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Impact of integrated nutrient management in boosting productivity of sunflower (*Helianthus annuus* L.): A comprehensive review

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Abstract

Sunflower (*Helianthus annuus* L.) is an oilseed crop of importance globally due to its high oil quality and wide adaptability to agro-ecological conditions; however, sunflower production in India is considerably lower than the world average due to declining soil fertility, nutrient imbalance and long-term dependence on mineral fertilizers. INM has emerged as one of the major role for improving productivity and maintaining soil health by combining inorganic fertilizers with organic manures and bio fertilizers in a strategic manner. This review is a critical synthesis of the world and Indian studies on the role of INM in satisfying the macro, secondary, and micronutrient needs of sunflowers and its effects on growth dynamics, yield characteristics, seed output, oil content, oil yield, and economic performances. Long-term and recent field studies all support the evidence that balanced application of FYM, vermicomposting, green manures, bio-fertilizers, sulfur, and micronutrients with recommended levels of fertilizers enhances nutrient use efficiency, optimal biomass partitioning, oil production, and physical, chemical, and biological quality of soils. The review defines INM as the basis for the sustainable production of sunflowers and points out areas of research priority for nutrient strategies in various agro-climatic areas.

Keywords: Sunflower, Integrated Nutrient Management (INM), oil yield, soil fertility, biofertilizers

Introduction

Sunflower (*Helianthus annuus* L.) is a short-cycle, day neutral oilseed crop that adapts well to various soils and climatic conditions. It ranks as the third most common oilseed crop globally, following soybean and groundnut. This crop is recognized for producing high-quality edible oil, which contains significant amounts of linoleic acid and oleic acid. Sunflower oil is particularly popular due to its light color, high concentration of polyunsaturated fatty acids, and absence of linolenic acid, all of which contribute positively to human health (GRDC, 2017). Sunflower has an area of approximately 29.8 million ha and a yield of approximately 55.23 million tonnes and average yield of 1.85 t ha⁻¹ (Dalima & Lal, 2025) ^[13]. Global sunflower production during 2025-2026 is projected to remain concentrated among a few major producing countries, with Russia leading global production by contributing about 32% (17.5 million metric tons), followed by Ukraine with 20% (11 million metric tons). The European Union, Argentina, Kazakhstan, and China also contribute substantially to global sunflower output. India ranks 14th among sunflower-producing countries, with comparatively lower production levels than the major global producers.

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Table 1: Recent Global Sunflower Production Statistics (2025-26)

Country/Region	% of Global Production	Total Production (Metric tons)
Russia	32%	17.5 Million
Ukraine	20%	11.0 Million
European Union	16%	8.66 Million
Argentina	13%	7.0 Million
Kazakhstan	5%	2.46 Million
China	4%	2.2 Million
Turkey	2%	1.25 Million
United States	2%	1.05 Million
Moldova	2%	851,000
South Africa	1%	780,000

Source: <https://www.fas.usda.gov/data/production/2224000>

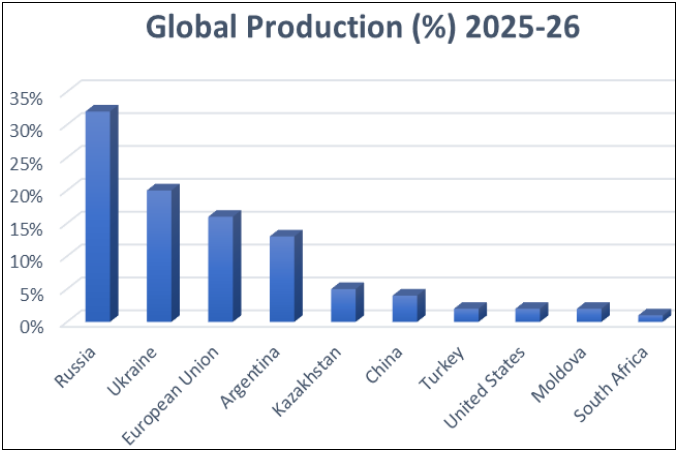


Fig 1: Global Sunflower Production trends (2025-26)

Table 2: Sunflower Production Trend in India

Year	Production (Thousand Tonnes)
2008 (Peak)	1357
2023	219
2024	177

Source: FAOSTAT database compiled by Helgi Library (2026 update).

