

OPTIMIZING SUNFLOWER (*HELIANTHUS ANNUUS* L.) PRODUCTIVITY AND PROFITABILITY THROUGH INTEGRATED NUTRIENT MANAGEMENT: IMPLICATIONS FOR SOIL HEALTH AND SUSTAINABILITY

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ABSTRACT

Sunflower (*Helianthus annuus* L.) is an important edible oilseed crop, yet its average productivity in India (about 440 kg/ha) remains far below the global average (about 1,900 kg/ha). Continuous and exclusive use of chemical fertilizers has contributed to declining soil organic carbon, emerging secondary and micronutrient deficiencies and low nutrient-use efficiency. Integrated Nutrient Management (INM), the combined use of inorganic fertilizers, organic manures and biofertilizers, offers a scientifically sound route to sustained productivity. This review synthesises Indian and international research on the principles and components of INM in sunflower and its effects on growth, yield attributes, seed yield, oil content and quality, soil health, cropping-system productivity, economics and environmental sustainability. Across the studies reviewed, the best INM combinations increased seed yield by 12–49% over the recommended dose of fertilizers (RDF) alone, raised oil content by 2–4.5 percentage points, improved soil organic carbon by about 20% and nearly doubled soil microbial biomass carbon, while raising the benefit:cost ratio from 2.00 to 2.41. Partial substitution (25–50%) of chemical fertilizers by organic and biological sources generally maintained or increased yield. Major constraints to adoption, research gaps and future prospects, including location-specific recommendations, precision nutrient management, next-generation microbial consortia and biofortification, are discussed.

KEYWORDS: Biofertilizers, integrated nutrient management, oil content, soil health, sunflower, sustainable agriculture, yield

1. INTRODUCTION

Sunflower (*Helianthus annuus* L.) is one of the world's major oilseed crops and ranks fourth in vegetable oil production after palm, soybean and rapeseed (canola). It is cultivated on about 26 million hectares worldwide, producing nearly 50 million tonnes of seed annually (NMOOP, 2022). In India, sunflower occupies about 0.55 million hectares with an annual production of 0.24 million tonnes and an average productivity of 440 kg/ha, far below the global average of 1,900 kg/ha (ICAR, 2021). Karnataka, Andhra Pradesh, Telangana, Maharashtra, Odisha and Bihar are the major producing states, with Karnataka contributing almost 50% of national production.

Sunflower is nutritionally valuable. The seed contains 38–45% oil rich in linoleic acid (omega-6; 60–70%) and oleic acid, which makes the oil desirable for human consumption, particularly for people with cardiovascular disorders (Tandon,

2013). The seed also contains 20–25% protein and is a rich source of vitamin E (tocopherols) and minerals, giving it value as food, nutraceutical and medicinal raw material. The oil cake remaining after extraction contains 28–34% crude protein and is an excellent livestock feed, adding further to the economic returns from the crop.

Despite this nutritional and economic importance, sunflower productivity in India has remained low because of a range of agronomic and soil constraints. Among these, imbalanced and exclusive reliance on chemical fertilizers, largely nitrogen (N), phosphorus (P) and potassium (K), is recognised as a major factor. Prolonged sole chemical fertilization lowers soil organic matter and microbial biomass, disturbs microbially mediated nutrient cycling, accelerates soil acidification and induces deficiencies of secondary and micronutrients, notably sulphur (S), which is important for oil quality, and boron (B) and zinc (Zn), which are critical for seed filling (Dhaliwal et al., 2019). Singh et al. (2010) reported that sole chemical fertilization under intensive high-input systems caused a 15–20% loss of soil organic carbon (SOC) over 10 years, substantially undermining soil productivity.

Integrated Nutrient Management (INM) is a scientifically sound and practically feasible alternative. INM is the judicious use of all available organic and inorganic sources of plant nutrients in an integrated manner to maintain soil fertility, maximise crop production per unit of input, minimise environmental degradation and achieve production at an economic optimum (Ahlawat and Sharma, 2012). The approach combines balanced chemical fertilization with organic amendments (farmyard manure, vermicompost, green manure), biofertilizers (Azotobacter, phosphate-solubilising bacteria and vesicular-arbuscular mycorrhizae) and crop residues. Its underlying premise is that no single nutrient source is sufficient on its own. Chemical fertilizers supply readily available nutrients but carry environmental costs; organic inputs improve soil structure, raise SOC, stimulate microbial activity and act as a nutrient reservoir; and biofertilizers contribute through biological N fixation, phosphate solubilisation and phytohormone production. Integrating the three produces a synergistic nutrition system that is ecologically sound, economically affordable and agronomically more effective than any component alone.

The relevance of INM to sunflower production has grown with climate change and resource constraints. Shrinking cultivable area, falling water tables, rising costs of synthetic inputs, consumer preference for residue-free oilseeds and the need to rejuvenate degraded soils all call for a shift from input-intensive to knowledge-intensive, ecologically integrated crop nutrition. This review synthesises the available evidence on the components of INM in sunflower and their effects on crop growth, yield, oil quality, soil health, cropping systems, economics and the environment, and identifies constraints and priorities for future research.

2. Principles and Components of INM

2.1 Definition and principles

INM may be defined as the maintenance or enhancement of soil fertility and the supply of plant nutrients at an optimum level for sustained crop productivity through the optimisation of benefits from all possible sources of plant nutrients in an integrated manner (Meena et al., 2020). Its principles are: (i) complementarity among nutrient sources; (ii) minimisation of nutrient losses by synchronising nutrient release with crop demand; (iii) strengthening soil biology as the driver of nutrient transformations; and (iv) long-term soil and environmental sustainability. The three principal components of INM and the outcomes expected from their integration are summarised in Fig. 1.

