves, photosynthesis, and organ development. Sulphur is also added in the production of the amino acid cysteine and methionine which are the precursors of essential proteins that determine the seed output and quality of

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oil. The deficiency symptoms are usually chlorosis and necrosis of the young foliage, low growth vigor and low seed set or seed quality. When not properly controlled, these physiological disturbances may cause massive losses to the yield (Abrol, 2003) ^[3]. Manure is a better organic nutrient source in the production of oil seeds, as they increase the fertility and soil structure by supplying the oil seeds with organic matter and essential nutrients; nitrogen, phosphorus, potassium, and sulphur. Organic manures have a slower rate of nutrient release as compared to chemical fertilizers and as such, this increases the nutrient-use efficiency and enables crop growth to be sustained. Moreover, the use of manure helps to promote positive microbial communities through the aid of nutrient cycling and conversion, thus decreasing the threat of leaching and nutrient shortages. Adequate manure feeding enhances the biomass of oilseeds, nutrient capturing, and performance, which correlates with the concept of sustainable and environment-friendly farming (Lee *et al.*, 2023; Bhatt *et al.*, 2019) ^[5].⁴⁾Effective management of deficiency depends on proper diagnosis by tissue test and monitoring of symptoms and balanced sulphur fertilization programs which depend on the soil properties, crop needs and phenological stages. The renewal of the sulphur level may also enhance the production of oil seeds and boost the quality of the seeds by availing the appropriate sulphur fertilizers like ammonium sulfate or elemental sulphur alongside an organic manure. When combined with other nutrient management systems such as organic nutrients, the provision of sulphur and its uptake will be optimized to ensure that the nutrient provision and uptake are optimized in intensive cultivation systems that are facing the challenge of sulphur depletion (Schnug and Haneklaus, 1998; Zenda *et al.*, 2021) ^[6].

Effect of organic sources on oilseed performance

The utilisation of organic sources is inherently a core principle of the improvement of oil-seed crop functioning since it enhances the health of the soil, expands the availability of nutrients and activates micro-organism activity. The use of organic amendments like manure, compost, and plant residues enhances the soil organic matter positively affecting the soil structure, aeration, and water retention that in return affects the healthy development of roots and overall crop development. Empirical studies prove that oil-seed production with the introduction of organic fertilizer not only increases the yield but also improves the quality of oil with the help of better nutrient cycling and less use of synthetic fertilizers, the influence of which is disastrous in the long term on soil health (Assefa, 2019) ^[8]. The microbial interactions caused by the organic supplies added to oil-seeds crops especially in soybean are mediated by the positive endophytic bacteria which improves the fixation of nitrogen and the uptake of nutrients. These microorganisms are quite useful in rejuvenating the soil, since they enhance the pool of nitrogen, and help in reabsorbing the lost nutrients thus the long run effect of sustainable agriculture. Integrating the application of organic sources and bio- inputs linked to the plant-related microbiomes is beneficial to the process of preserving plant growth, preventing pathogens, and stabilising soil ecology, which is critical to guaranteeing stable and enhanced oil-seed production (Ayilara *et al.*, 2022) ^[9]. There is also need to amend them with organic matter to reduce soil degradation and make oil-seeds production more sustainable. Organic materials such as biochar have been found to be effective soil amendments which enhance carbon sequestration, enhance physical and chemical properties of soil and also minimize greenhouse- gases emission. These amendments

enhance the levels of carbon and the nutrient-binding capacity within the soils, thus making the soil more convenient to the plant roots and soil microorganisms. The beneficial effects on the health of the soil, in turn, present as the enhancement of the resilience and productivity of the oil-seeds, which highlights the importance of the oil-seeds performance based on the organic amendments in order to achieve sustainability (Rahman *et al.*, 2019) ^[10]. The use of organic liquid by-products including molasses, vinasse has shown positive impacts on soil fertility and oleaginous crops. These by-products improve the biological and physicochemical properties of soil since they possess some nutrient elements and organic matters that increase the crop growth parameters. They have been demonstrated to boost the production of different crops such as soybean implying that well- allocated organic amendments can be more efficient than traditional chemical fertilizers (Stephen *et al.*, 2024) ^[11]. Organic additions have a long-term impact on the soil fertility and yield of crops. It has been shown that a significant increase in soil organic carbon and microbial biomass, increased enzyme activity and enhanced soil physical properties like aggregate stability could be obtained by frequent addition of organic rubbish, such as compost and manure. This improvement gives oil-seed crops the best growth conditions with yields possibly doubling up to 250 per cent as compared to soils that either have been left unfertilised or fertilised with the use of chemicals. In addition, organic amendments are also involved in the mitigation of climate-change by way of carbon sequestration hence guaranteeing the sustainability of the environment and agricultural production (Diacono and Montemurro, 2011) ^[12]. The enhancement of the performance of oil -seed crops, especially when combined with the application of organic amendments with other soil-management tools, such as crop rotation and cover cropping, can aid in restoring and maintaining soil biodiversity and stocks of nutrients. The practices will lessen reliance on chemical fertilizers, decrease the expenditure on inputs and decrease the environmental impact yet ensure production of agricultural yields in the long run. Organic sources boost the resilience of an ecosystem by boosting rhizospheric functions and microbial biodiversity, thus augmenting the oil-seed crop resilience to a stressful environment and its long-term adaptability (Khan *et al.*, 2024) ^[13].

Role of Farmyard Manure (FYM) in Oilseed Productivity

Farmyard manure (FYM) is an extremely valuable resource which contributes to the productivity of oilseeds crops because it enriches the soil and provides the necessary amount of nutrients. Organic composition endows FYM to enhance key physical characteristics of soil such as bulk density, porosity and water-holding capacity which are essential in the growth of roots and nutrient absorption in oilseeds. FYM has a slow and sustained release of nutrients; therefore it provides the primary nutrients of nitrogen, phosphorus and potassium in amounts that are needed during the growth of the oil seed crop. It has been empirically proved that when FYM is used in combination with inorganic fertilizers, significant changes in the yield-related parameters are observed, which include the grain weight, the number of fully filled grains per plant, and the overall seed yield of different cultivars, especially oilseeds (Satyanarayana *et al.*, 2002; Yang *et al.*, 2006) ^[15, 14]. Constant application of FYM increases the content of organic matter in the soils, which triggers biological activities and nutrient cycles in the soil. This increases the biological activity that maximises the uptake of nitrogen and enhances the quality of the oil seed crops. Furthermore, FYM has been found to bring about carbon and nitrogen levels in soil

microbial biomass, and as a result, the levels of mineralisation have risen, as well as the availability of nutrients. Moreover, the amount of organic carbon reservoirs in the soil during the use of FYM are larger than those obtained with the use of chemical fertilizers alone, which in turn promotes more and sustainable output in the oilseeds and cereal crops including wheat and rice (Majumder *et al.*, 2008; Meena *et al.*, 2017) [18, 16]. The combination of FYM and mineral fertilisers is the integrated nutrient management approach, which offers the total nutrient buffer, thus eliminating the threats of nutrient leaching and soil erosion. Such integration increases nutrient-use efficiency particularly to nitrogen that often is the limiting factor to oil seed production. To give an example, FYM has shown better performance regarding yield stability and nutrient uptake in oil

crops versus the use of mineral nitrogen fertilisers exclusively, which highlights the critical role of this type of fertiliser in promoting the efficacy of fertilisers (Laub *et al.*, 2023) [19].

In addition to an increase in productivity, FYM enhances the quality of oilseeds by modulating the protein concentration and other quality indicators. FYM as a standalone or in combination with other organic amendments enhance the levels of grain protein and the overall quality of the seed and makes the produce more nutritious and commercially worthy (Ali *et al.*, 2020) [20]. In addition to that, FYM enhances microbial activity in the soil, which leads to the maximum absorption and translocation of nutrients in plant tissues, which stimulates oilseeds growth (Koutroubas *et al.*, 2016) [21].

