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Organic farming in sesame (*Sesamum indicum* L.): Practices, challenges and future research directions

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Abstract

Organic cultivation has gained increasing attention as a sustainable alternative to conventional farming owing to its potential to maintain productivity through improved soil health. Organic sesame has a strong presence in international markets and demand has risen in recent decades owing to its use in salad dressings and bakery products in European countries. This review critically analyses recent advances in the management of nutrients, pests and diseases and their effects on sesame productivity and soil health. The available evidence demonstrates that use of farmyard manure, vermicompost, biofertilisers, green manures, biochar and microbial inoculants enhances nutrient availability, soil organic carbon, microbial activity, enzyme activity, crop growth and yield either alone or in combination with chemical fertilisers. Similarly, intercropping, live mulches, mechanical weed management, botanical pesticides and biological control agents provide environmentally sustainable alternatives for managing weeds, pests and diseases while reducing chemical inputs. However, the adoption of organic sesame production is constrained by slow nutrient release, variability in organic inputs, inconsistency of biofertilisers, labour-intensive weed management and the lack of standardised and region-specific production packages. Furthermore, long-term information on nutrient dynamics, soil biological processes, economic viability and multi-location validation remains limited. Future research should focus on developing integrated, location-specific organic production packages and evaluating innovative biological and non-chemical technologies to enhance the productivity, profitability and sustainability of organic sesame production systems.

Keywords: biological control; organic farming; sesame; soil health; weed management

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Introduction

India's agricultural sector is under increasing pressure to ensure food and nutritional security for a population projected to reach 1.6 billion by 2050 (1). However, long-term intensive cultivation has led to significant soil degradation, including depletion of soil organic carbon (SOC) by 23–64 % compared to uncultivated soils, reduced nutrient availability and declining water-use efficiency (2). These changes adversely affect crop productivity and threaten the sustainability of agricultural systems. Excessive fertiliser application, particularly nitrogenous fertilisers, may lead to undesirable changes in crop quality, increased nitrate accumulation, higher titratable acidity and acid-to-sugar ratio and reduced concentrations of vitamin C, soluble sugars, soluble solids, calcium and magnesium in some crops (3).

Organic farming has emerged as a sustainable approach to restore soil health and enhance agricultural productivity. It is defined as a production system that promotes and improves agro-ecosystem health, including biodiversity, biological cycles and soil biological activity (4). It aims to maintain soil fertility, biodiversity and environmental sustainability and produce high-quality food (5). Soil health itself is defined as the capacity of a living soil to function within ecosystem boundaries to sustain plant and animal productivity, maintain or enhance water and air quality and promote plant and animal health and is considered the primary indicator of sustainable land management (6). Organic amendments increase soil health by increasing organic carbon (SOC) and nitrogen content, stimulate microbial activity, enhance nutrient mineralisation and improve soil aggregate stability, biodiversity and overall soil fertility, thereby improving overall soil quality (7–9). Integrated nutrient management (INM), which combines organic manures, biofertilisers and inorganic fertilisers, has been reported to sequester approximately 0.95 megagrams of carbon per hectare per year (Mg C ha^{-1} $year^{-1}$) and mitigate soil degradation (10). Furthermore, organic farming contributes to climate change mitigation by reducing greenhouse gas emissions and enhancing soil carbon sequestration (11). These practices align with India's

commitment to reduce emission intensity by 45 % by 2030 and achieve net-zero emissions by 2070 (12). In addition, organic farming has been reported to improve crop nutrient uptake, nutritional quality, antioxidant content and food safety while reducing pesticide residues (13–17).

Oilseeds occupy a vital position in India's agricultural economy, second only to cereals. Although India accounts for nearly 20 % of the global oilseed area, it contributes only about 10 % of total production, indicating relatively low productivity (18). Rising domestic demand, with per capita edible oil consumption increasing from 15.8 kg in 2012–2013 to 23.5 kg in 2022–2023, has widened the demand-supply gap and increased India's dependence on imports (19). Therefore, improving oilseed productivity is critical for achieving self-sufficiency under the recent initiatives entitled National Mission on Edible Oils (NMEO) (20).

Among the oilseed crops, sesame (*Sesamum indicum* L.), often referred to as the "Queen of Oilseeds," is particularly suitable for low-input and organic farming systems and is valued for its high-quality oil and bioactive compounds such as sesamin, sesamolin and sesaminol glucosides, which contribute antioxidant properties and enhance its nutraceutical value (21) thereby promoting liver and cardiovascular health and contributing to the prevention of tumor development (22). The crop serves as a contingent crop, either during the kharif season or after rice harvest in several states of India (23, 24). Several studies have demonstrated that the use of organic manures and bio-fertilisers either alone or in combination with chemical nutrients significantly improved yield, nutrient uptake, soil health and economic returns in sesame cultivation (21, 25–28).

In addition to nutrient management, effective management of insect pests, diseases and weeds is essential for successful organic sesame production. Eco-friendly pest management approaches such as neem-based botanicals, biological control agents and intercropping systems have been reported to reduce pest incidence while conserving beneficial organisms (29, 30). Disease management strategies relying on bioagents like *Trichoderma* spp. and *Pseudomonas fluorescens*, along with cultural practices, help to suppress soil-borne pathogens and enhance plant health (31, 32). Weed management remains a major challenge, particularly during the early growth stages and requires integrated approaches including mechanical weeding, mulching and intercropping to minimise competition and yield losses (33, 34).

Therefore, this review aims to evaluate the effect of organic farming practices on nutrient management, pest and disease control, weed management and their combined effects on yield, soil health and microbial activity of sesame, with a focus on developing sustainable sesame production in the country.

Methodology

A structured literature search was conducted to identify evidence on organic farming and organic-input-based management of sesame, covering nutrient management, soil health, weed, insect-pest and disease management, crop quality, productivity, economics and environmental sustainability. Literature published from January 2000 to June 2026 was majorly considered, with greater emphasis on studies after 2015 to capture recent advances in soil health, microbial processes, biological inputs and sustainable crop management. Earlier studies were retained when they provided foundational, long-term or directly relevant evidence.