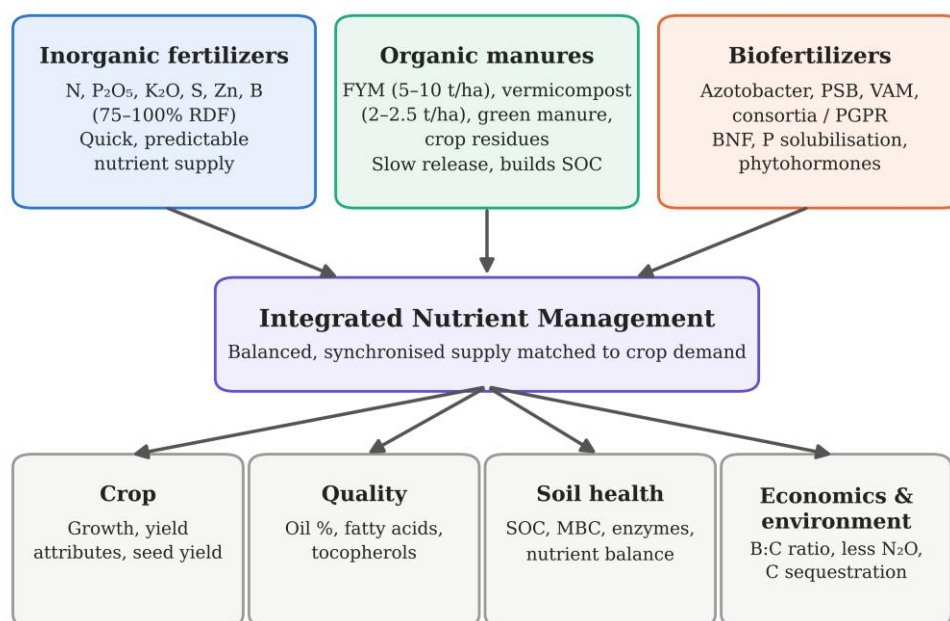


Figure 1. Conceptual framework of Integrated Nutrient Management (INM) in sunflower, showing the three nutrient-source components and the crop, quality, soil-health, economic and environmental outcomes of their integration. RDF, recommended dose of fertilizers; FYM, farmyard manure; PSB, phosphate-solubilising bacteria; VAM, vesicular-arbuscular mycorrhizae; PGPR, plant growth-promoting rhizobacteria; BNF, biological nitrogen fixation; SOC, soil organic carbon; MBC, microbial biomass carbon; B:C, benefit:cost ratio.

2.2 Chemical fertilizers

Mineral fertilizers are a core component of INM, supplying macronutrients (N, P, K) and secondary and micronutrients (S, Zn, B) in readily available forms. The recommended dose of fertilizers (RDF) for sunflower varies between states and regions: TNAU (2018) recommends 90:60:60 kg N:P₂O₅:K₂O/ha for irrigated sunflower, whereas ANGRAU recommends 80:40:40 kg/ha under rainfed conditions. Nitrogen governs vegetative growth, chlorophyll formation and, consequently, yield. Phosphorus is essential for energy metabolism, root development and oil synthesis, while potassium improves water-use efficiency and stress tolerance, which are vital in the semi-arid regions where much of India's sunflower is grown.

Sulphur deserves particular attention. It is a constituent of the sulphur-containing amino acids cysteine and methionine and is involved in pathways that influence fatty acid composition, especially the oleic:linoleic acid ratio. Sharma et al. (2016) reported that 30 kg S/ha applied as ammonium sulphate within an INM package increased seed yield by 12.3% and oil content by 1.8% over S-omitted treatments.

2.3 Organic sources

Organic manures are an integral component of INM. Farmyard manure (FYM) applied at 5–10 t/ha supplies a balanced array of macro- and micronutrients in slow-release form, increases water-holding capacity and aggregate stability, and provides a carbon source for soil microorganisms. Vermicompost, produced by earthworm-mediated bioconversion of organic wastes, is nutritionally superior to FYM, containing 2.5–3.0% N, 1.5–2.0% P and about 1.5% K, together with higher humic substances and plant growth-promoting hormones (Kumar et al., 2020).

Gomathi et al. (2014) found that 2.5 t vermicompost/ha combined with 75% RDF produced 23.6% higher seed yield than 100% RDF in Tamil Nadu. Incorporation of leguminous green manures such as *Sesbania aculeata* and *Crotalaria juncea* at 45–60 days after sowing adds 50–100 kg N/ha and increases soil microbial biomass carbon (Siddique and Wesley, 2018). In a rice–sunflower rotation, Babu et al. (2015) observed that green manure incorporation increased SOC by 0.28 g/kg over two cycles, leaving a beneficial nutrient legacy for the following sunflower crop.

2.4 Biofertilizers

Biofertilizers form the biological component of INM, harnessing the metabolism of beneficial soil microorganisms to improve nutrient supply. The free-living N fixer *Azotobacter chroococcum* can fix 20–30 kg N/ha per season and also produces auxins and gibberellins that stimulate root growth (Vessey, 2003). Phosphate-solubilising bacteria (PSB) such as *Bacillus megaterium* and *Pseudomonas fluorescens* secrete organic acids and phosphatases that convert insoluble Ca₃(PO₄)₂ and Fe/Al phosphates into plant-available orthophosphate. Vesicular-arbuscular mycorrhizal (VAM) fungi such as *Glomus fasciculatum* and *G. mosseae* expand the effective root absorbing area 10–100-fold, greatly enhancing uptake of P, Zn and Cu. Kalyan et al. (2013) reported that seed inoculation with *Azotobacter* + PSB increased sunflower seed yield by 14.8% over uninoculated 100% RDF.