Table 3: Recent Global Sunflower Oil Production

Year	Global Sunflower Oil Production (Million Tonnes)
2023-24	22.13
2024-25	20.08

Despite the crop’s importance as a high-quality edible oil source, sunflower production in India has declined considerably over the past decades due to nutrient depletion, deterioration of soil fertility, and imbalanced fertilizer use. These challenges highlight the growing importance of Integrated Nutrient Management (INM) practices for enhancing nutrient use efficiency, sustaining soil health, and improving sunflower productivity and oil yield under diverse agro-climatic conditions. The continuous use of inorganic fertilizers has led to the deterioration of soil quality, decreased fertilizer efficiency, and reduced yields (Gupta and Singh, 2025) [24]. Organic manures like farmyard manure, green manure, poultry manure and vermicomposting improve soil structure, water holding capacity, microbial activities and nutrient availability and thus increase the fertility of the soil (Gupta and Singh, 2025) [24]. Integrated Nutrient Management (INM), a blend of organic, inorganic and biological sources of nutrients, is the answer to these problems which is sustainable. INM promotes recycling of organic wastes, improves soil health, maintains balanced supply of nutrients, and increases crop productivity without adverse

impacts on soil quality (Chejara *et al.*, 2021) [4]. Sunflower productivity is limited by inadequate soil fertility and an uneven nutrient application. According to Gupta & Singh (2025) [24] continual use of inorganic fertilizers has led to reduction in soil quality, efficiency and yield. Hence, organic manures including farmyard manure, green manure, chicken manure, and vermicomposting boost the fertility of the soil by improving soil structure, water holding capacity, microbial activity, and nutrient availability (Gupta and Singh, 2025) [24]. To solve these problems, the solution lies in the use of sustainable Integrated Nutrient Management (INM) which combines organic, inorganic and biological sources of nutrients. Chejara *et al.* (2021) [4] reported that INM enhances organic waste recycling improves soil health, balanced supply of nutrients and increased crop output without affecting soil quality. This review summarizes the literature that exists on the nutrient requirements of sunflower and analyzes the effects of INM on growth, yield, oil quality, soil characteristics, and nutrient-use efficiency and importance of integrated nutrient management in optimizing these factors, ultimately leading to enhanced productivity and sustainability in sunflower cultivation. By understanding the specific nutrient needs and their interactions with various agronomic practices, farmers can make informed decisions to improve crop performance.

Integrated Nutrient Management - Concept and Principles

Integrated Nutrient Management is a term used to refer the wise and controlled application of chemical fertilisers, organic manures (farmyard Manure, Compost, vermicompost, green manure), crop residues and biofertilisers to provide the required nutrients to plants without compromising soil fertility. INM is expected to maximise nutrient supplies using minimum effective doses of fertilisers and increase soil organic carbon and microbial activity (Chejara *et al.*,2021) [4]. Organic inputs serve as stores of nutrients and a source of energy to soil microorganisms enhancing the soil structure, moisture retention and cation exchange capacity. Inorganic fertilisers, on the contrary, provide easily accessible nutrients that guarantee instant crop reaction. Phosphate-solubilizing bacteria (PSB), vesicular-arbuscular mycorrhiza (VAM) and biofertilisers including Azotobacter also increase the nutrient availability and root growth. It has been observed that INM adoption has enhanced improvement in crop development, water-use efficiency, economies returns and quality of products relative to only using chemicals to fertilise the soil (Soni & Nachiketa, 2023) [3].

Nutrient Requirements of Sunflower

Major nutrients (N, P, K)

Sunflower is a nutrient exhaustive crop which requires large quantities of nitrogen, phosphorus and potassium in the soil. According to the Australian GRDC guide on Sunflower Nutrition, the nutrient that is absorbed in the highest amount is nitrogen; a crop with a yield of 1 t ha⁻¹ absorbs approximately 40 kg N ha⁻¹ (26 kg in seed and 14 kg in stover). There is an increase in the total N uptake to 95 kg ha⁻¹ at 2.5 t ha⁻¹ yield. The second most limiting nutrient is phosphorus where 1 t ha⁻¹ of seed + stover consumes 5 kg P ha⁻¹ and 2.5 t ha⁻¹ consumes 12 kg P ha⁻¹. There is increased potassium loss; 1 t ha⁻¹ harvest losses 30 kg K ha⁻¹ (8 kg in seed and 22 kg in stover) and 2.5 t ha⁻¹ losses 73 kg K ha⁻¹ (Grains Research & Development Corporation [GRDC], 2017) [6]. Nitrogen plays a vital role in growth of the plant; however, too much N decreases the oil production, and too little N reduces the yields. Phosphorus

increases root development, early maturation and seed production, sufficient P and zinc is especially essential in the absence of arbuscular mycorrhizal fungi. Potassium is useful to regulate water relations, enzyme activation.