The search was conducted using Web of Science, Scopus, ScienceDirect, SpringerLink, Wiley Online Library, Taylor & Francis Online and Google Scholar, supplemented by Food and Agriculture Organization of the United Nations (FAO), ICAR and other institutional sources. The principal search string was ("sesame" OR "*Sesamum indicum*") AND ("organic farming" OR "organic agriculture" OR "organic production" OR "organic nutrient management"). The search included combinations of keywords "farmyard manure (FYM)", "vermicompost", "compost", "green manure", "oil cakes", "biofertilisers", "microbial inoculants", "Azotobacter", "Azospirillum", "Trichoderma", "phosphate-solubilising bacteria (PSB)", "potassium-solubilising bacteria (KSB)", "plant growth-promoting rhizobacteria (PGPR)", "nutrient substitution", "soil health", "soil organic carbon", "microbial activity", "enzyme activity", "seed quality", "oil quality", "fatty acid composition", "energy-use efficiency", "carbon sequestration", "carbon footprint" and "sustainable agriculture". Additional searches combined sesame with terms related to organic inputs, soil health, weeds, pests, diseases, biological control and crop productivity. Reference lists of relevant publications were also screened.

Records were screened by removing duplicates, followed by title/abstract screening and full-text assessment. Studies were included when they provided original experimental or quantitative evidence, systematic or meta-analytic evidence, or authoritative information relevant to organic sesame production or clearly applicable mechanisms. Sesame-specific studies were prioritised for conclusions on crop performance and management, whereas studies from other crops were used mainly for mechanistic interpretation. Studies were excluded if they were irrelevant, duplicated, lacked adequate methodological information or provided unsupported opinions. Studies involving inorganic fertilisers were not considered evidence of organic farming unless an organic production system was explicitly evaluated; integrated nutrient management studies were treated separately. The post-2015 emphasis was used to capture recent advances while retaining earlier studies that provided foundational, long-term or unique sesame-specific evidence.

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Nutrient management and nutrient substitution

Organic nutrient management aims to build and maintain soil fertility by enhancing soil organic matter, humus formation and biological activity rather than merely supplying nutrients to satisfy the immediate nutrient requirements of crops (35). Organic nutrient management emphasises efficient nutrient cycling, recycling of on-farm resources and the maintenance of long-term soil fertility while minimising dependence on external nutrient inputs.

Unlike inorganic fertilisers, organic manures generally contain lower concentrations of nutrients (36) and release them gradually through microbial decomposition. Consequently, synchronising nutrient release with crop demand remains a major challenge in organic production systems. Furthermore, crop residues such as straw often possess a wide carbon-to-nitrogen ratio (C : N) and, when incorporated before complete decomposition, may temporarily immobilise nitrogen, thereby reducing nutrient availability to crops (37). Therefore, effective nutrient management in organic farming focuses on ensuring an adequate and continuous nutrient supply while minimising nutrient losses through proper management of organic materials. Successful nutrient management depends on synchronising nutrient mineralisation with crop nutrient demand by adopting practices such as well-planned crop rotations, inclusion of legumes, recycling of crop residues, green manuring and compost application to sustain nutrient availability throughout the production system (38, 39).

Organic nutrient management in any crop involves the application of organic amendments either on a bulk basis or on a nutrient-equivalent basis according to the nutrient composition of the organic inputs and sesame is no exception. When applied on a bulk basis as normally followed as an organic nutrient management practice, it was found that applying 15 tonnes per hectare (t ha^{-1}) of farmyard manure in both growing seasons significantly boosted soil organic carbon (SOC), dissolved organic carbon (DOC) and key nutrients compared to one-season application in a sandy loam soil of semi-arid climate (40). This suggested that application of bulk of organic manure without any consideration of nutrient content needs recurrent application in each season. While bulk application contributes substantially to soil organic matter build-up and improvement of soil properties, nutrient-equivalent application ensures a balanced nutrient supply comparable to the recommended fertiliser dose. However, improvements in soil physical and chemical properties arising from manure application largely depend on the crops grown and the soil texture (41). Both approaches have been reported to enhance crop productivity, nutrient use efficiency, soil health and long-term sustainability in organic production systems.

The beneficial effects of organic amendments are further attributed to their influence on soil biological processes. Organic amendments stimulate microbial activity and root exudation, resulting in the production of low-molecular-weight organic acids such as citrate, malate and oxalate. These organic acids chelate metal ions and solubilise sparingly available phosphorus and micronutrients, thereby enhancing nutrient availability and uptake by plants (42). The different phosphorus fractions present in compost are reported in Table 1. Efficient nutrient management under organic systems therefore relies on the integrated use of bulky organic manures, concentrated organic amendments and beneficial microbial inoculants to enhance sesame growth, seed and oil yield, nutrient use efficiency, soil health and overall system sustainability (43–44).

Table 1. Phosphorus fractions in compost

Particulars	Water-soluble P (mg kg^{-1})	Olsen P (g kg^{-1})	Citric acid-soluble P (g kg^{-1})	Reference
Compost	73	1.28	0.73	(25)

In sesame, these nutrient-management principles are implemented through the integrated use of organic manures, biofertilisers and other biological inputs, which can improve nutrient availability, crop performance and soil health. Since sesame is an indeterminate crop producing capsules continuously from 50 to 90 days after sowing (DAS), nutrient sources capable of supplying nutrients gradually throughout the crop growth period are particularly important (45). Farmyard manure, vermicompost, green manures and other organic amendments provide sustained nutrient release that better matches crop demand, with nutrient mineralisation studies showing peak ammonium nitrogen (NH_4^+-N) release between 45 and 60 days after incubation (46) where release in general was highest at 45 days of incubation and declined thereafter. Biofertiliser integration further enhances nutrient cycling, biological nitrogen fixation, phosphorus solubilisation and microbial activity, thereby improving nutrient use efficiency and economic returns (27). Complementary evidence from other cropping systems provides a mechanistic basis for these responses, demonstrating that organic nutrient management improves crop nutritional quality, soil organic carbon, microbial diversity, nutrient cycling, carbon sequestration and biodiversity while reducing pesticide residues and greenhouse gas emissions (14, 15, 47–49). Organic farming provided diverse carbon and energy sources that supported a larger and more active microbial community, particularly fungal diversity (49). Recent evidence from the Gaoligong Mountains, a biodiversity hotspot in southwest China, showed that organic farming significantly increased soil organic carbon, total nitrogen (N) and phosphorus (P) compared with conventional systems. It also enriched C-cycling and N-cycling bacterial groups by 15.65 % and 11.59 %, respectively, versus 11 % and 9 % under conventional management and altered fungal guilds, including both beneficial and potentially pathogenic taxa (50). Furthermore, the enhanced soil biodiversity stimulated by organic amendments played a central role in nutrient cycling, organic matter decomposition, soil aggregation