2.5 Soil biological activity and nutrient cycling

A principal merit of INM lies in improved nutrient-cycling efficiency. Organic amendments and biofertilizers together enhance soil enzyme activities (urease, phosphatase and dehydrogenase), increase microbial biomass carbon and nitrogen, and accelerate humification of organic matter. In a long-term field study, Mandal et al. (2017) found that combined application of manures and chemical fertilizers increased soil dehydrogenase activity by 45% and microbial biomass carbon by 38% compared with chemical fertilizers alone. These processes are self-reinforcing: greater biological activity accelerates nutrient mineralisation, reduces leaching losses and improves soil structure, which in turn sustains crop growth (Fig. 2).

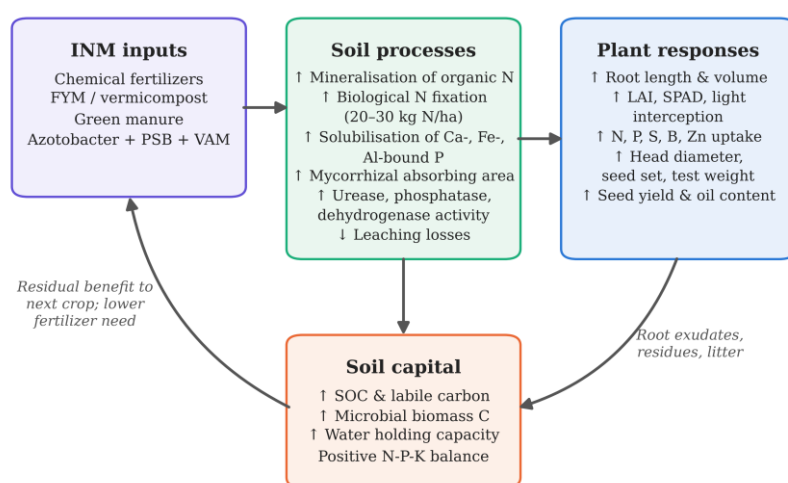


Figure 2. Mechanistic pathways through which INM inputs influence soil processes, plant responses and soil capital in sunflower. Arrows indicate the direction of effects; curved arrows show feedbacks through crop residues and root exudates and the residual benefit carried over to the following crop. ↑, increase; ↓, decrease; LAI, leaf area index; SPAD, chlorophyll meter reading.

3. Effect of INM on Growth of Sunflower

3.1 Plant height and leaf area index

Plant height and leaf area index (LAI) govern light interception and dry matter production, and positive responses to INM have been reported from several regions of India. Singh et al. (2010) found that 75% RDF + FYM 5 t/ha + Azotobacter + PSB produced significantly taller plants (182.4 cm) than 100% RDF (164.2 cm), an increase of 11.1% attributed to improved N availability and phytohormone production by the biofertilizers. Similarly, LAI at 60 days after sowing (DAS) was 4.82 under the best INM treatment compared with 3.96 under chemical fertilizers alone (Reddy et al., 2013). Devi et al. (2012), working in Manipur, recorded 25.8% higher LAI with 75% RDF + vermicompost 2 t/ha + Azotobacter than with the inorganic-only control. The larger canopy under INM increased light interception (95.4% vs. 86.2%), resulting in greater photosynthesis and carbohydrate accumulation. Pradeep et al. (2018) further documented that higher organic carbon improves root-zone aeration and temperature, favouring the development of large, expanded leaves in sunflower–sorghum systems of Andhra Pradesh.

3.2 Dry matter accumulation and partitioning

Total dry matter (TDM) is a basic index of crop growth. Bana et al. (2018) recorded a TDM of 9,854 kg/ha at harvest under the best INM treatment (100% RDF + FYM 5 t/ha + Azotobacter + PSB), 32.6% higher than the 7,432 kg/ha obtained with 100% RDF. Notably, the harvest index (HI) increased from 0.26 under chemical fertilizers alone to 0.31 under INM, indicating that INM not only increased biomass but also improved its partitioning to the economic sink (seed). This improvement has been attributed to better B and K nutrition under INM, which enhances phloem loading and assimilate translocation.

3.3 Root development

Although roots are critical for water and nutrient uptake, root growth is often overlooked in sunflower research. Patel et al. (2019) found that VAM inoculation within an INM package increased root length density (18.4 vs. 11.2 cm/cm³ in the uninoculated control), root volume (42.8 vs. 28.4 cm³/plant) and root surface area. Improved root growth under INM is attributed mainly to (i) phytohormone production by Azotobacter and PSB, (ii) extension of the effective rhizosphere through mycorrhizal hyphae and (iii) better soil physical conditions under organic amendments that facilitate root penetration.

3.4 Chlorophyll content and nutrient uptake

Leaf chlorophyll content is a reliable indicator of crop nutritional status and photosynthetic capacity. Nagre et al. (2015) recorded SPAD chlorophyll meter readings (SCMR) at 60 DAS of 52.4 under 75% RDF + FYM + biofertilizer compared with 45.8 under 100% RDF, i.e. 14.4% higher. Uptake of N and P under the best INM treatment was 168.4 and 32.6 kg/ha, respectively, compared with 138.2 and 26.4 kg/ha under RDF alone. Greater nutrient uptake under INM results from the combined supply of readily available nutrients from fertilizers and the gradual, microbially mediated release of nutrients from organic sources. The growth responses reported across studies are summarised in Table 1.

4. Effect of INM on Yield Attributes and Yield

4.1 Head diameter and seeds per head

Head diameter and number of seeds per head are the principal yield attributes of sunflower and are highly responsive to nutrient management. Gomathi et al. (2014) recorded increases of 30.2% in head diameter (from 17.2 to 22.4 cm) and 33.6% in seeds per head (from 789 to 1,054) under the best INM treatment. Better head development under INM is attributed to sustained nutrient availability during the critical reproductive stages (R1–R5), which improves pollen fertility and seed set; to improved B availability, which is essential for pollen germination and fertilization; and to the osmoregulatory role of K.