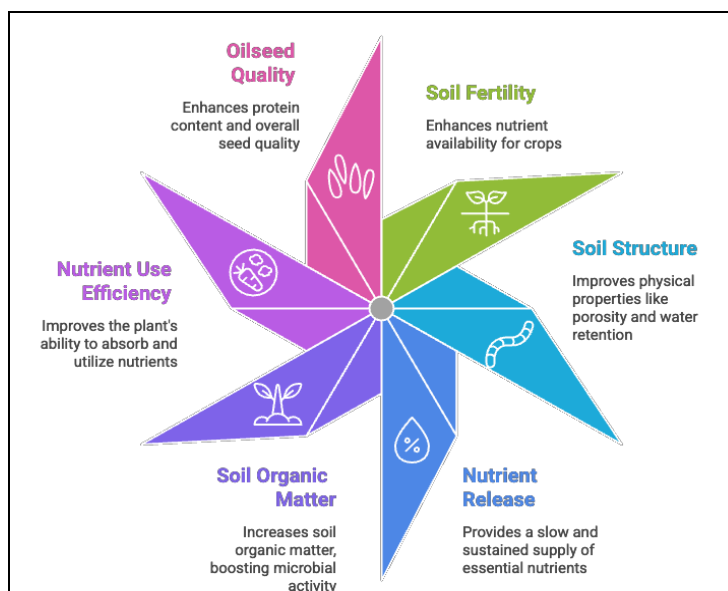


Fig 1: FYM's Impact on oilseed Productivity

Effect of Vermicompost on Growth and Oil Quality

Application of vermicompost has a positive effect on plant growth and quality of oil by increasing the absorption of nutrients and biological activity of the soil. The use of vermicompost tea in pak choi has led to the observation of increased plant production and chemical quality of plants as manifested by high content of total carotenoid and glucosinolates in plant tissues that are associated with enhanced nitrogen uptake and dry matter accumulation. Furthermore, vermicompost has provoked the dehydrogenase activity and soil respiration, factors that demonstrate improved microbial activity in soil (Pant *et al.*, 2011) [22]. Research has shown that vermicompost may not be the one that directly influences crop production, however it is capable of enhancing plant growth and the quality of certain crops. Microbial community within vermicompost teas can have an insidious resource to change soil microbial associations, thus helping to improve the quality of crops by controlling soil microbiota (Fritz *et al.*, 2012) [23]. In sweet corn, addition of vermicompost in the fertilization regimes has improved growth of the plants, fresh sales, and changed both chemical composition and quality of the ears at harvest. These are genotype-specific effects, which proves the multi-factor interaction of organic amendments and plant genetics. However, vermicompost has been useful in enhancing quality of crops and their quantity in the field (Lazcano *et al.*, 2011) [24]. In the quality of the essential oils, the experiment has indicated that when the medicinal plant *Dracocephalum moldavica* was treated

with vermicompost, the essential oils were produced in large amounts and the concentration of geranyl acetate, geranial, and geraniol was increased. It is credited to the microbial activity and nutrient mobilization of the soil especially when the use of vermicompost in intercropping systems is used. The results highlight the significance of vermicompost in the growth and quality of essential oils of plants (Rezaei-, Chiyaneh *et al.*, 2021) [25]. Organic fertilizer (vermicompost) improves the many parameters of growth which include seed germination, stem height, leaf area, root length, chlorophyll level, and biochemical parameters like carbohydrate and proteins. All of these benefits produce an overall positive effect on the productivity of the fruits and seeds and their quality, thus pointing to the usefulness of vermicompost in the context of sustainable agriculture as an alternative to chemical fertilizers (Joshi *et al.*, 2014) [26]. In addition, the mixture of vermiculite post and chemical fertilizer has significantly resulted in higher herbage and oil yield in some oil crops like rosemary. Despite the relatively small effect of the treatment on oil content and oil quality, vermicompost increased the nutrient availability of soil on postharvest, which maintained soil fertility and long-term productivity (Singh and Wasnik, 2013) [88, 27].

Poultry Manure and Concentrated Organic Nutrient Sources

In sustainable agriculture, poultry manure is a major source of organic nutrients because it is rich in organic matter content and

has the ability of improving the fertility of the soil. It is valued because of having a high level of organic matter and also because it contains important elements, such as nitrogen, phosphorous, potassium, calcium, and magnesium. The empirical evidence has shown that the usage of poultry manure encourages crop growth and nutrient absorption, which can be explained by its large nutrient levels and the beneficial effect it has on the microbial activity and the structure of the soil. As an example, poultry manure has been demonstrated to significantly raise the biomass increase and enhance the levels of potassium and magnesium in plant tissues, which highlights the effectiveness of the product as an organic fertilizer (Yaldiz *et al.*, 2019) ^[28]. The poultry manure can be composted as a practice aimed at enhancing the quality of the fertilisers, stabilising of the nutrients and also reducing the loss of nitrogen. The composting of the mixes of the feedstocks can be optimised to improve the key parameters, e.g. carbon to phosphorus ratio, the content of organic matter, and nutrient stability. When fresh manure is not available due to the composition of the feedstock used, the nutrient losses would be reduced and the resulting compost would have an optimum nutrient balance that can be used in the soils. In more particular terms, the stability of the compost product and its relations with the ancillary materials, i.e., biochar, have

an impact on the availability of phosphorus. Phosphorus recycling as a form of sustainable nutrient management, therefore, can be achieved through the application of poultry manure compost as a soil amendment to provide crops with balanced nutrients that are usable (Vandecasteele *et al.*, 2013) ^[29]. Used together with inorganic fertilisers, especially those based on nitrogen, poultry manure improves crop yield and soil fertility when compared to the situation, where only chemical fertilisers are used. These combined nutrient management approaches enable higher yields of grains, higher efficiency in the use of nutrients and increased stocks of soil organic carbon. To illustrate, where poultry manure has been used in combination with low concentrations of inorganic fertilisers in production systems of rice, this has enhanced photosynthetic activity, biomass growth and grain production, as well as, enhancing the soil structure and nutrient content after harvest. Such synergy can additionally advance soil carbon sequestration, which supports the environmental sustainability and the improvement of yield (Iqbal *et al.*, 2019; Urmi *et al.*, 2022) ^[31, 30]. Other sources of organic nutrient like farmyard manure, vermicompost and biochar are also added to poultry manure to enhance soil fertility and crop productivity especially in severe environmental factors such as dry weather. Fertilisers coupled with poultry manure tend to increase nutrient levels in soil such as nitrogen, phosphorus, potassium and organic matter hence boosting the crop development parameters and yield. As an example, when used simultaneously with poultry manure, the mixture of recommended nitrogen, phosphorus, and potassium dosage boosted cotton production by raising uptake of soil mineral nutrients, as well as crop biomass, and proved to be viable in integrated nutrient management programs (Ahmad *et al.*, 2021) ^[73, 32]. In addition to providing nutrients, poultry manure has an impact on the soil biology and health by promoting the activities of microbes that are critical in nutrient cycling. Adoption of organic amendments such as poultry manure leads to growth in soil organic matter, aggregate stability and water retention which promote soil fertility and crop resilience. The use of organic farming systems which bring in poultry manure and other nutrient-rich materials enhances the quality and quantity of crops and reduces environmental issues

that are related to the use of synthetic chemicals. Thus, the use of poultry manure as the source of concentrated organic nutrients can be discussed as the ecologically effective and sustainable approach towards enhancing the agricultural productivity by enhancing the health of the soil (Hazra *et al.*, 2016; Varma *et al.*, 2024) ^[34, 33].

Effect of sulphur on quality of oilseed

Sulphur nutrition determines the quality of the oilseed crops. Sulphur shortage has increased in most areas hence, negatively impacting the production and quality of some of the crops, such as oil seed rape and wheat. Sulphur fertilisation effectively improves quality properties of the seed; the excess of the sulphur use may increase glucosinolates in the seeds of the oil seed rape, which makes them inedible to the animals. Nitrogen, sulphur relationship is a critical one and balanced supply of these nutrients is a key to maximisation of yield of oil seeds as well as its quality (Zhao *et al.*, 1997) ^[49]. The responses to the different rates of sulphur and nitrogen fertilisation were tested under oil seed radish to determine the impact of the latter on seed quality and yield. Sulphur application of 30kg/ha had a small adverse effect on the quantity of crude fat, but

significant positive effect on the quantity of polyunsaturated fatty acids (PUFAs) and tocopherols, specifically, 00 - - tocopherol and 00 -tocopherol, and thereby enhanced the quality of oil. Conversely, nitrogen fertilisation caused elevation of protein and fibre contents and fatty-acid profiles. These findings highlight the idea that wise control over the practice of sulphur fertilisation can improve the quality of seed-oil by raising the percentage of healthy fatty acids and antioxidants (Szatkowski *et al.*, 2024) ^[53]. Canola is a good crop that reacts positively to the use of sulphur on seed growth and quality of the oil. Increasingly, soil sulphur fertilisation enhanced growth properties of leaf-area index, crop growth rate, and chlorophyll content, which also enhanced seed yield and parameters of oil and protein properties of oil and protein content in the seed. Thiourea is a sulphur- bearing substance that was used as a foliarly applicant, and thus, it also forms a possible alternative source of sulphur. In addition, the use of sulphur slowed down flowering and maturity, which may have been one of the reasons why the seed fill and quality were high (Rehman *et al.*, 2013) ^[56].

Correspondingly, in the same case when 45 kg ha⁻¹ of sulphur was applied to rapeseed cultivars, growth and yield parameters such as plant height, pod formation, number of seeds per pod, yield of seeds and oil content were improved. Another effect of this treatment was a pronounced rise in the oil content and glucosinolate concentrations, which prove that optimum supply of sulphur leads to increase in yield and quality of oil. Out of the cultivars studied, the cultivar, Oscar, recorded the best yield of seeds and oil content after being sprayed with sulphur thus demonstrating cultivar-specific reactions to sulphur nutrition (Imran and Khan, 2017) ^[36]. In general agricultural terms, sulphur is required in plant metabolism, growth, tolerance to stress, and yield. Sulphur being a major part of the major macromolecules and processes in the body affects the quality and productivity of crops. Therefore, the increased attention to the nutrition of the sulphur element is justified, especially when climate change is considered because of the increased crop cultivation, which exacerbates the situation with the lack of sulphur. Sulphur management can enhance the quality of the oil seed crop by increasing the nutrient use efficiency and stress resistance which ultimately leads to more sustainable production systems (Zenda *et al.*, 2021) ^[1].