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and maintenance of key ecosystem functions that sustain long-term soil fertility (51). Supporting these mechanisms, a laboratory soil incubation study demonstrated that corn straw, tobacco stalks and peanut shell biochar increased soil organic carbon by 13.9 %, 17.5 % and 44.8 % respectively, while increasing particulate organic carbon by 105.7 %, 20.2 % and 27.4 % respectively, compared with the unamended control. The amendments also altered the soil microbial community by increasing the abundance of *Bacteroidota* and reducing *Acidobacteria*, thereby enhancing soil carbon sequestration and fertility (52). Collectively, these findings provide a mechanistic basis for the beneficial effects of organic nutrient management on soil health and support the responses reported under sesame cultivation. However, these findings should be interpreted in relation to the duration and experimental conditions of the studies. Short-term increases in soil organic carbon, microbial biomass, enzyme activity or microbial community composition do not necessarily demonstrate sustained carbon sequestration, persistent changes in microbial diversity or long-term improvement in soil health. Evidence for such long-term effects requires multi-year or long-term field experiments assessing changes in soil carbon stocks, microbial communities and soil functioning over successive cropping seasons. Beyond soil health, a comprehensive review of 76 comparative studies concluded that organic farming consistently increased the species richness and abundance of birds, mammals, invertebrates and arable flora compared with conventional farming, highlighting its broader ecological benefits (53). Representative sesame-specific studies demonstrating the effects of organic nutrient management on crop productivity, quality, soil health and environmental sustainability are summarised in Table 2.

Table 2. Summary of evidence on organic nutrient management in sesame

Study context	Organic nutrient management practice	Major findings	Key outcome
Multi-location trial (Amreli, Mandor, Vridhachalam and Jalgaon; kharif) (43)	FYM (3.75 t ha^{-1}) + neem cake (900 kg ha^{-1}) + wood ash (75 kg ha^{-1}) + bone meal (75 kg ha^{-1}) + elemental sulphur (20 kg ha^{-1}) + PSB + Azotobacter + *Trichoderma viride* seed treatment + neem oil sprays	Significantly increased seed and oil yield across locations	Higher productivity under integrated organic package
Five-year comparison of organic vs conventional production, Hyderabad (2005–2009) (44)	FYM (3.7 t ha^{-1}) + neem cake (900 kg ha^{-1}) + wood ash (75 kg ha^{-1}) + bone meal (75 kg ha^{-1}) + elemental sulphur (20 kg ha^{-1}) + PSB 5 kg ha^{-1}) + Azotobacter + *Trichoderma viride* seed treatment + neem oil sprays	Organic yield about 20 % lower during first 3 years; yield gap reduced to 7–8 % by years 4–5	Transition period required before yield stabilisation under organic farming due to lower availability of readily mineralisable nutrients during transition
Bangladesh, silty loam soil (26)	Vermicompost (15 t ha^{-1}) + 70 % RDF + biofertilisers	Increased plant height, leaf area, leaf number, seed yield, nutrient uptake (N, P, K, S, Fe, Zn) and protein content	Improved productivity and seed quality
Balaghat, Madhya Pradesh (28)	Vermicompost (5 t ha^{-1}) + Rhizobium + PSB	Increased seed weight (88 %), biological yield, harvest index and gross monetary returns	Improved yield and profitability
Jaipur, loamy sand soil (54)	Vermicompost (4.5 t ha^{-1})	Improved chlorophyll content	Better physiological performance
Jhansi, kharif (27)	FYM + PSB + Mycorrhiza + SSB	Highest seed yield (15.63 q ha^{-1}) and B:C ratio (2.0)	Improved economics and nutrient uptake
Jhansi (27)	FYM (10 t ha^{-1}) + Rhizobium + PSB; Castor cake (2 t ha^{-1}) + Rhizobium + PSB	B:C ratio 3.16 with FYM; highest net returns (₹56,317 ha^{-1}) with castor cake	Economically viable organic nutrient packages
Junagadh, summer sesame (55)	FYM + castor cake + vermicompost	Highest oil content (51.54 %); statistically similar to lower FYM plus higher castor cake treatment	Improved oil quality
El Behaira Governorate, Egypt (56)	75 % RDF + 25 % organic + bio-organics	Increased oil and protein yields	Improved seed quality
Iran, loam soil under drought (57)	Biochar	Increased 100-seed weight, oleic acid, osmolytes and phenolics	Improved seed quality and stress tolerance
Iran, loamy soil (58)	Compost + FYM + Azotobacter + PSB	Improved oil quality and fatty acid composition	Better oil quality

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Compost + RDF study (25)	Compost (20–30 t ha^{-1}) + RDF	Increased field capacity, available moisture and porosity; reduced bulk density	Improved soil physical properties
Iran, clay loam soil (59)	Animal manure + fenugreek green manure	Increased Cu, Zn, Mn, Fe, dry matter, grain yield and oil yield	Improved soil fertility and productivity
Eight-season field study, Tamil Nadu (60)	Microbial-inoculated sesame stalk compost (5 t ha^{-1})	Increased SOC stock; reduced bulk density and penetration resistance; improved grain quality and oil yield	Improved long-term soil health
Jobner, Rajasthan (61)	Vermicompost (5 t ha^{-1}) and FYM (10 t ha^{-1})	Increased SOC, nutrient availability, microbial biomass, dehydrogenase and phosphatase activities	Enhanced soil biological activity
Saline soil study, Tamil Nadu (62)	PGPR inoculation	Increased SOC (0.25–0.32 %) and nutrient availability	Improved soil fertility under stress
Continuous sesame system, China (63)	Rice husk biochar (15 t ha^{-1})	Improved rhizosphere microbial community and suppressed *Macrophomina*	Improved soil biological health and disease suppression
Environmental assessment, Iran (11)	Biofertilisers and integrated nutrient management	Reduced greenhouse gas emissions, carbon footprint and environmental impact	Environmental sustainability
Andhra Pradesh, three-season field study (16)	*Trichoderma* seed treatment + inoculated FYM + Azospirillum + split neem cake + Jeevamrut + neem oil	12 % higher energy-use efficiency, 10 % higher productivity; improved oil and protein content, SOC and nutrient availability	Improved productivity, quality, energy efficiency and soil health

B:C: benefit–cost ratio; Fe: iron; FYM: farmyard manure; K: potassium; Mn: manganese; N: nitrogen; P: phosphorus; PGPR: plant growth-promoting rhizobacteria; PSB: phosphate-solubilising bacteria; RDF: recommended dose of fertilisers; S: sulphur; SSB: sulphur-solubilising bacteria; SOC: soil organic carbon; Zn: zinc.