4.2 Test weight and seed yield

Test weight (100-seed weight) reflects the degree of seed filling, which in turn determines oil yield. Sharma et al. (2016) recorded a 100-seed weight of 68.9 g under the best INM treatment (100% RDF + FYM + biofertilizers) compared with 56.2 g under 100% RDF, an increase of 22.6%. Improved seed filling has been ascribed to (i) longer leaf area duration owing to continuous N supply from organic sources, (ii) enhanced sucrose transport in well K-nourished plants and (iii) greater antioxidant capacity of the seed through S- and Zn-dependent tocopherol synthesis.

Seed yield is the most widely reported response to INM. Bana et al. (2018) obtained the highest seed yield (2,442 kg/ha) with 100% RDF + vermicompost 2.5 t/ha + Azotobacter + PSB in Haryana, 49.4% more than with 100% RDF (1,634 kg/ha). Importantly, partial replacement of chemical fertilizers by organic and biological sources (75% RDF + FYM + biofertilizers) produced yields equal to or greater than 100% RDF while substantially reducing fertilizer costs. Patel et al. (2019) reported that 75% RDF + vermicompost 2.5 t/ha + VAM + PSB yielded 2,468 kg/ha, 47.0% more than 100% RDF. The magnitude of yield gains reported across studies is compared in Fig. 3, and the growth and yield responses are summarised in Table 1.

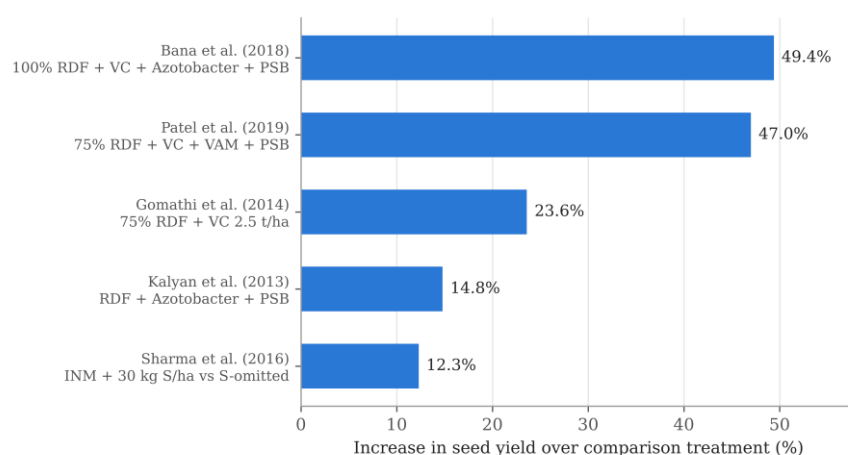


Figure 3. Percentage increase in sunflower seed yield under INM treatments reported in different studies. Comparisons are with 100% RDF alone, except Sharma et al. (2016), where the comparison is with the S-omitted INM treatment. VC, vermicompost; PSB, phosphate-solubilising bacteria; VAM, vesicular-arbuscular mycorrhizae.

Table 1. Growth, yield attributes, yield and quality of sunflower under 100% RDF and the best-performing INM treatment, compiled from published studies

Parameter	100% RDF	Best INM	Change (%)	Source
Plant height (cm)	164.2	182.4	+11.1	Singh et al. (2010)
Leaf area index (60 DAS)	3.96	4.82	+21.7	Reddy et al. (2013)
Light interception (%)	86.2	95.4	+9.2 pp	Devi et al. (2012)
Total dry matter (kg/ha)	7,432	9,854	+32.6	Bana et al. (2018)
Harvest index	0.26	0.31	+19.2	Bana et al. (2018)
Root length density (cm/cm ³)	11.2a	18.4	+64.3	Patel et al. (2019)
SPAD reading (60 DAS)	45.8	52.4	+14.4	Nagre et al. (2015)
N uptake (kg/ha)	138.2	168.4	+21.9	Nagre et al. (2015)
P uptake (kg/ha)	26.4	32.6	+23.5	Nagre et al. (2015)
Head diameter (cm)	17.2	22.4	+30.2	Gomathi et al. (2014)
Seeds per head	789	1,054	+33.6	Gomathi et al. (2014)
100-seed weight (g)	56.2	68.9	+22.6	Sharma et al. (2016)
Seed yield (kg/ha)	1,634	2,442	+49.4	Bana et al. (2018)
Oil content (%)	38.8	43.2	+4.4 pp	Reddy et al. (2013)

RDF, recommended dose of fertilizers; DAS, days after sowing; pp, percentage points. aUninoculated control. Best INM treatments differ between studies and are described in the text.

5. Effect of INM on Oil Content and Quality

5.1 Oil content

Oil content is the key economic trait of sunflower and is strongly influenced by nutrition. Under optimised INM, oil content ranged from 41.2 to 43.5%, compared with 38.5–39.8% under conventional fertilization, an increase of 2–4.5 percentage points. Reddy et al. (2013) recorded 43.2% oil under 100% RDF + FYM 5 t/ha + Azotobacter + PSB against 38.8% under 100% RDF in Karnataka (Table 1). Higher oil content under INM is attributed to (i) longer green leaf area duration, which supplies more assimilates to the developing seed, (ii) better S nutrition, which promotes fatty acid synthesis and (iii) higher antioxidant enzyme activity, which limits lipid peroxidation during seed filling.