Influence of Sulphur on Oil Content (%)

Sulfur is a vital macronutrient that has a great effect on the quantity and the general quality of oil in oil seed crops. It is empirically proven that sulfur use does not only promote vegetative growth and yield, but also increases the concentration of oil in seeds, mostly the sunflower, canola, and groundnut species. Sulfur fertilisation has been found to boost the accessibility of nutrients and metabolic activities that are essential in the production of oil in the oils seeds, thus enhancing the quantity and quality of oil. As a case in point, there is a synergistic relationship between sulfur and other compounds in sunflower in which the simultaneous application of sulfur and nitrogen fertilisers increases the oil and achene levels (Perveen *et al.*, 2021) ^[35]. Nutrition of sulfur plays an important role in seed production and oil production in canola. The use of sulfur fertilisers in the cultivation of different varieties of canola has been recorded to have significantly increased seed yield and oil content especially with the use of 45,000kg per ha minus. Some of the parameters that were found to have improved in the course of the investigation include the number of seeds

per pod, the height of the plants, and the biological yield which all leads to an increase in the amount of oil. In addition, the use of sulfur fertilisation was linked to an improved quality of oil properties, especially elevated glucosinolate levels, which are

one of the determinants of the quality of seed oil (Imran and Khan, 2017) ^[36]. Additional field research on the subject in Canada shows that, seed oil concentration and quality is significantly increased by correcting canola soils with different types of sulfur fertilisers. Ammonium sulfate, especially, was found to be very successful in enhancing oil content, which was postulated to be because of the high concentration of sulfates. The use of sulphur also increased the level of sulphur in the seed and in some instances it decreased the amount of nitrogen in the seed meaning that there might be a trade off that affects seed composition. Notably, evidence was provided in the research that better nutrition in sulphur in most cases increases the oil production hence showing the important role of the nutrient in the process of oil production (Grant *et al.*, 2003) ^[37]. With reference to groundnut production in semi arid regions, sulfur fertilisation is unavoidable in improving the pod and kernel yield and quality of the oil. The 40kg S/ha added considerably lowered the oil yield and content and also enhanced protein content and zinc bio fortification in the kernels. These results show that not only sulphur has a direct positive effect on the oil production process but also regulates the quality of oilseeds nutrition, and imparts control to the activity of other nutrients that can enhance quality and yield of crops (micronutrients) (Noman *et al.*, 2020) ^[38].

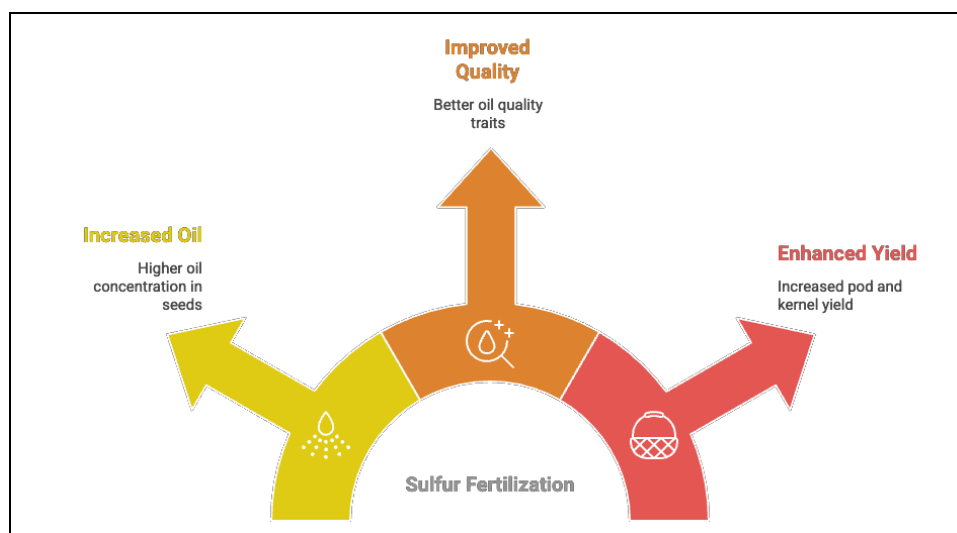


Fig 2: Sulfur Boosts Oil Content in oilseeds

Effect of Sulphur on Fatty Acid Composition

Sulfur is also vital in the determination of fatty acids in the oilseeds, which is an important element in the growth and metabolism of plants such as in protein synthesis and lipid-metabolic enzymes. Assessing the quality and nutritional value of the oil produced by oilseeds can be achieved by changing the production of fatty acids by sulfur to alter the enzyme functions and pathway, which can alter the quality and nutritional value of the oil produced by the oilseeds. It is discovered that the nutritional condition of sulfur dictates the total amount of oil and also the level of fatty acid in various oilseeds. As an example, changes in the sulfur content of peanuts have been associated with the changes in seed weight which in turn translate to changes in the fatty-acid composition of the seed, particularly the increase of the proportion of oleic acid and a reduction in the proportion of linoleic acid as seed weight increases. It means that the indirect impact of sulfur on the fatty-acid structure is through altering the seed-developmental properties (Li *et al.*,

2022) ^[43]. In addition to having effects on seed characteristics, the lack or excess of sulfur can affect the processes of fatty-acid desaturation and elongation by affecting enzyme activities. The Sulfur dependent cofactor enzymes including fatty-acid desaturases are critical in transforming saturated fatty acids to unsaturated ones. Other genes, such as FAD2, a gene pivotal to the process of defining the amounts of oleic, linoleic and linolenic acid levels in oleic oil seeds like rapeseed, may also be modified by the amount of sulfur. More concentration of sulfur may boost the production of oleic-acids as it activates the desaturase gene, thereby boosting the concentration of monounsaturated fatty acids in oil which enhances the quality of oil (Huang *et al.*, 2020; Shi *et al.*, 2022) ^[45, 44]. Sulfur is added into fatty-acid biosynthesis by the production of sulfur-containing fatty acids, more commonly known as thia fatty acids, that have new metabolic properties including lipid biosynthesis and fatty-acid remodeling. These sulfur-substituted fatty acids can also regulate the mitochondrial proliferation and

lipid metabolism, and it is proposed that the availability of sulfur may have a wider physiological implication to the fatty-acid composition in oil seed plants (Berge *et al.*, 2002) ^[46]. Further, the composition of fatty-acids may be changed under environmental conditions, which the nutrition of sulfur can control, such as temperature during seed growth. The oleic/linoleic acid ratio of the sunflower oilseeds can also be changed indirectly by environmental factors (temperature) due to the effects of sulfur on the plant metabolism and stress reaction. These correlations show that oilseeds contain fatty acids as a product of the interaction between sulfur nutritional value and environmental parameters (Neto *et al.*, 2016) ^[47]. Sulfur has a well known impact on the composition of fatty-acids, and it is quite known to have an effect on the plant hormones, which control seed production and oil production. Phytohormone metabolism that is caused by sulfur nutrition can also influence seed maturation, fatty-acid accumulation and composition, especially of soybean crop. Such hormonal interaction shows that the effects of sulfur on the formation of fatty-acids is not limited to the direct metabolic activities, but also to the regulatory systems that define the quality of seed-oil (Nguyen *et al.*, 2016) ^[48].

Impact of Sulphur on Protein Content and Quality

Sulphur (S) is very important in the content and quality of the proteins in the crops of oilseeds. It has been demonstrated that sufficiency of sulfur in nutrition has the effect of augmenting protein content in the seed, as well as having a role in the structure of sulfur-containing amino acids, considered crucial in protein structure. One such instance is that of oilseed rape (*Brassica napus*) in which the effect of low levels of sulfur will lower the total protein content, and more directly decrease the levels of sulfur-containing compounds, including cysteine and methionine which gets compromised and reduces the nutritional and functional qualities of the seed protein (Zhao *et al.*, 1997; Timms *et al.*, 1981) ^[50, 49]. Sulfur fertilisation also increases the degree of glucosinolates in rapeseed seeds, a category of secondary metabolites containing sulfur and influencing antimicrobial functioning and resistance to diseases. Although with rising glucosinolate levels, the level of utilization of oilseed meal in livestock feeds could change, the higher concentrations are correlated with an enhanced antimicrobial potential and plant defence. Plants that lack sulfur in oilseed rape have low concentrations of antimicrobial secondary metabolites and are extremely vulnerable to disease, which indirectly affects the quality of proteins by reducing the health of crops (Dubuis *et al.*, 2005; Marazzi *et al.*, 2004) ^[52, 51]. Fertilisation with nitrogen (N) and sulfur also regulates protein content and quality in the oilseed crops. Oilseed radish (*Raphanus sativus*) experiments have shown that in cases where nitrogen fertilising is increased to an optimal extent, total seed protein is increased, but that there is also a rise in fatty- acid profiles and tocopherol (vitamin E) concentration which increases seed quality. Even though these studies did not find direct effects of sulfur on total protein content, the effect of sulfur on related seed metabolites would positively affect the nutritional value of protein and seed processing properties (Szatkowski *et al.*, 2024) ^[53]. In addition, the availability of sulfur affects the proportions between nitrogen and sulfur in the grains and elimination of sulfur-amino acids to seed proteins. An example would be a high nitrogen / low sulphur imbalance in wheat which will lower the percentage of high sulphur proteins in the product as a result of which there will be less protein of high quality in the product despite the fact that the total protein content in the product was high. On the

other hand, oilseeds with a balanced nutritional level of sulfur provide the ideal sulfur- amino-acid ratio, required in human and animal food (Timms *et al.*, 1981; Zhao *et al.*, 1997).