Overall, the available evidence indicates that organic nutrient management can improve soil organic carbon, nutrient availability, microbial activity and sesame productivity, but the magnitude of these effects varies considerably with the type, nutrient composition and rate of organic amendment, soil characteristics and climatic conditions. Sesame-specific studies from India, Iran and other regions generally reported positive responses to organic amendments and integrated nutrient management. However, yield responses were not always proportional to the quantity of organic material applied. This variation is partly attributable to differences in nutrient release rates, C : N ratios, soil fertility status and environmental conditions. Organic amendments therefore cannot be considered interchangeable nutrient sources and their agronomic effectiveness depends on synchronising nutrient mineralisation with crop demand. Moreover, much of the available evidence is based on short-term or single-location experiments, limiting the extrapolation of results across contrasting agro-ecological regions. Long-term, multi-location studies are needed to determine whether the observed improvements in soil quality and productivity are sustained over successive sesame-growing seasons.

Nutrient substitution

When nutrient availability is adequate, crop yields obtained with organic nutrient sources are generally comparable to those achieved with inorganic fertilisers (39). Compost, chicken manure and farmyard manure (FYM) applied at 12, 24 and 48 cubic metres per hectare (m^3 ha^{-1}), either alone or in combination with reduced mineral nitrogen (72 kilograms of nitrogen per hectare (kg N ha^{-1})), were evaluated on sesame grown under drip irrigation in newly reclaimed calcareous soil in Egypt. Among the organic nutrient sources, chicken manure produced the highest seed, oil and protein yields, whereas FYM combined with 72 kg N ha^{-1} achieved seed yield comparable to or exceeding that obtained with the recommended mineral nitrogen dose (108 kg N ha^{-1}). Nitrogen fertiliser replacement values varied among the manure sources, with FYM exhibiting the highest nitrogen equivalency (62 %), followed by chicken manure (50 %) and compost (30 %), indicating their potential to partially substitute inorganic nitrogen fertilisers. The differences in apparent nitrogen equivalency among organic amendments should not be interpreted as evidence that one amendment is universally superior to another. Nitrogen equivalency depends on the chemical composition and decomposition characteristics of the material, particularly its total N concentration, C : N ratio, degree of decomposition and the proportion of N present in

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readily mineralisable forms. The maturity and humification characteristics of microbial-inoculated sesame stalk compost are presented in Table 3. Farmyard manure may provide a relatively greater proportion of plant-available N when it is adequately decomposed, whereas mature compost can contain a larger proportion of stabilised organic N, resulting in slower mineralisation and lower short-term N availability. Conversely, the slower release from compost may contribute to longer-term soil organic matter accumulation and nutrient retention. Therefore, N-equivalency values obtained under one soil, climate and management system should not be directly extrapolated to other regions. Differences in manure source, animal diet, storage conditions, composting method and maturity can substantially alter nutrient concentration and mineralisation behaviour. The key differences between fresh and composted manure are summarised in Table 4.

The practical value of organic nutrient substitution is also influenced by the low nutrient concentration and relatively high bulk volume of many organic amendments. Meeting crop N requirements entirely through FYM or compost may therefore require substantially larger quantities of material than mineral fertilisers, increasing loading, transportation, handling and field-application costs. These constraints become particularly important where organic amendments must be transported over long distances. Consequently, nutrient substitution should be evaluated not only on the basis of percentage N replacement but also in terms of nutrient concentration, application rate, availability of locally produced materials and the cost and energy required for their transport and application. The nutrient concentrations of organic manures at different locations are mentioned in Table 5.

The C : N ratio of organic amendments is another important determinant of short-term N availability. Materials with a relatively high C : N ratio can stimulate microbial immobilisation of mineral N during decomposition, temporarily reducing the amount of N available to the crop. In contrast, well-decomposed materials with a lower or more stabilised C : N ratio generally release N more gradually and predictably. Thus, the timing of organic amendment application and the synchronisation between N mineralisation and sesame nutrient demand are critical for minimising temporary N immobilisation and improving nutrient-use efficiency.

Organic amendments also enhanced the concentrations of phosphorus, iron, manganese and copper in sesame seeds, demonstrating their contribution to improved nutrient uptake and seed quality (64). This conclusion supports the idea that organic manures can effectively supplement mineral nitrogen while improving soil fertility and sustaining sesame productivity. The substitution of recommended nitrogen through FYM, vermicompost and neem oil cake for two consecutive kharif seasons on Vertisols at Jabalpur, Madhya Pradesh, revealed that the highest seed and straw yields were obtained with 100 % recommended dose of fertiliser (RDF); however, these were statistically at par with 50 % RDF supplemented with 50 % of the recommended nitrogen through neem oil cake, vermicompost, or FYM, suggesting that partial nutrient substitution can sustain sesame yield while reducing dependence on chemical fertilisers. The highest relative growth rate was recorded when the entire recommended nitrogen requirement was supplied through FYM, indicating enhanced crop growth under complete organic nitrogen substitution (65). In a clay soil at Navsari, Gujarat, meeting 100 % of the nitrogen requirement through equal proportions (16.7 kg ha^{-1} each) of biocompost, vermicompost and castor cake increased available nitrogen and diethylenetriaminepentaacetic acid (DTPA)-extractable iron in the soil (66).