5.2 Fatty acid composition

Fatty acid composition determines oil quality and market value. For good nutritional quality, linoleic acid (C18:2, omega-6) should constitute 60–70% of total fatty acids, while higher oleic acid (C18:1) is preferred in high-oleic sunflower. Nagre et al. (2015) found that INM including S (30 kg/ha) and organic manure raised oleic acid from 24.8 to 31.2% without affecting linoleic acid (63.4%). Sulphur plays a key role in the desaturase-mediated pathways of fatty acid synthesis, and S deficiency increases palmitic acid at the expense of polyunsaturated fatty acids (PUFA).

5.3 Role of micronutrients

Boron and zinc require special attention in managing sunflower quality. Kalyan et al. (2013) reported that 1.0 kg B/ha (as borax) within INM increased pollen viability by 18.4%, seed set by 12.6% and oil content by 1.2 percentage points over B-omitted INM. Besides its roles in chlorophyll synthesis and enzyme activation, Zn is involved in tocopherol (vitamin E) biosynthesis in sunflower seed and improves oil quality; Choudhary et al. (2016) reported 28.4% higher α -tocopherol in oil from Zn-enriched INM compared with Zn-omitted INM.

6. Soil Health and Nutrient Dynamics

6.1 Soil organic carbon

Soil organic carbon underpins soil health and future productivity. Prolonged exclusive use of chemical fertilizers generally depletes SOC, because microbial activity stimulated by added N increases carbon demand beyond the supply of organic matter. Srinivasarao et al. (2014) reported a decline in SOC from 6.2 to 5.1 g/kg after 15 years of sole chemical fertilization in rainfed systems, whereas combined organic–inorganic management raised SOC to 7.8 g/kg. In sunflower, Das et al. (2017) observed 6.89 g/kg SOC after three years under FYM 10 t/ha + 50% RDF compared with 5.74 g/kg under 100% RDF (20.0% higher). Pradeep et al. (2018) also reported 35–45% higher labile carbon (particulate organic carbon and permanganate-oxidisable carbon) under INM than under sole inorganic fertilization, indicating improved SOC quality.

6.2 Microbial biomass carbon and enzyme activity

Soil microbial biomass carbon (SMBC), the active fraction of organic matter that drives nutrient cycling, is a sensitive indicator of soil biological fertility. In a long-term experiment on sunflower-based systems, Mandal et al. (2017) recorded SMBC of 312 $\mu\text{g/g}$ under the best INM treatment compared with 158 $\mu\text{g/g}$ under 100% RDF, almost doubling the biological capital of the soil. This was accompanied by 67% higher urease, 48% higher acid phosphatase and 52% higher dehydrogenase activity, reflecting more active nutrient fluxes and greater functional diversity of the soil microbiome.

6.3 Nutrient availability

Post-harvest soil nutrient status reflects the short- to medium-term nutrient balance of a system and its long-term sustainability. As shown in Table 2, INM resulted in higher soil nutrient availability than sole chemical fertilization. Available N increased from 194 kg/ha (100% RDF) to 254 kg/ha (best INM), a 30.9% gain attributed to enhanced mineralisation by a more active microbial population. Available P increased by 40.3% under INM, owing both to PSB activity and to chelation by humic acids that releases Fe/Al-bound P. Sustained nutrient availability under INM also helps to buffer the crop against stress-induced yield losses.

Table 2. Soil health indicators and nutrient balance under 100% RDF and INM in sunflower-based systems

Indicator	100% RDF	INM	Change	Source
Soil organic carbon (g/kg)	5.74	6.89	+20.0%	Das et al. (2017)
Labile carbon (POC, POXC)	–	–	+35–45%	Pradeep et al. (2018)
Soil microbial biomass C ($\mu\text{g/g}$)	158	312	+97.5%	Mandal et al. (2017)
Urease activity	–	–	+67%	Mandal et al. (2017)
Acid phosphatase activity	–	–	+48%	Mandal et al. (2017)
Dehydrogenase activity	–	–	+52%	Mandal et al. (2017)
Available N (kg/ha)	194	254	+30.9%	Not citeda
Available P	–	–	+40.3%	Not citeda
N balance (kg/ha/year)	–12.4	+22.4	Deficit $\rightarrow$ surplus	Mandal et al. (2017)
P balance (kg/ha/year)	–3.8	+8.6	Deficit $\rightarrow$ surplus	Mandal et al. (2017)
K balance (kg/ha/year)	–8.2	+14.2	Deficit $\rightarrow$ surplus	Mandal et al. (2017)
Carbon sequestration (Mg C/ha/year)	–0.08	0.22–0.48	Loss $\rightarrow$ gain	Das et al. (2017)

POC, particulate organic carbon; POXC, permanganate-oxidisable carbon; –, absolute values not reported (relative change only). aSource not cited in the original text; please add the reference.

6.4 Residual effects in cropping systems

The residual effect of INM on the succeeding crop is an important but less studied aspect of integrated nutrition. In a long-term rice–sunflower rotation, Yadav and Singh (2015) found that INM applied to sunflower increased the yield of the following rice crop by 8.4–12.6%, owing to mineralisation of residual organic matter, carry-over of slowly soluble nutrients and improved soil physical properties.

7. INM in Sunflower-Based Cropping Systems

7.1 Rice–sunflower system

The rice–sunflower system, practised in West Bengal and Odisha in eastern India and in Karnataka, is strategically important because the two crops differ in rooting depth and nutrient demand. Babu et al. (2015) evaluated INM in sunflower over three years in Sikkim and found that 75% RDF + FYM 5 t/ha + Azotobacter + PSB produced 2,186 kg/ha seed yield and increased the yield of the following rice crop by 11.2% compared with 100% RDF applied to sunflower. The rice yield gain was attributed to residual organic matter, improved puddling behaviour and bulk density, and greater K and P availability to rice.