Sulphur Nutrition and Seed Physical Quality

Sulphur nutrition has a significant effect on the growth and yield of plants, and on the physical quality of the seed, oil species like canola, rapeseed and other related crops. Regardless of whether it is being sprayed on the ground or sprayed on the leaves, sulphur is found to have a great impact on crop growth parameters (leaf area index, crop growth rate, chlorophyll content) which all have positive impact on yield parameters (plant height, number of branches, silique per plant, seeds per silique, 1000-seed weight). It has also been shown that the growth, yield, and quality of canola seeds are enhanced when the soil is applied with 40kg/ha of sulphur which highlights the essence of the compound in enhancing yield and the quality of harvest (Rehman *et al.*, 2013) ^[56]. The effects of interaction between the fertilisation of sulphur and nitrogen on the seed yield and quality in oil seed rape also influence the same. Optimal rates of sulphur and nitrogen have a synergistic effect on seed yield and protein quality, significantly increasing the percentage of sulphur-containing proteins in seed storage, e.g. napins. Sulphur applications applied fractionated or delayed have been reported to improve protein quality in seeds due to increased levels of the sulphur percent and structure of protein storage that promotes the existence of S- containing amino acids. These results suggest that a sustainable farming framework can ensure or even enhance the sustainability of seed production and nutritional value by preventing excessive use of sulphur and nitrogen fertilisation (Poisson *et al.*, 2019) ^[57]. Sulphur deficiency in addition to reducing the yield interferes with the physical quality characteristics of the seeds such as storage protein composition and oil content. To illustrate, it has been observed that winter wheat and oil seed rape nourished with sulphur has better quality in its flour and the seed oil properties. Nevertheless, when the levels of sulphur become excessive, it is likely to reduce the utilitarian value of rapeseed meal in animal feeds by enhancing the glucosinolate levels and consequently, parameter of yield and seed quality protein composition and glucosinolate (Zhao *et al.*, 1997) ^[49]. Experiments on canola that have been conducted in the fields have reported significant gains in seed productivity, biological productivity, oil concentration and harvest index in cases where sulphur is used in the suggested quantity. Specifically, cultivars like Oscar react remarkably with a higher increase in plant height, more production of pods per plant, and more seeds per pod with a high quality of seeds per pod. These findings support the fact that appropriate management of sulphur could increase seed physical characteristics and the overall plant productiveness in various agro-climatic regimes (Imran, 2017) ^[36]. Other economically important crops such as soybean have been found by the studies conducted on the plant to contain sulphur, which is critical in metabolism of nitrogen and seed productivity. Sulphur shortage reduces the ability to use nitrogen resulting in poor seed yield and quality. The use of optimal fertilisation technique split nitrogen application with sulphur has a significant positive effect on the yield of soybean seeds, and the nutrient balance is the most important factor in determining the amount of seeds and their physical properties (Glowacka *et al.*, 2023) ^[60]. The sulphur fertilisation time, rate and place in combination with tillage practices in soils affect the canola seed quality. The deficiency of sulphur in soils is overcome by the application of sulphur fertilizers which are readily available to

plants and hence increase concentration of seed oil and chlorophyll in the seeds produced on the deficient soils. Ammonium sulphate has always proved to be more efficient than the elemental sulphur among other sources of sulphur in enhancing the quality of seeds in a given season. Besides, the concentration of sulphur obtained by such fertilisation is negatively related to seed nitrogen concentration but positively related to the concentration of seed oil and the total physical seed quality (Grant *et al.*, 2003) ^[37]. Sulphur has varied functions in plant metabolism that include structural functions in biomolecules and physiological control of seed development and quality. It also influences the physical character of the seeds by adding into the rearrangement of the seed composition, particularly in the presence of abiotic stress conditions including heat hence contributing to the storage proteins profiles and fatty acids composition. It is found that seed filling can be influenced by a changing provision of sulphur to modify germination parameters and storage capacity, meaning that combined temperature and sulphur nutrition controls seed yield and quality properties (Brunel-Muguet *et al.*, 2015) ^[62].

Climate change effect on oilseed performance

The climate changes experienced with global warming are slowly transforming the environment in which crops are cultivated and thus drastically changing the yield and quality of the oilseeds; namely, soybean, sunflower, canola, peanut and cotton seed. The two major environmental conditions, temperature and water supply, influence the physiological events relating to the synthesis of seed-oil as well as the stability of fatty-acid composition. Genetic factors and the environment interaction is thus an important factor in oil content and composition determination under varying climatic conditions. With climate change, genomics and bioinformatics technologies have been used to help breeders predict and develop stable oil-quality phenotypes (Attia *et al.*, 2021) ^[74]. In climatic change, forecasts of soybeans in Iran suggest that maximum temperature and precipitation will increase and this will positively affect the yields in some regions but on the contrary, increase in minimum temperature would be a negative effect. Specifically, the anticipated change in the production of soybean is larger in the Ardabil and Golestan provinces than others, which represent how the effects of climate change on the production of oilseeds are spatially uneven. These results highlight the importance of adapting to the geographic location so that soybean production can be optimised in terms of future climatic conditions (Yuzbashkandi and Khalilian, 2019) ^[63]. Raising the average temperature by about 1.5 °C in the next two decades is one of the biggest threats to the oilseed crops since it will influence the biomass, phenology, physiology, and yield traits. The effects of heat stress are negative on oil, seed production and seed quality. The natural defence system of the oilseeds cannot completely resist the heat stress hence causing losses in yield. Recent research has been narrowed on the multi- gene response that comprises of heat-shock proteins, antioxidant system and metabolic changes, which form the foundation of heat tolerance. New methods, including CRISPR/Cas genome editing and omics technology, are being explored to come up with heat-resistant cultivation of oilseeds (Ahmad *et al.*, 2021) ^[73, 32]. Waterlogging is a condition that is increasingly becoming prevalent because of climate change as it causes the oilseed rapeseed (*Brassica napus*) yield to decline especially when it happens at the most crucial stage of growth like during stem elongation or flowering. In spite of the fact that waterlogging

causes the decrease in plant growth and decreases nutrient adsorption, resulting in yield losses, the studies under the controlled conditions indicate that seed oil quality is not largely affected (Wollmer *et al.*, 2017) ^[66]. Sunflower, which is a significant oil seed crop in the southern and eastern Europe, is susceptible to heat stress during anthesis and to drought during growth periods. The consequences of both stresses include great losses in yield, decreased oil content, and fatty-acid profiles. The adaptation measures are the breeding of early- maturing, stress-resistant cultivars, changing planting time, and switching cultivation to more favourable northern latitudes. Mitigation benefits are also provided by sunflower because its greenhouse-gas emissions are less than most other crops (Debaeke *et al.*, 2017) ^[67].

Climatic change effects on oilseed production in South Africa respond inconsistently to modelling instruments. In the prevailing climatic conditions, the yield of soybean and sunflower is likely to reduce in most parts, with groundnut yield likely to go up in some parts. It is expected that the greenhouse-gas emissions related to crop management would also increase with intensification, which can be a significant challenge; hence, strategies aimed at adaptation have to be able to compromise between yield resilience and emission mitigation (Kephe *et al.*, 2024) ^[68]. In Europe, the climate change will lower the size of area in which rapeseed (*Brassica napus*) can be cultivated because arid climate and rising temperatures will adversely influence the level of oil content and harvesting of the seeds. However, white mustard (*Sinapis alba*) can be a prospective alternative oilseed crop that is more adapted to the future climate of the Mediterranean. According to species -distribution models, the number of climatically favorable locales of white mustard has been increasing, which will allow the creation of biofuels and diversify agricultural systems in warmer and drier climates (Jaime *et al.*, 2018) ^[69]. Lastly, the projections of a climate-change model of Switzerland suggests that the increase and greater temperature variability have a negative influence on canola production, but the rise of the atmospheric CO₂ can have a neutralizing effect on the negative effect. Adaptive changes in sowing dates and establishment of new cultivars that can survive changing climatic conditions could be maintained or even improved to ensure the oilseed crop yields (Torriani *et al.*, 2007) ^[70].

Phenological Shifts in Oilseed Crops under Climate Change

Phenological changes refer to changes in the regimes of development of critical stages of crop growth, which is extensively affected by climatic factors like temperature and precipitation. Oilseed crops undergo a change in their phenology except the few crop species that have been observed to be resistant to such modifications hence they do change directly the growth durations and yields of the same. High temperatures hasten phenological development resulting in the earlier flowering and maturity hence reducing the total growing period. The rapid growth rate caused by heat may affect vital winter crop growth phases like vernalisation and decrease crop yield in case of too short growth period (Liu *et al.*, 2018; Xiao *et al.*, 2021) ^[94, 72, 71]. In the oil-bearing crops, in particular, temperature and water levels become absolute necessities in the production of the seed oil and in the quality of the yield, which are especially vulnerable to the warming of the climate. The relative increase of 1.5 °C in heat stress is particularly harmful, having an adverse impact on biomass production, phenology, physiology, and yield components. Natural defence mechanisms against heat induced stress in the oil seed crops are not enough

leading to massive losses in the seed quantity and oil quality. The adaptation strategies are thus needed and they involve the analysis of the genotype environment interaction and application of molecular tools like CRISPR, omics, and other technologies to come up with heat tolerant genotypes (Ahmad *et al.*, 2021; Attia *et al.*, 2021) ^[73, 74, 32].