Table 3. Compost maturity and humification characteristics of microbial inoculated sesame stalk compost

Organic amendment	Humic acid (mg g^{-1} compost)	Fulvic acid (mg g^{-1} compost)	Total humic substances (mg g^{-1} compost)	CO_2-C evolution (mg 100 g^{-1} compost)	Reference
Microbial inoculated sesame stalk compost	122	23–24	145–146	186–188	(-60)

Table 4. Comparison between fresh manure and composted manure (38)

Parameter	Fresh manure	Composted manure
Nitrogen availability	High	Lower (more stabilised)
Risk of ammonia loss	High	Lower
Weed seeds	Present	Mostly destroyed
Pathogens	May survive	Largely eliminated
Organic matter stability	Low	High
Long-term soil fertility	Moderate	High

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Table 5. Nutrient composition at various locations

Organic amendment	N (%)	P (%)	K (%)	EC (dS m^{-1})	pH	Fe (mg kg^{-1})	Mn (mg kg^{-1})	Zn (mg kg^{-1})	Cu (mg kg^{-1})	Organic carbon (%)	Reference
Bio compost	1.32	1.19	1.65			1264	132	58	34		
Vermicompost	1.14	0.95	1.91			1148	102	52	18		(66)
Castor cake	4.50	1.41	1.30			1022	95	54	28		
Animal manure				0.52	7.36	5000	250	55.5	14	5.96	(59)
Vermicompost	3.19	0.41	0.086	18.85	7.4	473	69	10	10		(58)
	1.5	0.8	1.0								(61)
Microbial inoculated Sesame stalk compost	1.45–1.50	0.22–0.25	0.23–0.25			510–514	150–154	286–288	540–542		(60)
FYM	0.5	0.2	0.5								(16,60)
	0.87*	84.5**	84**	2.81	7.96					12.87	(56)
Neem cake	3.0	0.5	0.7								(16)
Compost	1.8	2.06*	1.95*	1.67	8.15					26.2	(25)

*Total; ** ppm.

EC: electrical conductivity; FYM: farmyard manure; N: nitrogen; P: phosphorus; K: potassium; Fe: iron; Mn: manganese; Zn: zinc; Cu: copper; ppm: parts per million.

Field experiments conducted at International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Hyderabad, on deep Vertisols under a fixed-plot soybean-sesame cropping system established in 2018 evaluated different organic nutrient management modules comprising 100 % RDF through FYM, green leaf manure (*Gliricidia* sp.), castor cake, or neem cake, each supplemented with rock phosphate and phosphate-solubilising bacteria (PSB), along with *Trichoderma viride* seed treatment and other organic best management practices. Among the treatments, castor cake maintained the highest soil organic carbon (0.81 %) after harvest compared with 0.59 % in the control and an initial soil organic carbon (SOC) of 0.42 % in 2018 (21). Similarly, the same cropping system showed that green leaf manure and a combination of FYM, vermicompost and goat manure produced sesame yields comparable to 100 % recommended inorganic fertilisation, while continuous application of FYM-based organic modules increased soil organic carbon up to 0.78 % without affecting seed oil content, highlighting their potential for sustainable sesame production (67). Application of 100 % recommended nitrogen through 50 % FYM and 50 % vermicompost, together with the remaining recommended phosphorus supplied through rock phosphate, resulted in the highest growth parameters, yield attributes and seed yield of summer sesame grown during the Zaid season under irrigated sandy loam soil at Bhubaneswar, Odisha (68).

A two-year field experiment conducted during the kharif seasons at Jobner, Rajasthan, evaluated nutrient substitution through FYM and vermicompost in a loamy sand soil. The study compared 100 % recommended nitrogen through organic sources with partial substitution of recommended nitrogen (50 % recommended dose of nitrogen (RDN) + 50 % N through FYM or vermicompost). Among the integrated nutrient management treatments, application of 50 % RDN + 50 % N through vermicompost recorded the highest seed yield (799 kg ha^{-1}), while 50 % RDN + 50 % N through FYM produced statistically comparable seed (756 kg ha^{-1}) and stalk yields (2329 kg ha^{-1}). Both treatments significantly enhanced N, P, K and S concentration and uptake, as well as seed protein and oil content, compared with the other nutrient management practices (27).

An experiment comparing organic farming (FYM applied on an N-equivalent basis), inorganic farming (recommended dose of fertilisers and other chemicals), integrated nutrient management (5 tonnes (t) FYM ha^{-1} + the remaining N through inorganic fertilisers) and natural farming (following natural farming protocols, including Jeevamrutha and Beejamrutha) showed that microbial populations, including *Pseudomonas*, *Azotobacter* and total bacterial count, as well as soil enzymatic activities such as dehydrogenase (2.6–6.8 µg triphenyl formazan (TPF) g^{-1} day^{-1}) and phosphatase, were higher under organic farming with FYM applied on an N-equivalent basis. This treatment also improved crude fat content (54.71 %), which was attributed to enhanced carbohydrate metabolism and carbon partitioning towards lipid biosynthesis under balanced, slow-release nutrient conditions in summer sesame grown on sandy clay loam soil at Jagtial, Telangana (69).

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Collectively, these studies demonstrate that integrated use of organic manures, biofertilisers and biological inputs not only sustain sesame productivity and improves seed quality but also enhances soil fertility, microbial activity and ecosystem resilience, thereby supporting long-term sustainable sesame production.

Weed management

Weed management is a major challenge in organic sesame cultivation, particularly during the early growth stages. *Portulaca oleracea* L., *Cyperus rotundus* L., *Euphorbia* spp., *Physalis angulata* L., *Heliotropium europeum*, *Echinochloa crusgalli* (L.) P.Beauv, *Convolvulus arvensis* L., *Hibiscus trionum* L., *Tribulus terrestris* L., *Solanum nigrum* L. and *Cucumis melo* var. agrestis Naudin were identified as the most common weeds in sesame at Yumurtalık, Adana, Turkey (70). They deduced a critical period of weed control (CPWC) as 14–64 days after emergence, which typically occurs between 15–45 days after sowing (DAS), although the exact duration may vary depending on the cultivar and prevailing environmental conditions (34). It is argued that in organic farming systems, the concept of CPWC can be misleading (71) if treated as a fixed prescription for weed removal. This is particularly relevant where herbicides are not used and weed management depends on preventive, cultural and mechanical measures. Nevertheless, CPWC can provide useful information on the period of greatest crop-weed competition when interpreted together with weed emergence dynamics, weed seed-bank characteristics, crop competitiveness, soil and climatic conditions, labour availability and the efficacy of non-chemical control methods. Thus, for organic sesame, CPWC is better considered as a management guide rather than a rigid recommendation for a single weeding operation, while the timing of initial weed removal may be particularly important.