7.2 Maize–sunflower system

In the maize–sunflower sequence common in Karnataka and Maharashtra, the high N requirement of sunflower and the large residue load from maize must be considered in designing INM. Choudhary et al. (2016) found that incorporating maize stover before sunflower sowing, together with an additional 25–30 kg N/ha to offset N immobilisation, increased sunflower yield. INM in this sequence gave the highest seed yield (2,312 kg/ha) and benefit:cost (B:C) ratio (2.38).

7.3 Pigeonpea–sunflower system

The pigeonpea–sunflower system holds promise in the drylands of the Deccan Plateau. Deep-rooted pigeonpea contributes substantial biologically fixed N and improves soil structure through root channels, benefiting the following sunflower crop. Sharma et al. (2016) showed that sunflower grown after pigeonpea with 50% of recommended N + FYM 3 t/ha + Azotobacter + PSB yielded as much as sunflower receiving full RDF after a non-legume (2,080 vs. 2,040 kg/ha), confirming the N credit of pigeonpea. This has wide implications for lowering fertilizer costs and improving system N-use efficiency.

7.4 Sustainability and nutrient balance

INM must be evaluated on long-term, system-level nutrient balances. Mandal et al. (2017) constructed nutrient budgets for sunflower production systems and found positive annual balances of N, P and K (+22.4, +8.6 and +14.2 kg/ha/year) under INM, whereas cost-equivalent chemical fertilization alone resulted in negative balances (−12.4, −3.8 and −8.2 kg/ha/year; Table 2). Positive balances under INM build soil nutrient capital over time and provide a buffer against input-supply shocks and climatic variability.

8. Economics of INM

8.1 Cost of cultivation and gross returns

Economic evaluation of INM must account for both input costs and the value of improved yield and quality. INM typically raises the cost of cultivation by 10–25% over chemical fertilization because of the costs of organic inputs, biofertilizers and labour for composting and manure application. This is more than offset by 30–100% higher gross returns from increased seed yield and, in some cases, premium prices for organically produced seed. In a two-year analysis, Bana et al. (2018) found that the cost of cultivation increased by 22.1%, from ₹28,500/ha under 100% RDF to ₹34,800/ha under the best INM system (75% RDF + vermicompost + VAM + PSB), whereas gross returns rose by 46.9%, from ₹57,120/ha to ₹83,912/ha, owing to higher seed yield and a slightly higher price (Fig. 4a).

8.2 Net returns and benefit:cost ratio

Net returns and the B:C ratio are the key criteria for technology adoption. Net returns under the best INM system (₹49,112/ha) were 71.6% higher than under 100% RDF (₹28,620/ha). The B:C ratio of the best INM system (2.41) was clearly higher than that of 100% RDF (2.00) and of organic-only management (1.84), indicating that INM achieves the best balance between production cost and output (Fig. 4b). Rathore et al. (2015) similarly reported B:C ratios of 2.35–2.48 for different INM treatments against 1.98 for conventional RDF in multi-location trials across five districts of Rajasthan.

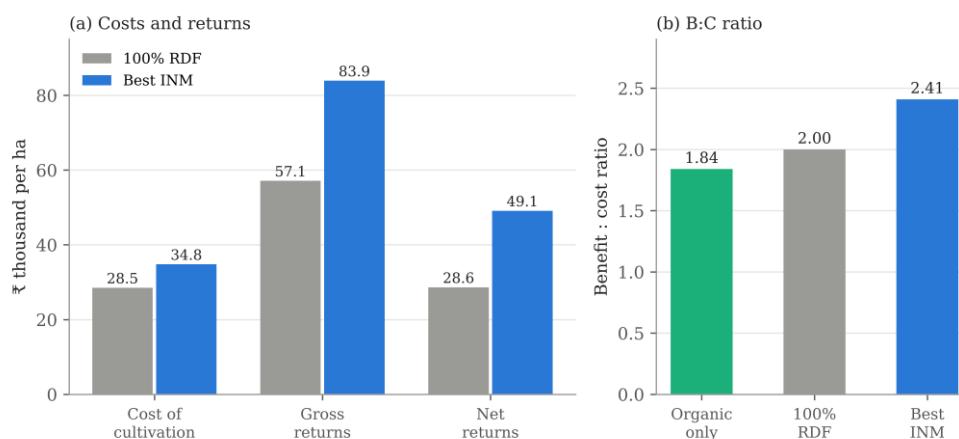


Figure 4. Economics of sunflower production under different nutrient management systems: (a) cost of cultivation, gross returns and net returns (₹ thousand/ha) under 100% RDF and the best INM system (data from Bana et al., 2018); (b) benefit:cost ratio under organic-only management (FYM 10 t/ha), 100% RDF and the best INM system.

8.3 Organic-only systems

An important economic finding is that organic-only management (FYM 10 t/ha without chemical fertilizer) consistently gives lower net returns than either conventional fertilization or INM under Indian conditions. Its seed yield (1,420 kg/ha) is insufficient to recover the cost of organic inputs, and its B:C ratio (1.84) is the lowest among the systems compared (Fig. 4b). This finding does not support the complete replacement of chemical fertilizers by organic sources and favours INM as the preferred agronomic and economic option for Indian sunflower growers.

9. Environmental and Sustainability Aspects

9.1 Reduction in chemical fertilizer use

INM strategies that maintain or increase yield with 25–50% less chemical fertilizer have significant environmental benefits. Lower N inputs reduce emissions of nitrous oxide (N₂O), a greenhouse gas with a global warming potential about 298 times that of CO₂, from nitrification–denitrification, as well as nitrate losses in runoff and the energy embodied in crop production. Meena et al. (2020) estimated that a transition to INM in India's oilseed-growing regions could reduce synthetic N use by 22–35%, avoiding 0.8–1.2 million tonnes of CO₂-equivalent emissions annually.