Secondary nutrients (S, Ca, Mg)

The fourth nutrient that is required is Sulphur. 1 t ha⁻¹ crop has a 4.7 kg S ha⁻¹ removal, and a 2.5 t ha⁻¹ crop has a 12 kg S ha⁻¹ removal (GRDC, 2017). Sulphur has an effect on the production of proteins and oils; in sunflower, a report revealed that an average increase of 3.8% in the level of oil was achieved as a result of sulphur fertilisation (Thakur *et al.*, 2021) [17]. Lack of it leads to low oil content, pale leaves and less filling of seeds. The levels of calcium and magnesium are moderate, most of the soils provide sufficient levels of these nutrients, though in some cases deficiency can be witnessed in acidic or the sandy soils. The pH should be maintained at the neutral level (pH 6.5-7.5); the sunflowers are susceptible to acidic aluminium poisoning on soils.

Micronutrients (B, Zn, Fe and Mn)

Boron demand by sunflower is comparatively high. Boron deficiency is not very common in alkaline soils but can exist in case of rapid growth or moisture stress; the symptoms are malformed upper leaves, necrotic growing points, inaccurate seed set and lodging (GRDC, 2017). Adequate boron may be supplied through either application of borax to the soil (such as 1-2 kg ha⁻¹ borax) or spraying the plant. Another important micronutrient is zinc; the reaction is typical on alkaline soils that are heavy. It is proposed that foliar sprays of zinc sulfate or banded at sowing be used (GRDC, 2017). Iron and manganese are needed in chlorophyll synthesis and photosynthesis; it is not very common but can happen on calcareous soils. Nutrient uptake and development of roots can be promoted through foliar feeding of nutrients (Ramesh *et al.*, 2019) [13].

INM Effect on Growth parameters of Sunflower

Integrated nutrient management has a great impact on the vegetative growth parameters including the plant height, the leaf area index (LAI), the accumulation of dry matter and the development of roots.

Plant height

An experiment was conducted in Dharwad in 2006-07 kharif season and the finding revealed that the taller plants were obtained on the application of farmyard manure (8 t ha⁻¹) with the recommended dose of fertiliser (RDF: 62.5 kg N, 75 kg P₂O₅ and 62.5 kg K₂O ha⁻¹). Similarly, the combined use of humic acid granules (12.5 kg ha⁻¹) and RDF significantly improved height of plants and LAI. Fertilisation with Sulphur at 60 kg ha⁻¹ gave significant contribution to the height of the plant in comparison to fertilisation at 20 or 40 kg ha⁻¹. 30 kg S ha⁻¹ and sulphur oxidising biofertiliser generated plant height of 195 cm and LAI of 1.48 at the harvest (Mahapatra *et al.*, 2020) [8]. In a micronutrient management experiment in hybrid sunflower, the foliar administration of a mixture of micronutrients (250 G/ha⁻¹ at 25 and 45 days post-sowing) and 150% RDF (60 N: 90 P₂O₅: 60 K₂O kg ha⁻¹) led to 64.9 cm, 145.3 cm and 166.2 cm at harvest, which were higher than the control (Ramesh *et al.*, 2019) [13]. These findings indicate that vegetative growth increases with the incorporation of organics and micronutrients with fertilisers.

Leaf area index and number of leaf leaves

FYM (8 t ha⁻¹) and RDF has enhanced the quantity of leaves (19-33 leaves per plant) and LAI relative to the control. Sulphur level 60 kg ha⁻¹ enhanced LAI and leaf area as compared to lower levels (Mahapatra *et al.*, 2020) [8]. It was found that the highest LAI and dry matter accumulation was at 30 kg S ha⁻¹. RDF together with humic acid granules also enhanced LAI and stem girth (Mahapatra *et al.*, 2020) [8]. The micronutrient foliar feeding used to provide nutrients below 150% RDF resulted in increased number of full seeds per capitulum and photosynthetic area (Ramesh *et al.*, 2019) [13].