Adaptation to climatic change in olefin and other crops commonly entail sowing date and cultivar changes. In the case of major cereals, the introduction of cultivars with varied thermal needs has been effective in offsetting shortened growth phases because of warming and therefore, crop expansion has been able to respond to the alteration in the environmental conditions. It is

urgent that breeding of oilseeds is done to achieve sustainable yield and quality during altered phenological regimes. Flowering and maturity are some of the variations which may disorient the oil synthesis processes thus impacting volume and quality of the final product. Therefore, genomics and bioinformatics remain as part of breeding programmes that seek to predict and optimize crop response to harsh environmental conditions (Liu *et al.*, 2018; Attia *et al.*, 2021) ^[94, 71, 74].

Effect of Rising Temperature on Oilseed Growth and Yield

Temperature increases have severe negative impact on the growth and yield of oil seed crops, including canola (*Brassica napthum*). High chronic heat stress (especially above 36 °C) significantly affects reproductive fitness by interfering with the viability of pollen and germination. This, in turn, results in asynchronous development of male and female reproductive structures that block the growth of pollen and eventually decreases the production of seeds. The seed yield reduces significantly beyond 32 °C, and over 50 percent of the entire seed yield and seed weight is lost. Additionally, heat stress causes a deleterious effect on seed vigor, oil composition, and fatty acid composition and can also reduce the nutritional value of the oil through altered ω-6/ -8 ratios (Lohani *et al.*, 2021) ^[76]. The inherent prone nature of oilseed crops to high temperatures is further enhanced by the fact that the genetic basis of heat tolerance and physiological levels of heat tolerance are also complex. The various pathways mediate heat-stress resilience in oil seed crops like soybean, sunflower, and canola, and these pathways are hormonal signaling, membrane stability, heat-shock protein synthesis, reactive oxygen species scavenging, antioxidants accumulation, and compatible solutes accumulation. Recent technological progress in biotechnology, which is largely based on CRISPR/Cas genome editing and omics applications, has made it possible to identify and alter genes that provide superior thermotolerance. This would be critical in designing cultivars that would be able to endure oil production and harvest at the high temperatures linked with climate change (Ahmad *et al.*, 2021) ^[73, 32]. There are also fluctuations in temperatures which severely affect photosynthesis and accumulation of biomass in oilseed crops. As an example, high temperatures decrease net photosynthetic carbon assimilation and biomass in soybean, despite the elevated CO₂ levels in the atmosphere- a condition that tends to stimulate photosynthesis. The high temperatures reduce the stomatal conductance and CO₂ levels between the cells thus leading to losses in yield in high CO₂ conditions. These findings indicate the weak capacity of augmented atmospheric CO₂ to counter the harmful effect of heat on photosynthesis and growth of C₃ oil seed crops, highlighting the issue of increased temperatures to oil seed production (Ruiz-Vera *et al.*, 2013) ^[79]. These findings are supported by regional studies, which indicate

not constant effects of temperature on yield of oilseeds. Projections in Iran show that increased maximum temperatures would promote the yield of soybean in some provinces and increases in minimum temperatures would reduce the yield. These opposite effects indicate the heterogeneity of the effect of temperature on crop productivity and focus on the need to implement location-specific adaptation policies in particular crops and regions due to local climatic conditions and specific crop reactions (Yuzbashkandi & Khalilian, 2019) ^[63]. Also, higher temperature could lower the quality and yield of oil through the interference of the metabolism of lipids in growing oilseeds of crops like rapeseed. Triacylglycerol lipase activity suppression in the genetics when seeds are developing can increase the yield of oil, implying that extreme temperatures can change the lipid metabolic pathways that predetermine fat content in the final products. The detailed knowledge of molecular and physiological mechanisms of temperature impacts is thus a necessity in breeding more productive and constant varieties of oil production (Kelly *et al.*, 2012) ^[81].

Elevated CO₂ and Its Influence on Oilseed Productivity

High CO₂ levels in the atmosphere have a strong effect on the yield of oil seed crops, mostly by stimulating photosynthesis and development in C₃ species like soybean and canola. It has been shown by both modelling and experimental studies that elevated CO₂ can boost gross primary productivity (GPP) in soybean due to both a direct CO₂ fertilisation impact and changes in canopy structure that can be associated with the ability of the canopy to intercept more light at an earlier stage of the growing season. Moreover, a ratio of foliage that was restricted by Rubisco carboxylation increases and aids in the stimulation of photosynthesis, especially at high irradiance, at high CO₂ concentrations, showing a positive interaction effect between CO₂ and light in crop development (Song *et al.*, 2019) ^[82]. However, benefits of elevated CO₂ on the productivity of oilseeds might be limited by environmental stressors like drought and heat. Therefore, temporary heat stress during the flowering period of canola triggers significant decreases in seed yield, yield components, and the quality of oil, which can be explained by the damage of reproductive fitness and changes in the fatty-acid composition. Climate-change conditions reduce the viability and germination of pollen at temperatures above 36 °C and reduce overall seed production and seed weight above 38 °C, which reduce the quality and yield of oilseeds (Lohani *et al.*, 2021) ^[76]. The yield of oilseed crops to high CO₂ levels is mostly non-linear as it appears to be the case with wheat since the effect is at its maximum when CO₂ reach a certain threshold of about 600 ppm. This saturation effect suggests that even though small increments of CO₂ stimulate the number of grains and yield, continued increase produces lower returns, particularly in highly productive locations.

In addition, the effect on yield was demonstrated to be stronger in low-productivity systems and not dependent on the method of fumigation or the place of rooting, which underscores difficulties in forecasting yield increases with increasing CO₂ in different agroecological regions (Broberg *et al.*, 2019) ^[85]. One constraint to maximizing the use of elevated CO₂ to enhance the yield of oilseeds is the photosynthetic acclimation in which the acute effect of elevated CO₂ on photosynthesis is short lived and eventually physiologically down-regulated. This acclimation is also coupled with nitrogen limitation since the activity of Rubisco and carbon assimilation largely depends on the adequate level of nitrogen. It is thus urgent to increase the efficiency of nitrogen utilisation and photosynthetic capacity in

oil rich crops in order to maintain the increase in yield in high CO₂ conditions. Genetic engineering that aims at optimization of nitrogen absorption and allocation may counter the effects of photosynthetic acclimation and enhance productivities of crops in future climatic circumstances (Kant *et al.*, 2012) ^[86]. In the presence of both abiotic and high CO₂ levels, interactions between stresses could have an additional impact on the productivity of oilseeds. Even though higher CO₂ should lead to better biomass and yield due to the water-use efficiency (with decreased stomatal conductance), the occurrence rate and intensity of drought may cancel the benefits. As an example, the drought stress of soybean was observed to reverse the positive effect of increased CO₂ since the radiating use efficiency more than transpiration efficiency was enhanced showing the challenge of supporting the yield increases that were caused by the rise in CO₂ (Jin *et al.*, 2017) ^[87]. Likewise, phosphorus deficiency may reduce the growth and photosynthetic advantages of high CO₂ concentration in oil

seed crops like cotton. Phosphorus stress causes retarded growth, early leaf senescence, low biomass and low photosynthesis and elevated CO₂ cannot overcome the impacts completely. The beneficial impacts of increased CO₂ were also invalidated by the changes in nutrient uptake and utilisation with nutrient stress as well, highlighting that nutrient regulation will play a crucial role in reaping the benefits of increased CO₂ in oilseeds in the future (Singh *et al.*, 2013) ^[88, 27]. Lastly, even though the increased CO₂ concentration might increase the productivity of oil seed crop by improving the photosynthesis and biomass increase, the interaction of high CO₂ concentration, temperatures or other climatic factors can yield intricate and possibly damaging results. The advantages of CO₂ are usually counterbalanced or counteracted by the heat stress or nutrient deficiencies, and thus, it can be highlighted that the need of combined breeding and agronomic approaches to maintain and enhance oil seed production under the changing climatic conditions (Prasad *et al.*, 2005; Mohapatra *et al.*, 2022) ^[90, 89].