9.2 Carbon sequestration and climate resilience

The organic amendments used in INM also sequester atmospheric carbon in more stable SOC pools. Das et al. (2017), studying SOC dynamics over seven years, reported net carbon sequestration of 0.22–0.48 Mg C/ha/year under INM, compared with a net loss of 0.08 Mg C/ha/year under chemical fertilization alone (Table 2). INM also improves the resilience of sunflower production to climate variability: higher SOC increases soil water storage (each 1% increase in SOC can retain about 20,000 L more water per hectare) and thereby improves drought tolerance.

10. Constraints and Future Prospects

10.1 Constraints to farmer adoption

Despite substantial evidence of the agronomic and economic advantages of INM in sunflower, adoption in India remains low. The main constraints are: (i) limited awareness of INM principles and of how to combine its components; (ii) high initial labour costs of preparing and applying organic inputs; (iii) poor availability of quality biofertilizers, particularly VAM, in rural markets; (iv) variable quality and nutrient content of organic inputs such as FYM; and (v) the perception among farmers that organic amendments act too slowly to meet immediate crop demand. Strengthened extension services, farmer field schools and INM demonstration plots are essential to address these constraints.

10.2 Lack of location-specific recommendations

A key research gap is the lack of location-specific INM recommendations for the different sunflower-growing zones of India. Most published studies were conducted at a single location for one or two years. The best INM combination for Alfisols in Karnataka may not suit alluvial soils of the Indo-Gangetic Plains or Vertisols of Maharashtra, and biofertilizer strains effective in hot semi-arid environments may perform poorly in humid subtropical conditions. A multi-location network project on INM in sunflower, covering diverse soils and agro-climatic zones, is therefore needed.

10.3 Precision nutrient management

Precision nutrient management, based on real-time soil and crop sensing and decision-support tools, represents the next frontier for INM. Soil health card data, remotely sensed crop N-stress indices (NDVI, NDRE) and Internet-of-Things (IoT) soil moisture and nutrient sensors can together support variable-rate, in-season nutrient application that improves nutrient-use efficiency and reduces losses. Nanotechnology-based slow-release fertilizers and biofertilizer coatings could further synchronise nutrient release with crop demand. Development of artificial intelligence-based INM decision-support systems for Indian sunflower agro-ecosystems is a priority.

10.4 Microbiome engineering and next-generation biofertilizers

Microbiome engineering offers promising avenues for next-generation biofertilizers in sunflower. Consortium biofertilizers that combine compatible microorganisms (N fixers, PSB, K-solubilisers, mycorrhizal fungi and plant growth-promoting rhizobacteria) on suitable carriers have proved superior to single-strain inoculants. Metagenomic studies of the sunflower rhizosphere and endophytic microbiome may identify novel organisms with enhanced N-fixing, P-solubilising or biocontrol potential. Commercialising such second-generation products with proven shelf stability under tropical Indian conditions would be a major step towards high-efficiency INM in sunflower.

10.5 Biofortification through INM

An emerging research area is the use of INM as a biofortification strategy to improve the mineral and vitamin content of sunflower seed. Soil and foliar micronutrient applications within INM have been shown to increase Zn, selenium (Se) and vitamin E concentrations in the seed. Biofortification of sunflower through targeted INM therefore offers an opportunity to help address the widespread Zn and Se deficiencies in the Indian population, linking agricultural production with human nutrition, and warrants dedicated research attention.

11. CONCLUSION

The research reviewed here shows that Integrated Nutrient Management is a scientifically, economically and environmentally sound approach to sunflower nutrition. By combining chemical fertilizers, organic manures and biofertilizers, INM overcomes the main drawbacks of sole chemical fertilization (declining soil quality, low nutrient-use

efficiency and environmental pollution) while matching or exceeding the productivity of high chemical fertilizer doses. The best INM treatments in the studies reviewed increased seed yield by 12–49% over 100% RDF and raised oil content to 41–44%, compared with 38–40% under sole chemical fertilization. These gains translated into higher B:C ratios (2.35–2.48 under INM vs. 1.98–2.00 under sole chemical fertilization), providing a sound economic rationale for adoption. The benefits of INM to soil health, including higher SOC, microbial biomass, nutrient mineralisation and water-holding capacity, represent a long-term investment in the productivity of India's sunflower belt. From a sustainability perspective, the ability of optimised INM systems to reduce chemical fertilizer inputs by 25–50% without yield penalty could help contain India's fertilizer subsidy burden and contribute to national climate change mitigation targets. The CO₂ mitigation potential of INM-induced SOC accumulation is an ecosystem service not captured in conventional economic analyses but increasingly valued in emerging carbon markets. The potential of INM in Indian sunflower production is only beginning to be realised. Bridging the gap between research and farm practice will require stronger extension support, a reliable market for quality biofertilizers, site-specific INM recommendations and policy support for sustainable intensification. Precision sensing, bioinformatics and artificial intelligence-based decision-support tools are likely to advance INM research further, and INM-based biofortification could improve the nutritional value of sunflower seed, benefiting both food security and livelihoods. Ultimately, INM is not merely a substitute for chemical fertilizers but a shift in thinking about sunflower nutrition, from a reductionist input–output view to a systems perspective that recognises soil biological capital, nutrient-cycling efficiency and long-term ecosystem services as decisive determinants of sustainable oilseed production.