Dry matter accumulation

INM also leads to increased dry matter accumulation as a result of increased nutrient availability and photosynthesis. FYM 8 t ha⁻¹ + RDF improved DMA relative to control, in Dharwad (Mahapatra *et al.*, 2020) [8]. FYM 20 t ha⁻¹ + 120 kg N ha⁻¹ + 60 kg S ha⁻¹ had a better output of DMA and LAI than the other treatments (Rasool *et al.*, 2013) [14]. The use of 225 kg N ha⁻¹ + sufficient potassium boosted the height of the plants (140.5 cm) and yield in the form of dry matter (Mahapatra *et al.*, 2020) [8]. Applications of foliar micronutrients that were less than 150 per cent of RDF increased accumulation of biomass and higher harvest index (Ramesh *et al.*, 2019) [13].

Root development and the absorption of miscellaneous nutrients

Even though not a lot of studies directly measured root parameters, integrated nutrient management helped improve root growth by improving soil structure and microbial activity. Foliar sprays of micronutrients lead to nutrient uptake by the root because it induces root development (Ramesh *et al.*, 2019) [13]. Combination experiments involving the use of vermicompost with chemical fertilisers and adequate irrigation enhanced the concentration and uptake of nutrients in seeds and stover as well as enhanced residual organic C, available P and K in soil (Puste *et al.*, 2013) [12]. These findings indicate that INM enhances stronger root systems and efficient utilisation of nutrients.

Influence of INM on Yield Attributes of Sunflower

Head diameter

The balanced supply of nutrients has a positive effect on the head or capitulum diameter. Use of 50 kg S ha⁻¹ gave capitulum diameter of 18 cm and larger number of seeds per head than the 25 kg S ha⁻¹ or control (Mahapatra *et al.*, 2020) [8]. The combination of humic acid (12.5 kg ha⁻¹) as a micro-nutrient foliar feeding and RDF was used to reach head diameter (20.7 cm). 150 percent RDF was used to reach capitulum diameter (20.85 cm) (Ramesh *et al.*, 2019) [13].

Number of seeds per head

An important determinant of yield is achenes filled per capitulum. The resulting FYM 20 t ha⁻¹ generated 364 filled achenes per head and yield of oil 1.02 t ha⁻¹. Banerjee *et al.*, (2012) concluded that N₁₀₀P₅₀K₅₀ fertilisation was followed by about ~1129 seeds per capitulum, which was equivalent to 100% RDF and much higher than the fertiliser application by farmers. Foliar micronutrient management at rates below 150% RDF registered 1040 seeds per head (925 full and 88.9% filled). Tahir *et al.*, (2014) [15] study revealed that the use of 4 kg B ha⁻¹ gave 1183 seed per head and the greatest seed and biological yield (Mahapatra *et al.*, 2020) [7].

100-seed weight

Test weight has size and density of the seed. FYM 7.5 t ha⁻¹ + 100 Percent RDF increased seed weight (100 percent) to 49.26 g in comparison to control (36.62 g). Use of 50 kg S ha⁻¹ resulted in the weight of 1000 seeds to be 42.8 g, and the weight of test with the use of humic acid granules (12.5 kg ha⁻¹) and RDF was 51.9 g (Mahapatra *et al.*, 2020) [7]. Micro-nutrient foliar spray at a concentration of less than 150 percent RDF produced a 100-weight measured at 5.9 g.