Weed control in organic systems focuses on management techniques designed to prevent the introduction and growth of weeds, by using clean seed and equipment, using well-decomposed composts as well as the production of a crop vigorous enough to outcompete weeds, i.e., crop competitive cultivars. Mechanical methods such as hand weeding and intercultivation at appropriate stages have been found effective in reducing weed competition and improving crop yield (72). Organic amendments such as compost improve soil structure and crop competitiveness, indirectly contributing to weed suppression.

In addition to these practices, mulching with crop residues generally helps suppress weed emergence by limiting light penetration and conserving soil moisture (73). Furthermore, in sesame, it was reported that the use of *Calendula officinalis* L. as a living mulch significantly suppressed weed growth, reducing grass weeds by 51 %, broadleaf weeds by 72 % and total weed biomass by 62.6 % (74).

Intercropping acts as an eco-friendly approach for weed management in sesame. Intercropping sesame with legumes enhances ground cover and reduces weed growth by increasing crop competition. Use of cover crops and crop rotation further helps in reducing weed seed bank and breaking weed life cycles, thereby contributing to long-term weed management in organic sesame systems. Intercropping sesame with black gram in an 8:2 ratio significantly reduced weed population along with fresh (11.01 g m^{-2}) and dry weed biomass (3.71 g m^{-2}) (33). Similarly, a 3 : 1 sesame-mung bean intercropping system (75 % sesame : 25 % mung bean) effectively lowered weed density and reduced weed diversity, as indicated by a lower Shannon diversity index (75).

Allelopathy also contributes as a supplementary mechanism in weed suppression through natural biochemical interactions. Sorghum aqueous leaf and stem extracts (sorgaab) enhanced the activities of antioxidant enzymes, including polyphenol oxidase (PPO), peroxidase (POD) and phenylalanine ammonia-lyase (PAL), in both sesame and weeds. However, the extracts alone did not effectively suppress weed growth, highlighting the need for integrated weed management strategies rather than sole reliance on sorgaab (76). Extracts of *Parthenium hysterophorus* L. and *Nerium oleander* L. suppressed weed growth in a concentration-dependent manner (77), while *Ageratum conyzoides* Sieber ex Steud. and *Ocimum sanctum* L. extracts effectively suppressed sedges, broadleaf weeds and grasses respectively (78). However, promising allelopathic strategies are not yet available and the efficacy and selectivity of allelopathic extracts are strongly dependent on extract concentration, application timing, plant species and environmental conditions and the possibility of phytotoxic effects on the crop or other non-target plants should also be considered when determining suitable application rates. Therefore, further field-based validation is required before these approaches can be recommended as reliable weed-management options in organic sesame.

Natural-substance herbicides such as vinegar (acetic acid) and clove oil may be permitted under United States Department of Agriculture (USDA) organic standards, subject to applicable organic production requirements. Overall, organic weed-management practices can suppress weeds in sesame through physical, cultural and biological mechanisms, but their effectiveness is strongly influenced by weed composition, soil and climatic conditions, crop density, timing of intervention and availability of labour. Mulching and intercropping can provide effective weed suppression in some environments, whereas mechanical weeding and allelopathic approaches may show variable results depending on the dominant weed species and field conditions. In addition, many studies have evaluated individual practices over a single season, limiting conclusions about their long-term effectiveness and economic feasibility. Therefore, integrated combinations of preventive, cultural, mechanical and biological approaches may be more appropriate than reliance on a single weed-management practice, although multi-location and long-

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term validation under certified organic production systems remains limited.

Insect-pest management

Insect-pest management in organic sesame relies on an integrated approach involving cultural practices, biological control, botanical pesticides and conservation of natural enemies. Cultural practices such as timely sowing to escape peak pest incidence, increasing seed rate to reduce ant damage and management of aphids and whiteflies help minimise pest infestation. Biological control is promoted by conserving or augmenting natural enemies including parasitoids (e.g., braconid wasps and *Diadegma* spp.) and predators such as lacewings, hoverflies, ladybird beetles, damsel bugs and spiders. Biological control in sesame can be strengthened through the conservation and augmentation of specific parasitoids and predators associated with major insect pests. For the sesame leaf webber *Antigastra catalaunalis*, several larval parasitoids have been recorded, including *Eriborus* spp., *Trathala flavoorbitalis*, *Bassus* sp., *Habrobracon hebetor*, *Phanerotoma* sp. and members of Agathidinae (79). Earlier observations also documented *Phanerotoma* sp., *Apanteles* sp., *Elasmus brevicornis* and *T. flavoorbitalis*, with parasitism of 19.17, 16.92, 15.49 and 13.85 % respectively, in western Uttar Pradesh (80). Botanical pesticides prepared from neem (*Azadirachta indica* A.Juss.), chilli (*Capsicum* spp.), lantana (*Lantana camara* L.), pawpaw (*Carica papaya* L.), *Tephrosia* spp., black jack (*Bidens Pilosa* L.), castor (*Ricinus communis* L.) and maize flour are commonly recommended for the management of aphids, whiteflies, sesame webworm and other insect pests, providing environmentally safe alternatives to synthetic insecticides (81).

Host plant resistance constitutes an important component of integrated organic pest management, as varietal differences can influence pest development and infestation levels. For field pests, substantial variation in resistance to the sesame leaf webber *Antigastra catalaunalis* has been reported among sesame germplasm. Screening of 276 germplasm at ICAR-Indian Institute of Oilseeds Research, Hyderabad, identified 46 germplasm that remained highly resistant across two seasons; in the first season, B 203, DSK-1-A, EC-511212, EVC-101, IC-205201, IC-205775, IC-413205, IC-500343, IS-17 and SL-11 showed no leaf-webber incidence (82). In another field evaluation of 86 sesame genotypes, S-0301, NSS and 03-Oct showed moderate resistance to *A. catalaunalis* at vegetative, flowering and capsule stages, while NIC-8473, IC-131943, NIC-16248, ES-47 and KMR-32-A showed moderate resistance based on flower and capsule damage (83). The biology of the red flour beetle, *Tribolium castaneum*, was evaluated on three sesame varieties under laboratory conditions. Significant variation was observed in insect development among the varieties, with the black-seeded cultivar GT-10 being the least preferred, as indicated by the longest incubation period (6.48 days), larval duration (37.22 days) and adult longevity (33.20 days). In contrast, the white-seeded cultivar Swetha was the most preferred host, supporting faster insect development (84). These findings suggest that varietal characteristics influence the susceptibility of stored sesame to *T. castaneum* infestation and may be considered in developing integrated storage pest management strategies. Besides host plant resistance, habitat management practices such as intercropping and organic mulching have also been reported to reduce pest incidence by disrupting pest colonisation and enhancing the activity of natural enemies (29, 73).