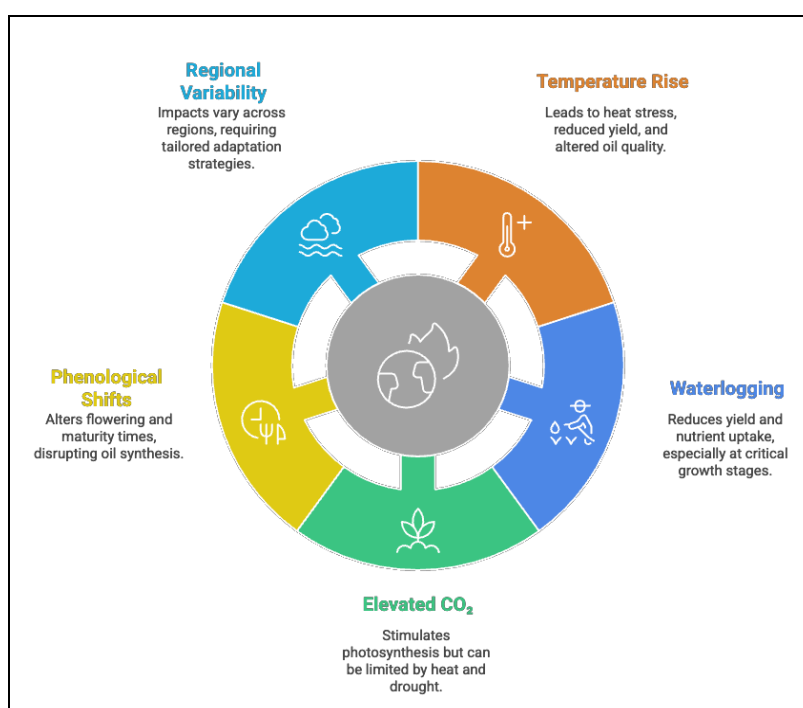


Fig 3: Climate Change Impacts on Oilseed Crops

Effect of fertilizer on oilseeds

The effect of fertilizers on the growth and yield of oilseeds is a strong one. A good case in point is oil seed rape which is a critical type of oilseeds that require high levels of nitrogen fertilisation, to achieve their best productivity levels. However, overuse of nitrogen is dangerous to the environment. Studies have shown that introduction of plant-growth-promoting bacteria (PGPB) such as *Pseudomonas sp. G31* and *Azotobacter sp. PBC2* can boost seed production by an average of 27 per cent and at the same time, lowers ammonium- nitrogen levels on the soil, therefore, offering a solution to the use of traditionally harmful nitrogen fertilisers, which effectively increase oilseed development (Dobrzyński *et al.*, 2024) ^[91]. The application of nitrogen- containing (N), phosphorus-containing (P), potassium-containing (K), and Sulphur-containing (S) fertilisers is likely to result in a high yield and nutritional value of oil crops. Even though the concentration of oil and other nutrients in the oilseeds increases with the fertilisers, when the concentration of nitrogen fertilisation is too high, it leads to the development of negative

changes, which include the high nitrate concentration and reduced levels of vitamin C and soluble sugars. Accordingly, balanced fertilisation is needed to achieve the best quality of oilseeds by removing the unwanted changes in the crop composition (Wang *et al.*, 2007) ^[92]. The major crop in sunflower, an oil seed, shows great disparity between organic and inorganic fertilisers, which has an impact on the quality of both the seed and oil, and on the soil. Inorganic fertilisers usually promote the growth of plants in terms of plant height, biomass and chlorophyll, but organic fertilisers, like compost with biofertiliser or filter mud cake, increase the amount of oil and the total seed yield. The properties of the plants subjected to organic fertilisers are different, and in most of the cases such oils which are obtained in case of inorganic treatment have darker colour as compared to those obtained under organic treatment. This fact shows the need to preserve the health of soil and the high nutritive value by using organic fertilisation (Alzamel *et al.*, 2022) ^[93]. The long-term fertilisation approaches to the arid and semi-arid soils show that organic and mixed organic-and- nitrogen fertilisers improve the soil nutrient levels,

organic carbon and nitrogen and also improve crop yields. This type of regimes raises the carbon to nitrogen to phosphorus ratio of the soil, which is important in the production of oilseeds under nutrient-restricted conditions. The results justify the inclusion of organic amendments with mineral fertilisers to enhance the development of soils and crops (Liu *et al.*, 2021)^[94]. Applied with nitrogenous fertilisers, biofertilisers have been found to increase growth, yield components and nutrient content of crops like stevia and similar on oilseeds. The joint use leads to the enhancement of height, biomass, chlorophyll content, protein, and overall nutrient content of plants, which in turn supports the effectiveness of biofertilisers in growing oilseeds and the full use of fertiliser (Yousef *et al.*, 2021)^[95].

Fertilizer Effects on Oil Content and Fatty Acid Profile

Fertilizer use has a major implication on the oil content and fatty-acid composition of different crops bearing oil, which ultimately impacts the quality of yield and the nutritional value. As it can be seen, the soybean has been shown to be influenced by the nitrogen fertilisation in terms of fatty-acid content of soybean seeds. The study has discovered that the levels of increased nitrogen concentration (30 to 60 kg/ha⁻¹) did not make any difference when compared to starter levels of fertilizers, but when inoculated with *Bradyrhizobium japonicum*, the concentration of saturated fatty acids like palmitic acid (C16:0) was reduced. This is beneficial to the nutrition process as excessive consumption of saturated-fats causes hypercholesterolemia. The relationship between the soybean cultivars and the inoculants also resulted in the inverse relationship between palmitic acid and the unsaturated fatty acids such as oleic (C18:1), linoleic (C18:2) and linolenic (C18:3) acids. The results show that the fatty-acid composition of soybean oils can be fully optimized through the application of microbial treatments in combination with fertilisers (Szpunar-Krok *et al.*, 2021). Organic manure like vermicompost applied on rapeseed has a good effect on growth parameters and a change in fatty-acid profile in drought conditions. Application of vermiculost compost elevates the levels of palmitic and linoleic acid but decreases the levels of linolenic acid. It also increases the total yield of oil and the fatty-acid composition, indicating that organic fertilizers can increase the quantity and quality of rapeseed oil by controlling the production of fatty-acids and adapting plants to tolerate stress (Feizabadi *et al.*, 2020). Foliar fertilizers that have potassium (K), nitrogen (N), calcium (Ca) and boron (B) have been known to increase the fruit and oil production and quality in olives. Combined with conventional NPK fertilisation, these foliar treatments enhance oil production and composition as well as modifying the physicochemical properties of the product like acidity and phenol content. As a result, these approaches to fertilisation have an impact on quality factors of olive oil, by altering nutrient absorption and biochemical processes in the process of oil production (Esetlili *et al.*, 2024). Oil quality is also a major factor of fertiliser regimes, together with the environment. As an example, the ambient temperature at which seeds develop can have a significant impact on the oleic /linoleic acid ratio; the higher the ambient temperature is, the higher the concentration of oleic acids in the normally grown genotypes. Even though the main purpose of the study was to determine the impact of the environment, the findings indicate that the management of fertilizers in changing growing conditions might have to be modified to capture the influence of temperature on fatty-acid composition and quality of oil (Neto *et al.*, 2016)^[47]. The aim of bioengineering of soybean oil is to alter the fatty-

acid production in order to increase the oil production and develop the compositions more nutritionally and industrially advantageous. These changes affect agronomic features and emphasise the importance of using combined approaches to genetic, physiological, and fertilisation controls to optimize the yield of oil and the composition of fatty-acids (Song *et al.*, 2023).

Sulphur Fertilization and Oil Quality Enhancement

Sulphur fertilisation is very important in improving the quality of oil in oil crops of different types, because it affects the biochemical constituents, especially proteins, oil level as well as fatty acid composition. An example of this is the nutrition of sulphur in wheat and rapeseed; not only yield but also quality qualities have been found to be affected by the amount of sulphur used; glucosinolate levels have been found to increase when rapeseed seeds are fed on sulphur and so this would be useful in animal feed, but in large quantities would limit meal consumption. Nitrogen/sulphur interaction is also crucial with the balance of supply being critical to the maximization of both yield and seed quality hence the need of the integrated management of nutrients to improve the quality of oil (Zhao *et al.*, 1997)^[49].

Sulphur fertilisation of canola in the presence of sulphur deficiency conditions is found to enhance seed oil concentration greatly and also decreases the chlorophyll concentration that is favorable in the quality of oil. The effect is dependent on the sulphate solubility of the fertilizer source with the ammonium sulphate giving a stronger positive effect as compared to the sources of elemental sulphur. Moreover, the use of sulphur raises the level of sulphur in the seeds and occasionally lowers the level of nitrogen in the seeds thus showing an inverse correlation between the seed oil content and the protein content. These effects were stable in the framework of various tillage systems and proved the sulphate supply as a major determinant of canola seed quality and oil improvement (Grant *et al.*, 2003)^[37]. The research works on oilseed radish prove that the fertilisation by sulphur also influences not only productivity but also biochemical characteristics of the seeds (crude fat, protein content, fatty acid profiles). Sulphur elevates the polyunsaturated fatty acids (PUFAs) and tocopherol (vitamin E) and lowers the content of monounsaturated fatty acids (MUFAs). The changes improve the nutritional quality of oil, with the PUFAs and tocopherols having health benefits and oil stability. The topic of balanced nitrogen and sulphur application is of vital importance, as nitrogen has a tendency to enhance the amount of saturated and polyunsaturated fatty acids and some tocopherols, and sulphur positively influences the PUFA content and the level of antioxidant vitamins in the oilseed radish (Szatkowski *et al.*, 2024)^[53]. Sulphur fertilisation in the groundnut which is a legume oil crop significantly improves pod and kernel yield, oil content and oil yield hence improving the overall oil quality. The interaction of sulphur and zinc also enhances the sowing productivity and foams kernels of zinc as part of biofortification to nutrition. The best level of sulphur was found to be 40 kg/ha⁻¹ and this greatly enhanced the content of oil and proteins. This highlights the two-fold advantage of the sulphur fertilisation on agronomic productivity and the improvement of the nutritional value of oilseeds in soil with sulphur deficiency (Noman *et al.*, 2020)^[38]. Research on the sunflower crop brings out more findings that the application of sulphur enhances the content of oil, efficiency of nitrogen use (NUE), and yield in arid soils. Sulphur application at the rate of 60 kg/ha has a strong and positive effect on the presence of oil

contents with an increase of over 10% when polymer -coated urea is the nitrogen source. This interaction improves physiological development and oil production, and this would offer a good approach to sustainable production and improvement of oil quality in sunflower (Perveen *et al.*, 2021)^[35]. Sulphur-oxidising bacteria also play an important role in ensuring the maintenance of the sulphur levels in the soils to support the oil seed crops. These microorganisms increase nutrient cycling and uptake of sulphur by converting elemental sulphur to plant-available sulphate. This biological change contributes to the production of the sulphur based amino acids like methionine and cysteine that is essential towards protein synthesis and enzymatic activities connected with the production of oil. This microbial activity may be used to sustain oil yield and quality using biofertilisers to sustain the soil fertility (Joshi *et al.*, 2020)^[101].