Seed yield Biological yield

Combined nutrient management has a huge improvement in seed and biomass yields. According to research summarised by Mahapatra *et al.*, (2020) seed and oil yield were 2.51 t ha⁻¹ and 1.02 t ha⁻¹ respectively at 500 FYM 20 t ha⁻¹ + 120 kg N ha⁻¹ + 60 kg S ha⁻¹. According to Akbari *et al.*, (2013) [1] the highest seed yield (2.823 t ha⁻¹), biological yield (9.92 t ha⁻¹) and oil yield (1.276 t ha⁻¹) was recorded with 50% N + 50% FYM in Iran, whereas the highest oil content (49.4%) was recorded in 100% FYM. S ha 30 kg S ha⁻¹ on west Indian soil raised seed yield to 2.048 t ha⁻¹ versus 1.732 t ha⁻¹ in the absence of sulphur (Mahapatra *et al.*, 2020). It was more effective with treatment at 150% RDF + humic acid grain (higher seed yield 1.875 t ha⁻¹ and harvest index 28.7%). The 2018-19 summer experiment seed yield (2.59 ha⁻¹) and oil yield (1.114 t ha⁻¹) at soil-test based fertiliser recommendation (60:100:60 N:P₂O₅: K₂O kg ha⁻¹) plus FYM 5 t ha⁻¹ were better than those at RDF alone.

Harvest index

Harvest index (HI) is the efficiency of allocation of biomass to seeds. HI was better with 50 kg S ha⁻¹ than 25 kg S ha⁻¹ (Mahapatra *et al.*, 2020) [7]. Granules of humic acid containing RDF took a HI of 28.7%. Spraying foliar with 150% or below RDF resulted in a harvest index of 38.2%, which was higher than the one that was controlled (Ramesh *et al.*, 2019) [13]. These findings demonstrate that INM has the ability of enhancing HI with respect to seed yield and biomass production.

Other current studies discoveries

The recent researches that were published after 2023 help to expand our knowledge of INM strategies and their relations with various management variables. Two years field experiment in eastern Uttar Pradesh compared different organic manures and combinations of fertilisers on sunflower in alluvial soils. Green leaf manure at 20 t ha⁻¹ + 50% of recommended dose of fertiliser (RDF) yielded the tallest plants (178.03 cm), largest head diameter (20.08 cm), highest head weight (413.72 g) and the highest number of seeds per head (704), yielded the best results in terms of seed yield per head (37.57 g), test weight (5.35 g) and biological yield (64.94 q ha⁻¹). Growth in green leaf manure to 40 t ha⁻¹ increased the root volume (70.94 cm³), which indicates the advantage of high biomass inputs (Gupta & Singh, 2025) [24].

The research determined twelve nutrient management treatments in a rabi experiment on heavy clay soils in Punjab. The mix of 75 per cent RDF + 5 t ha⁻¹ farmyard manure + 2t ha⁻¹ vermicompost + seed inoculation with *Azotobacter* and phosphate-solubilizing bacteria (PSB) provided the most optimal growth parameters (plant height 151.18 cm, LAI 3.17) and gave the highest seed yield (26.28 q ha⁻¹ or 2.63 t ha⁻¹) and straw yield and harvest index; it also provided the highest net return (₹ 126,710 ha⁻¹) and benefit-cost ratio of 3.37. The authors put the high performance to be the synergies of organic manures, mineral fertilisers and biofertilisers that enhanced nutrient

availability and plant vigor (Dalima & Lal, 2025) [13]. The hybrid COSFH spacing of 60 × 30 cm test indicated that the INM treatment with 75 percent of the recommended nitrogen (RDN) + 100 percent phosphorus + 12.5 percent N using vermicompost + 12.5 percent N using poultry manure and 45 kg S ha⁻¹ (B5) had the highest seed yield (2441.74 kg ha⁻¹) compared with the control; it was observed that there was an interaction of genotype selection and plant (Rao *et al.*, 2025).

Another combined practice is a combination of nutrient management and apiary. Sunflower plots that were integrated with bee hives close to Chennai were applied with 100% of the RDF and vermicompost, *Azospirillum* and *Phosphobacteria*. This mixture had a very great influence of raising the height of the plant, the dry matter production, the number of seeds per head and the percentage of seed filling as compared to the sunflower alone. The researchers observed that the area and production of the sunflower in India have reduced drastically (1.63 M ha in 2002-03 to 0.228 M ha in recent years) and that national productivity (930 kg ha⁻¹) is lower than the global average; they concluded that the incorporation of organic manure, biofertiliser and apiculture control are essential in enhancing pollination, germination and seed filling (Jebarathnam, 2024) [25].