Among botanical pesticides, neem-based formulations such as neem oil and azadirachtin have received considerable attention because of their antifeedant, repellent and insect growth-regulating properties. Intercropping sesame with greengram combined with a 9 parts per million (ppm) azadirachtin spray at the flowering stage reduced *Antigastra* incidence from 24.79 % to 13.04 % and *Macrophomina* incidence from 16.88 % to 6.25 % (29). Sesame + pigeonpea intercropping at a 3:1 ratio combined with two foliar sprays of 1 % neem oil resulted in the lowest incidence of *Antigastra* and bud fly, along with the highest seed yield (619 kg ha^{-1}) (85). Similarly, *Calendula officinalis* L. used as a living mulch reduced the densities of *Myzus persicae*, *Brevicoryne brassicae*, *Helicoverpa armigera* and *Spodoptera exigua*, while increasing the abundance of natural enemies such as *Coccinella septempunctata*, *Coccinella undecimpunctata* and *Orius niger* (73). Experiments conducted in Zimbabwe further demonstrated that mulching significantly increased populations of ground-dwelling spiders, particularly Lycosidae, followed by Gnaphosidae and Thomisidae, thereby highlighting the role of habitat management in enhancing biological pest control (86).

Bio-pesticides and botanicals, including neem seed kernel extract (NSKE) 5 %, neem oil 0.3 %, *Beauveria bassiana* 0.1 %, *Lecanicillium lecanii* 0.4 % and azadirachtin 0.0006 %, were evaluated against whitefly, leaf hopper and leaf webber in sesame. The NSKE 5 % effectively reduced the population of leaf webber and was statistically at par with *B. bassiana* 0.1 %, neem oil 0.3 % and azadirachtin 0.0006 % in minimising leaf, flower and capsule damage. It also recorded the highest seed yield, with a 56.65–93.27 % increase over the untreated control, along with the highest benefit-cost ratios of 1 : 9.86 and 1 : 7.74 during the summer and kharif seasons respectively (87).

Recent integrated management approaches have shown strong potential for reducing pest pressure in sesame. An intensive organic pest management package comprising 75 % N through FYM + 25 % N through neem cake, seed treatment with *Trichoderma* spp. (10 g kg^{-1} seed), furrow application of enriched *Trichoderma* (2.5 kg culture + 100 kg vermicompost at 250 kg ha^{-1}), release of *Trichogramma chilonis* (5 cubic centimetres (cc) egg cards ha^{-1} at 10-day intervals, 6 times), maize as a border crop, one sticky trap per plot and foliar sprays of neem oil (10 mL L^{-1}) at 30 and 45

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DAS reduced *Antigastra* larval populations to 0.20–1.00 larvae plant^{-1} and lowered plant damage (30).

Seven botanical extracts were evaluated against sesame webworm under field conditions at Humera, Ethiopia. Three sprays of *Azadirachta indica* and *Ricinus communis* extracts were the most effective, reducing webworm incidence from 82.59 % in the untreated control to 28.89 % and 29.63 % respectively. Leaf damage declined to 8.56 % and 8.68 % compared with 21.8 % in the control, while capsule damage decreased to 3.34 % and 2.66 % respectively, compared with 11.51 % in the control. Among the botanicals tested, *Azadirachta indica* produced the highest seed yield (0.71 t ha^{-1}), representing a 222.73 % increase over the untreated control, indicating that both extracts can serve as effective alternatives to synthetic insecticides in sesame (88). However, this substantial yield response was observed under the specific experimental conditions of the study and should not be generalised across production environments, as botanical efficacy can vary with formulation, concentration, application timing, pest pressure and environmental conditions.

Biopesticides such as nuclear polyhedrosis virus (NPV) and *Bacillus thuringiensis* have also been found effective against lepidopteran pests under field conditions. Foliar application of *Bacillus thuringiensis* var. *kurstaki* significantly reduced *Antigastra catalaunalis* infestation and improved sesame seed yield compared with the untreated control, indicating its potential as an eco-friendly component of integrated pest management, although its efficacy remained lower than that of conventional chemical insecticides (89).

Eco-friendly storage practices also play an important role in minimising post-harvest losses caused by storage insect pests in sesame. An investigation on hermetic storage technologies demonstrated that storing sesame seeds in high-density polyethylene (HDPE) bags, either alone or in combination with sweet flag (*Acorus calamus* L.) rhizome powder at 10 g kg^{-1} seed, significantly reduced seed damage caused by the rice moth (*Corcyra cephalonica*) and the red flour beetle (*Tribolium castaneum*) compared with conventional cloth and jute gunny bags after 6 months of storage (90).

Collectively, botanical pesticides, biological control agents, host plant resistance and habitat management can reduce pest pressure in sesame, but their effectiveness varies with pest species, environmental conditions, crop stage and application method. Botanical and biological approaches may also require repeated application or appropriate timing because their persistence and efficacy can be lower than conventional insecticides. In addition, limited information is available on their compatibility, cost-effectiveness and performance when several methods are combined within complete organic pest-management programmes.