Sulphur fertilisation, 45 kg/ha, raises seed yield (went up by approximately 53 percent) and yields of oil, as well as other growth measures, including plant height and pod count, in rapeseed (canola) significantly. Compared to the unfertilised controls, oil levels are increased by almost 3 percentage points. The higher amount of sulphur translates into the enhanced glucosinolate content of the seed, which is associated with the agrotechnical and nutritional characteristics of the crop, and thus the fertilisation with sulphur is very advantageous in appropriate agro-climatic conditions (Imran and Khan, 2017)^[36].

Adaptation strategies of nutrient management of oilseeds

The importance of combining metabolic, physiological, and ecological responses to various biotic and abiotic stresses continues to increase in nutrient-management adaptation strategies of oilseed crops. Metabolomic studies have indicated that primary and secondary metabolites in oilseeds include sesame, peanut, soybean, sunflower and rapeseed change dynamically in case of stress. Such metabolites can be used as physiological condition indicators, at the same time, as key information to develop resistant cultivar types that can endure nutrient stress and environmental changes, and thus, facilitate sustainable production of oilseeds (Kefale *et al.*, 2024)^[103]. Nutrient-management practices like the use of antioxidants along with the necessary nutrients are used to control drought and salinity stresses that problem the oil seed crops like canola. Such uses alleviate damage of physiological functions, such as photosynthesis, leaf and water condition, and membrane stability. It is possible to reduce the negative effects on the incorporation of compatible solutes and nutrients into management practices, which will maximize the oil productivity under the conditions of stressful climatic conditions (Sabagh *et al.*, 2019)^[104]. The soybean farming methodology involves integrated nutrient-management (INM) which entails organic amendments, phosphorus fertilisation, and bio-inoculants (phosphate-solubilising bacteria (PSB)). Field experiments have demonstrated that, optimum level of phosphorus and potassium fertilisation, utilisation of composts and PSB inoculation have a considerable effect on yield components, protein content and yield of oil in soybean under irrigated and dry land conditions. These measures maximize nutrient supply and absorption thus increasing productivity and profitability in a sustainable way (Amanullah *et al.*, 2025)^[105]. Soybean root microbiome symbiotic and associative interactions are known to enhance nutrient cycling and availability, which increases nitrogen fixation and replenishment of soil nutrients. The process of bioprospecting and application of useful endophytic bacterium is very essential in the management of nutrients sustainably

through enhanced nutrient uptake, growth, and resistance to diseases in plants. The contact of these microbial associations by the use of molecular and organic farming methods is a potential approach to enhance the efficiency of nutrient-use of oilseed crops (Ayilara *et al.*, 2022)^[9].

Northern Great Plains and no-till seeding No-till seeding is used in a system of adapting oilseason crops to nutrient management, which involves rotation with cereals, seeding-soil interactions, nutrient management with crop and environment, and optimization of nutrient inputs to crops. The practices also improve the incorporation of the oilseeds like canola, mustard and sunflower into the crops, enhance efficiency in resource-use and provide economic and environmental gains (Johnston *et al.*, 2002)^[107]. The management of phosphorus fertiliser, which is a foundation crop to most of the oilseeds i.e. canola and rapeseed, has developed to adopt the concept of 4R which includes right source, right rate, right time and right place in order to maximise performance. Among new technologies are placing ammonium phosphate next to the seed at sowing and time keeping phosphate application and crop uptake, to enhance yields, sustainability and environmental protection, especially in areas like the northern Great Plains (Grant and Flaten, 2019)^[108].

Climate-Smart Nutrient Management Practices

The climate-intelligent nutrient management production in oilseed farming is aimed to boost agricultural productivity and enhance soil health and resilience to climate change, at the same time minimizing greenhouse gas emissions. These measures form a critical component of Climate-Smart Agriculture (CSA) which incorporates sustainable agricultural methods such as precision nutrient management to maximize the use of fertilizers, facilitate the retention of carbon in the soil and adjust to changing climatic conditions. Precision nutrient management in oilseed systems involves the site-specific application of the essential nutrients, which reduces the losses of the nutrients and the environmental effects and conserves or enhances the crop yield and quality (Safdar *et al.*, 2024; Kabato *et al.*, 2025). One of the main goals of climate-smart nutrient management of oilseeds is to improve the nitrogen use efficiency (NUE). The average NUE in the world is about 55 per cent, which indicates that the improvement opportunities are significant. Precision nitrogen fertiliser application combined with organic amendments and cover crops as well as biochar can be used as integrative approaches to increase nutrient retention and nutrient availability in the soil and reduce nitrogen loss through leaching and emission of nitrous oxide, a strong greenhouse gas. These practices will help in carbon sequestration and increasing the general soil fertility, which will keep oilseeds growing over more unpredictable climate conditions (Kabato *et al.*, 2025; Bai *et al.*, 2019). The CSA practices that are particularly useful in oil seed systems are cover cropping and the use of biochar. Cover crop boosts the concentration of organic carbon in soils, improves the soil structure, prevents soil erosion, and biochar additions significantly enhance the soil carbon storage and nutrient retention potential. Empirical studies have shown that biochar can increase the amount of organic carbon in soil up to 39 percent and, therefore, it is a powerful tool in climate-change mitigation and the management of nutrients. Such amendments promote favourable soil conditions that improve water retention and nutrient availability that are critical in oilseeds growth and yield under drought-prone and degraded soils (Bai *et al.*, 2019). Introduction of the advanced technologies in managing the nutrient processes is also imperative in optimising of inputs in growing oilseeds. Technology based on soil and solution

nutrient sensors, which include IoT-based sensors, electrochemical and optical sensors, and AI- based predictive tools, are used to monitor nutrient state in real-time. This will allow the accurate application of nutrients based on demand of the crop and the availability of nutrients in the soil, therefore minimising the over-use of fertiliser and pollution of the environment. These methods of precision-agriculture increase the sustainability of oil production and the efficiency of the use of resources (Reza *et al.*, 2025). Further, soil health and the long-term productivity of oilseed systems are enhanced further through the use of crop diversification, residue management, and zero-tillage or low-tillage of climate-smart nutrient management. These practices reduce soil disturbance and maintain the protective soil cover and recycle the nutrients efficiently and thus increase the resilience of the soil to climate-induced stresses like drought and unpredictable rainfall. They also help decrease the number of carbon footprints of oilseed farming because they reduce the amount of greenhouse-gas emissions related to soil management (Bhanuwanti *et al.*, 2024). In response to the biotic and abiotic stress-induced effects which reduce oilseed productivity in changing agro- climates, genomic and transcriptomic technologies are being added to nutrient management strategies to develop stress-tolerant varieties which efficiently use nutrients in such unfavorable environments. Hypermodern breeding and genome-editing, which can be an example of CRISPR/Cas9, will focus on metabolic pathways of nutrient uptake and stress resilience, which will help to maintain production in a climate-wise system (Kaushal *et al.*, 2025). To realize the effective and extensive application of climate-smart nutrient management in the oilseeds, there is a need to have enabling policies, financial incentives, and capacity-building programs. The farmers need support in knowledge transfer and the availability of affordable technologies, which are inclusive of their agro-ecological and socio-economic conditions. The incorporation of ecosystem services (e.g., the prevention of soil erosion and the improvement of habitat quality) into the evaluation of the nutrient management practices also supports the idea of the CSA adoption by highlighting the environmental benefits that are not directly linked to crop yields (Neupane *et al.*, 2024; Souza *et al.*, 2025).

Use of Organic Amendments to Buffer Climate Stress

The organic amendments are very instrumental in buffering the

stresses caused by climate in the oil seed crops, by making the crops more tolerant to unfavorable conditions like salinity and drought. These amendments such as biochar, vermicompost, green manure and farmyard manure increase the nutrient content in the soil and also augment physiological activities of the plants. To illustrate, the use of organic fertilizers in soybean reduces salinity stress, which affects the electrolyte leakage, maintains the nutrient balance, and improves antioxidant activity that in turn saved the growth and yields of the plants in salty environments (Sabagh *et al.*, 2019) ^[104].