INM Effect of INM on Oil Content and Oil Yield Influence of INM on seed oil percentage

The balance of the nutrients is sensitive to the oil content. All the excess nitrogen will lower the percentage of oil, whereas sufficient levels of sulphur and micronutrients will raise it. A study revealed that application of 60 kg S ha⁻¹ was found to increase the oil content by 3% and yield by 13.6% compared to 30 kg S ha⁻¹ (2009 season), whereas in the year 2010, the study indicated an increase of 2.4% and 10% respectively (Mahapatra *et al.*, 2020) [7]. Akbari *et al.* observed the highest oil content (49.4%) when using 100 percent of FYM. The oil contained 39% after the application of 30 kg S ha⁻¹ and sulphur-oxidising biofertiliser (Pujari *et al.*, 2017). Foliar micronutrient management at 150% of RDF at 43% of oil content. These results have indicated the significance of adding sulphur and micronutrients to INM to improve the percentage of oil (Ramesh *et al.*, 2019) [13].

Role of nitrogen, sulphur and micronutrients in oil synthesis

Nitrogen is needed in the production of proteins but too much N leads to excessive vegetative growth and low oil content since carbon is used in the production of proteins (GRDC, 2017). Balanced nitrogen (50-60 kg ha⁻¹) mixed with FYM and micronutrients increase the production of oil. Sulphur is essential in metabolism of proteins and oils; it is necessary to cysteine and methionine and oil-forming enzymes. The mean growth in the oil content as a result of sulfur fertilisation in the oilseeds is 3.8% in the case of sunflower (Thakur *et al.*, 2021) [17]. Boron is engaged in the transport of sugars and in cell wall formation; insufficiency of this nutrient decreases the number of seeds and the oil content in the seeds. Zinc is also required to activate enzymes and pollen; zinc deficiency can result in the production of empty seeds and oil of low quality (GRDC, 2017). High NPK regimes which practice foliar application of micronutrients (Fe, Mn, Zn, B) enhance oil content and oil yield.

Effect of organic manures and bio fertilisers on oil quality

Organic manures like FYM and vermicompost help in improving oil quality by providing gradual release nutrients and enhancing the soil microbiology. The study revealed that 50% N

+ 50% FYM produced the highest yield of oil ($1275.9 \text{ kg ha}^{-1}$) whereas 100% FYM produced the highest oil percentage. FYM 7.5 t ha^{-1} at 100 percent RDF improved test weight and oil content Akbari *et al.*, (2011) ^[1]. Sulphur oxidising bacteria are microbial inoculants to enhance the availability of sulphur and the oil content (e.g. 39% oil with S + biofertiliser). Biofertilisers such as Azotobacter and PSB also aid in fixing atmospheric nitrogen and solubilizing phosphorus and hence lead to improved oil quality and nutrient uptake (Mahapatra *et al.*, 2020) ^[7].

Oil yield as influenced by INM practices

One economic characteristic is the yield of oil (seed yield $\times$ oil percentage). In Iran, 50% N + 50% FYM yielded 1.276 t ha^{-1} oil (Mahapatra *et al.*, 2020) ^[7]. STBFR + FYM (2.59 t ha^{-1} seed yield and 43 per cent oil) gave 1.114 t ha^{-1} oil in India. The foliar RDF 150% micronutrient treated foliar produced 0.944 t ha^{-1} oil (Ramesh *et al.*, 2019) ^[13]. These outcomes highlight the importance of balanced forms of nutrient regimes that involve organics and micronutrients in order to achieve optimum yield of oil.

Recent discoveries of sulphur, zinc and organic amendments

Recent research also emphasizes the need to manage micronutrients and organic amendments of sunflower. A field experiment was carried out in Pakistan over a period of two years to investigate four levels of sulphur (0, 20, 30 and 40 kg ha^{-1}) and zinc (0, 10, 15 and 20 kg ha^{-1}) on two hybrids. The 40 kg S and 20 kg Zn treatments increased a height of the plants by 7-8 per cent flowering and maturity and seed yield by 68 and 33 per cent respectively than that of the unfertilized control. Less drastic reductions in the rates (30 kg S and 15 kg Zn) also enhanced growth and yield and the dwarf hybrid PARSUN-3 was more responsive. These results show that the S and Zn increase the achene production and oil composition (Hussain *et al.*, 2025) ^[20].