REFERENCES

- Ahlawat, I. P. S., & Sharma, R. P. (2012). Integrated nutrient management in sunflower. *Indian Journal of Agronomy*, 57(2), 112–118.
- Babu, S., Singh, R., Avasthe, R. K., & Yadav, G. S. (2015). Influence of organic and inorganic nutrient sources on productivity and soil health in rice–sunflower cropping system. *Indian Journal of Agronomy*, 60(3), 388–394.
- Bana, R. S., Grover, M., Walia, S. S., & Kumar, S. (2018). Integrated nutrient management for improving productivity and profitability of sunflower (*Helianthus annuus* L.). *Journal of Oilseeds Research*, 35(1), 38–44.
- Choudhary, R. L., Jat, M. L., & Sharma, S. K. (2016). Soil health management through INM in sunflower-based cropping systems in semi-arid India. *Field Crops Research*, 192, 44–52.
- Das, A., Patel, D. P., Kumar, M., Ramkrushna, G. I., Mukherjee, A. K., Layek, J., & Buragohain, J. (2017). Impact of seven years of organic farming on soil and produce quality and crop yields in eastern Himalayas, India. *Agriculture, Ecosystems & Environment*, 236, 142–153.
- Devi, K. N., Singh, L. N. K., & Devi, T. S. (2012). Influence of organic and inorganic sources of nutrients on growth and yield of sunflower. *Journal of Agricultural Sciences*, 7(4), 178–183.
- Dhaliwal, S. S., Naresh, R. K., Mandal, A., Singh, R., & Dhaliwal, M. K. (2019). Dynamics and transformations of micronutrients in agricultural soils as influenced by organic matter build-up: a review. *Environmental and Sustainability Indicators*, 1–2, 100007.
- Gomathi, R., Krishnasamy, S., & Subramanian, M. (2014). Effect of integrated nutrient management on growth, yield and quality of sunflower. *Madras Agricultural Journal*, 101(4–6), 177–181.
- ICAR. (2021). Annual Report 2020–21. Indian Council of Agricultural Research, New Delhi.
- Kalyan, S., Lal, M., & Khandelwal, S. K. (2013). Effect of biofertilizers and chemical fertilizers on yield, quality and economics of sunflower. *Indian Journal of Agricultural Sciences*, 83(2), 197–201.
- Kumar, A., Singh, M., & Sharma, A. (2020). Vermicompost in combination with reduced chemical fertilizers enhances yield and soil biological properties of sunflower in Indo-Gangetic Plains. *Bioresource Technology*, 308, 123274.
- Mandal, A., Patra, A. K., Singh, D., Swarup, A., & Masto, R. E. (2017). Effect of long-term application of manure and fertilizer on biological and biochemical activities in soil during crop development stages. *Bioresource Technology*, 98(18), 3585–3592.
- Meena, R. S., Kumar, S., Datta, R., Lal, R., Vijayakumar, V., Brtnicky, M., & Dokulilova, T. (2020). Impact of agrochemicals on soil microbiota and management: a comprehensive review. *Agronomy*, 10(8), 1157.
- Nagre, P. K., Kothari, I. L., & Patel, B. D. (2015). INM effect on growth, yield and oil content of sunflower in alluvial soils of Gujarat. *Journal of Oilseeds Research*, 32(1), 55–60.
- NMOOP. (2022). National Mission on Oilseeds and Oil Palm: Annual Progress Report. Ministry of Agriculture & Farmers Welfare, Government of India.
- Patel, M. M., Patel, I. C., & Patel, H. K. (2019). Effect of integrated nutrient management on sunflower (*Helianthus annuus* L.) yield under rainfed conditions of central Gujarat. *Gujarat Agricultural Universities Research Journal*, 44(2), 35–42.
- Pradeep, T., Rao, A. V., & Rajesh, G. (2018). Long-term effect of INM on soil organic carbon fractions and nutrient availability in sunflower–sorghum system. *Journal of the Indian Society of Soil Science*, 66(1), 78–86.
- Rathore, S. S., Shekhawat, K., Yadav, S. K., Singh, V. K., Premi, O. P., & Kandpal, B. K. (2015). Biofertilizers: a way towards organic farming and sustainable agriculture. *International Journal of Plant Research*, 25(1), 73–83.
- Reddy, B. G. M., Shivaraj, B., & Prasad, T. G. (2013). Integrated nutrient management for improving yield and quality of sunflower in southern India. *Mysore Journal of Agricultural Sciences*, 47(1), 49–54.
- Sharma, R. P., Datta, S. C., & Chaudhary, D. C. (2016). Effect of integrated use of organic and inorganic fertilizers on yield, economics and soil fertility of sunflower. *Indian Journal of Agronomy*, 61(4), 458–462.
- Singh, A. K., Bharati, R. C., Manibhushan, N. C., & Pedapati, A. (2013). An assessment of faba bean (*Vicia faba* L.) current status and future prospect. *African Journal of Agricultural Research*, 8(50), 6634–6641.

22. Singh, R., Bohra, J. S., Singh, Y., Singh, K., & Shinde, S. N. (2010). Effect of integrated nutrient management on growth, productivity and economics of sunflower in Indo-Gangetic Plains. *Journal of Oilseeds Research*, 27(2), 153–157.
23. Srinivasarao, Ch., Venkateswarlu, B., Lal, R., Singh, A. K., Kundu, S., Vittal, K. P. R., & Patel, J. J. (2014). Long-term manuring and fertilizer effects on depletion of soil organic carbon stocks under pearl millet–cluster bean–castor rotation in western India. *Land Degradation & Development*, 25(2), 173–183.
24. Tandon, H. L. S. (2013). *Fertilizers in Indian Agriculture – From 20th to 21st Century*. Fertilizer Development and Consultation Organization, New Delhi.
25. TNAU. (2018). *Package of Practices for Oilseed Crops*. Tamil Nadu Agricultural University, Coimbatore.
26. Vessey, J. K. (2003). Plant growth promoting rhizobacteria as biofertilizers. *Plant and Soil*, 255(2), 571–586.
27. Yadav, R. L., & Singh, V. K. (2015). Residual and direct effect of integrated nutrient management in rice–sunflower cropping system. *Field Crops Research*, 175, 60–68.