In heat-stress environments, which become more and more common as a result of climate change, the oil seed crops lose their biomass and have a different physiological appearance, which is essential to oil production. Organic amendments lead to a state of heat-stress tolerance due to the enhancement of soil health and microbial activity which supports the mechanism of plant resilience like the maintenance of membrane integrity, the activation of heat-shock proteins, as well as antioxidant and compatible solutes accumulation. The ultimate effect of these interactions is stabilization of the oil yield and quality of crops like soybean, sunflower, and canola (Ahmad *et al.*, 2021) ^[73, 32]. Abiotic stresses that severely affect the productivity of oil seed crops in the various parts of the world include soil salinity and heavy-metal pollution. Organic amendments serve the benefit of minimizing bioavailability of the toxic metals and salt ions by converting it into less soluble forms through precipitation and immobilization of the soil. This lowers metal uptake leading to minimization of oxidative damage and enzymatic disruption effects in plants hence enhancing tolerance and maintaining growth. Farmyard manure, and biochar are other amendments that enhance beneficial microbial communities that help to alleviate metal toxicity and enhance nutrient uptake by crops like rapeseed, mustard and sunflower (Rizwan *et al.*, 2017) ^[112]. The organic amendments increase the resistance of plants to salinity through changes in ionic homeostasis, photosynthetic potential, and antioxidant protection. These amendments increase the capacity of the plant to control the sodium and potassium ions and minimize the oxidative stress, which eventually increases growth and yield in oilseeds crops in salty environment. Specifically, vermicompost and bio-fertilizers were found to enhance salt tolerance by maintaining the levels of chlorophyll and preventing cellular membranes against salt-induced damages (Hoque *et al.*, 2022) ^[113].

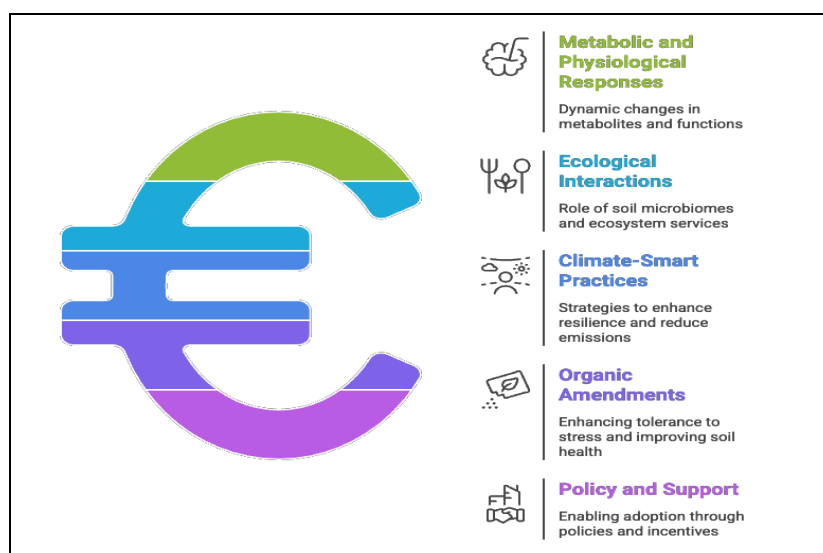


Fig 4: Comprehensive Nutrient Management for Oilseeds

Moreover, organic amendments result in positive changes in soil microbial communities, thus promoting climate-sensitive agriculture activities. Such changes in microbes lead to the reduced emission of greenhouse-gases by soil and promote the growth of microorganisms that promote nutrient cycling and growth of crops. These types of microbiome modulation make it easier to sustainably produce oilseeds by enhancing carbon sequestration in the soil and reducing the reliance on mineral fertilizers (Brenzinger *et al.*, 2021) ^[114].

Moreover, organic amendments improve symbiotic relationship between oil seed crops and arbuscular mycorrhizal fungi (AMF) thus increasing nutrient absorption and tolerance to stress. The nutrient acquisition mechanisms mediated by AMF, coupled with the use of organic amendments, make the environment more resistant to the environmental stresses like drought and salinity of soil. It is based on this symbiosis that plant growth fitness and yield stability occur in oilseed crops when exposed to climatic stresses (Slimani *et al.*, 2024) ^[115].

Table 1: Effect of Sulphur on oil content and seed yield of different crops.

Crop(common name)	Botanical name	Effect of sulphur	Oil content(%)	Seed yield	References
Soybean	<i>Glycine max</i> (L.) Merr.	Treated (30–40 kg S ha ⁻¹): Improved nodulation, chlorophyll synthesis, and N-use efficiency; enhanced seed filling. Control (0S): Reduced growth and lower productivity under S-deficient soils.	Treated: 19.8–20.6% Control: 18.1–18.9%	Treated: 2.45–2.70 t ha ⁻¹ Control: 2.05–2.20 t ha ⁻¹	Glowacka <i>et al.</i> , 2023 ^[60]
Groundnut	<i>Arachis hypogaea</i> L.	Treated (40–60 kg S ha ⁻¹): Enhanced kernel development, nutrient uptake and quality. Control: Poor kernel filling and reduced oil quality.	Treated: 47.2–49.0% Control: 44.5–45.8%	Treated: 2.30–2.60 t ha ⁻¹ Control: 1.85–2.00 t ha ⁻¹	Yadav <i>et al.</i> , 2020 ^[93]
Indian mustard	<i>Brassica juncea</i> (L.) Czern. & Coss.	Treated (30–60 kg S ha ⁻¹): Improved growth, silique number and seed weight. Control: Severe S deficiency symptoms and yield reduction.	Treated: 39.5–41.2% Control: 36.8–37.5%	Treated: 1.80–2.10 t ha ⁻¹ Control: 1.40–1.55 t ha ⁻¹	Rana <i>et al.</i> , 2020 ^[90]
Sunflower	<i>Helianthus annuus</i> L.	Treated (20–40 kg S ha ⁻¹): Increased head diameter, seed filling and harvest index. Control: Reduced achene development.	Treated: 40.2–42.5% Control: 37.5–38.8%	Treated: 1.75–2.00 t ha ⁻¹ Control: 1.40–1.55 t ha ⁻¹	Asif <i>et al.</i> , 2023 ^[87]
Sesame	<i>Sesamum indicum</i> L.	Treated (30–60 kg S ha ⁻¹): Increased capsule number and seed quality. Control: Lower capsule formation and oil content.	Treated: 49.0–51.5% Control: 46.2–47.8%	Treated: 0.95–1.20 t ha ⁻¹ Control: 0.70–0.85 t ha ⁻¹	Venkatesh <i>et al.</i> , 2021
Safflower	<i>Carthamus tinctorius</i> L.	Treated (25–50 kg S ha ⁻¹): Improved fatty acid profile and oil accumulation. Control: Reduced oil biosynthesis.	Treated: 32.5–34.8% Control: 29.8–30.5%	Treated: 1.20–1.45 t ha ⁻¹ Control: 0.95–1.05 t ha ⁻¹	Sabaghnia <i>et al.</i> , 2024 ^[91]
Niger	<i>Guizotia abyssinica</i> (L.f.) Cass.	Treated (20–30 kg S ha ⁻¹): Improved seed set and oil yield. Control: Lower biomass and seed production.	Treated: 38.5–39.8% Control: 35.0–36.2%	Treated: 0.65–0.80 t ha ⁻¹ Control: 0.50–0.58 t ha ⁻¹	Praveen <i>et al.</i> , 2020 ^[89]
Castor	<i>Ricinus communis</i> L.	Treated (40–60 kg S ha ⁻¹): Enhanced capsule number and oil recovery. Control: Reduced spike length and oil yield.	Treated: 46.0–48.5% Control: 42.5–43.8%	Treated: 1.90–2.20 t ha ⁻¹ Control: 1.50–1.65 t ha ⁻¹	Mukhtar <i>et al.</i> , 2022 ^[88]
Linseed	<i>Linum usitatissimum</i> L.	Treated (20–40 kg S ha ⁻¹): Improved capsule formation and seed weight.	Treated: 39.5–41.0% Control: 36.8–37.9%	Treated: 1.10–1.35 t ha ⁻¹ Control: 0.85–0.95 t ha ⁻¹	Solo <i>et al.</i> , 2021 ^[92]

Conclusion

Sulfur is a vital nutrient to oilseeds crops, and it is very crucial in the growth of plants, metabolism, and seed quality development. Sustained supply of sulphur is known to stimulate major physiological and biochemical functions including protein synthesis, enzyme activity, and the development of sulphur amino acids such as cysteine and methionine. The processes eventually boost the seed production, oil-level structure of fatty acids, and total crop productivity. Sulfur deficiency has also become frequent in most agricultural soils and this factor impacts negatively on development of plants, the quality of oil and efficiency of nutrient use. Thus, the balanced sulfur fertilization is required to sustain maximum crop performance. The sources of organic nutrients (farmyard manure, vermicompost and poultry manure) also contribute to the enhancement of oil seed productivity by increasing the soil fertility, microbial activities, and nutrient levels. Organic amendments coupled with the incorporation of sulfur fertilization are sustainable in the management of soils, enhance the soil structure and enhance the efficiency of nutrient-use. Integrated nutrient-management practices are also beneficial in enhancing crop production and the quality of oil, as well as long-term soil health. Climate-smart nutrient-management practices are required in the climate change scenario and growing pressure on agro systems. By combining sulfur fertilizers, organic amendments, accurate nutrient control and enhancement of the crop varieties, the resilience, production, and sustainability of oilseed production systems can be improved in different agro-ecological areas.

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