The other experiment in coastal char land of Bangladesh had a comparison between the fertiliser recommendations as recommended by soil testing and that of integrated plant nutrient systems (IPNS) that is a mixture between inorganic fertiliser and organic sources. Addition of 1.5 t ha^{-1} vermicompost with IPNS enhanced the height of plant and head diameter, seeds per head and seed yield ($2.06\text{-}2.23 \text{ t ha}^{-1}$ depending on site) significantly in relation to the absolute control which yielded only $1.021\text{-}1.10 \text{ t ha}^{-1}$. The therapy also had the greatest net profit, and benefit-cost ratio, which proved the economic benefits of INM (Farhad *et al.*, 2020) ^[19].

Seventeen years of continuous research in India indicates that inferior quantities of organic manures in combination with fertilisers maintain yields and enhance soil carbon. Seed yield (1.88 t ha^{-1}) and straw yield (3.92 t ha^{-1}) and organic carbon in soil (9.8 g kg^{-1}) were significantly greater in 12 year maize-sunflower rotation using 100% NPK and FYM (12.5 t ha^{-1}) than in control (5.4 g kg^{-1}). The researchers found that fertilisers with FYM and chemical ones are sufficient to ensure the sustainability of the yield and the health of the soil (Sridevi *et al.*, 2024) ^[22].

Controlled pot experiment of Nagaland University compared various rates of FYM ($2\text{-}10 \text{ t ha}^{-1}$) and 100% recommended nitrogen (RDN) on sunflower. The 10 ha^{-1} FYM + 100 percent RDN significantly increased growth parameters including plant height, number of leaves, dry weight and leaf area and yielded the highest and best seed and stover yields (26.7 g and 48.3 g pot^{-1}) and harvest index (36.1 percent). This means that even a

percentage of the required fertiliser could be replaced at greater levels of FYM, and could potentially improve growth and yield (Rhakho *et al.*, 2024) ^[21].

Constraints and Limitations of INM in Sunflower

Although experimental studies indicate a robust support of INM, its application on a large scale in the cultivation of sunflower is limited to numerous agronomic and socio-economic constraints. Organic manures have a wide range of availability, quality, and nutrient composition depending on the area, which restricts the homogenization of nutrient recommendations. The cost of production also rises due to the high labour demand, high transportation costs and bulkiness of organic inputs especially to the smallholder farmers. The organic sources of nutrients release is naturally slow and not synchronized with peak crop demand, which makes it difficult to accurately schedule nutrients. Poor accessibility to soil testing, poor knowledge of micronutrient deficiencies, and poor technical expertise on biofertiliser handling and compatibility are other limiting factors to effective implementation. Also, the majority of the available research is short-term and site-based, which restricts the extrapolation of the benefits of INM to the rest of the soil types, cropping systems, and climatic regimes.

Research Gaps and Future Research Needs

Micronutrient interactions within INM: Although the interactions of sulphur and boron have been performed, interactions of the micronutrients (Zn, Fe, Mn, Mo) and macro-nutrient management have not been well studied. Studies are needed to test the right combinations and application means of sunflower (soil or foliar).

INM under climate-stress conditions: Climate change will subject sunflower to heat, drought and salinity stress. Future researches need to test the ability of INM to change plant tolerance to abiotic stresses and to affect water-use efficiency and nutrient uptake during stress.

Region-specific recommendations: There is a concentration of experiments into specific regions (eastern and southern India). More studies in different agro-ecological regions of the country, soil types and seasons, are required to come up with region specific INM packages.

Conclusion

This review shows clearly that Integrated Nutrient Management is a sustainable and viable method of enhancing growth, yield, oil content, oil yield, and economic returns of sunflower and at the same time maintaining soil health. Integrated application of chemical fertilisers, organic manure, biofertilisers, sulphur, and micronutrients provides balanced nutrient supply, increased nutrient use efficiency, and alleviated the negative impact of the single use of chemical fertilisers. The evidence of research indicates that INM does not only enhance the productivity of seeds and oils, but also enhances the physical, chemical, and biological characteristics of the soil, thus enabling long-term sustainability. Nevertheless, there are some limitations connected with access to organic inputs, the lack of knowledge, and recommendations based on the regions that should be considered. Enhancing long-term research, awareness in farmers and site-specific nutrient management plan will play a significant role in the further adoption of INM and close the yield gap of sunflower in India and other comparable agro-ecological areas.

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