Disease management

Organic disease management in sesame relies primarily on preventive cultural practices, biological control agents and integrated crop management strategies to suppress soil- and seed-borne pathogens. TKG-21, RT-125 and RT-103 are reported to be tolerant to phyllody, whereas RT-46, RT-125, MT-75, TKG-22 and Nirmala are reported to be tolerant to stem and root rot caused by *Macrophomina phaseolina* (91). Crop rotation, intercropping and sanitation practices help reduce soil-borne pathogen inoculum and limit disease spread. Cultivation of onion and garlic as preceding crops reduced the populations of *Fusarium oxysporum* and other rhizospheric fungi associated with sesame (92). Likewise, a sesame-pearl millet (4:1) intercropping system combined with early sowing was recommended for reducing the incidence of *Phytophthora* blight and *Cercospora* leaf spot (93). Sanitation practices, including the removal of infected crop residues and deep ploughing, reduce the survival of *Macrophomina phaseolina* microsclerotia in the soil (94). In addition, maintaining proper field drainage and well-drained soils helps minimise the incidence of *Phytophthora* blight (89).

Several studies have demonstrated that *Trichoderma* spp., are highly effective in managing soil-borne diseases of sesame, with seed treatment and soil application significantly reducing disease incidence while improving plant vigour, yield and soil microbial activity. Seed treatment with *Trichoderma viride* at 10 g kg^{-1} seed followed by soil application at 2.5 kg ha^{-1} effectively reduced *Macrophomina* root and stem rot in sesame (95). Seed treatment with *Trichoderma viride* (5 g kg^{-1} seed) in combination with *Pseudomonas fluorescens* (10 g kg^{-1} seed), along with soil application of *T. viride*- or *P. fluorescens*-enriched FYM and neem cake (250 kg ha^{-1}), reduced the incidence of *Macrophomina phaseolina* root and stem rot to about 11 %, compared with 38 % in the untreated control (32). Extending these findings, an integrated *Trichoderma*-based disease management strategy comprising seed treatment with *Trichoderma viride* (10 g kg^{-1} seed), furrow application of *T. viride*-enriched vermicompost (2.5 kg culture + 100 kg vermicompost at 250 kg ha^{-1}), rhizosphere inoculation with *T. viride* and foliar sprays of *T. viride* (5 g L^{-1}) during thinning, flowering and capsule stages resulted in the lowest incidence of *Macrophomina* stem/root rot (12.85 %). The treatment also enhanced soil microbial activity, suppressed pathogenic organisms and significantly reduced the incidence of *Macrophomina* stem/root rot (12.85 %), *Cercospora* leaf spot (14.38 percent disease index (PDI)) and *Phytophthora* blight (12.20 PDI) under field conditions, demonstrating that the combined application of *Trichoderma* through multiple delivery methods provides broad-spectrum disease suppression in sesame (96).

Fluorescent *Pseudomonas* spp., have shown promise as biological control agents against sesame diseases when applied as seed treatments, soil

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applications, or both, either alone or in combination with *Trichoderma* spp., to suppress soil-borne pathogens and reduce disease incidence. Similarly, *Pseudomonas aeruginosa* LES4, a fluorescent *Pseudomonas* isolated from the tomato rhizosphere, inhibited *Fusarium oxysporum* f. sp. *sesami* by 69 % under *in vitro* conditions and also reduced wilt incidence in sesame under field conditions (97).

The antagonistic potential of these bioagents has also been confirmed under laboratory conditions. The efficacy of *Trichoderma harzianum*, *Trichoderma viride* and *Pseudomonas fluorescens* against *Macrophomina phaseolina* was compared using dual culture, volatile and non-volatile metabolite assays. Among the bioagents evaluated, *T. harzianum* exhibited the strongest antagonistic activity, recording 66.94 % inhibition of pathogen growth in the dual culture assay and approximately 59 % inhibition through both volatile and non-volatile metabolites. *Trichoderma viride* also showed substantial suppression of the pathogen, followed by *P. fluorescens*. These findings demonstrate the superior antagonistic potential of *Trichoderma* spp., particularly *T. harzianum*, against *M. phaseolina* and support their inclusion in integrated biological disease management programmes for sesame (31).

Organic soil amendments can further enhance biological disease suppression. Soil amendment with spent mushroom substrate (SMS) of oyster mushroom + *Trichoderma harzianum* (Th) before sowing reduced disease severity by 51.41 % over the control and increased yield by 44.55 %. Spent mushroom substrate (SMS) + Th + *Pseudomonas fluorescens* (Pf) also cut disease incidence by 20.04 % (98) highlighting the synergistic effects of organic amendments and microbial bioagents in sesame disease management.

Collectively, biological control agents, cultural practices and other non-chemical approaches can contribute to disease suppression in sesame, but their effectiveness depends on the pathogen, inoculum pressure, soil conditions and timing of application. The performance of individual biocontrol agents may also vary, making integrated approaches more reliable than dependence on a single method. Further attention is needed to optimise combinations of compatible biological and cultural practices for consistent disease management under organic sesame production.

Economic viability

The economic viability of organic sesame depends on input costs, labour requirements, yield response and the price premium obtained for organic produce. Sesame-specific evidence indicates that organic production may involve higher cultivation costs and lower yields during the initial years, making access to premium prices important for maintaining profitability (16). However, favourable returns have also been reported with suitable combinations of organic manures and biofertilisers, indicating that profitability varies with the nutrient-management strategy and production environment (27). Thus, economic assessment of organic sesame should consider both production costs and potential market premiums rather than yield alone.

Policy and institutional support

Policy and institutional support are important for the adoption, certification and marketing of organic sesame in India. Major initiatives include the Paramparagat Krishi Vikas Yojana (PKVY), which promotes cluster-based organic farming, capacity building and certification support and the Mission Organic Value Chain Development for the North Eastern Region (MOVCDNER), which supports organic production together with value-chain development and market linkages. The National Programme for Organic Production (NPOP), implemented by Agricultural and Processed Food Products Export Development Authority (APEDA), provides standards for organic production, accreditation of certification bodies, inspection and certification and use of the India Organic logo. Under National Programme for Organic Production (NPOP), certification is generally based on third-party inspection and certification, making it particularly relevant to certified commercial and export-oriented organic production. For domestic and local markets, the Participatory Guarantee System of India (PGS-India) provides a decentralised, farmer-group-based approach to organic assurance. Products under PGS-India may carry the PGS-India Organic logo after meeting the prescribed requirements, while PGS-India Green identifies produce from farms under conversion to organic production. In contrast to third-party certification, PGS-India relies on participatory mechanisms involving farmers and local stakeholders. The Jaivik Bharat logo provides a common identity for organic food products in the Indian market, while the India Organic logo is associated with certification under the NPOP framework.

These institutional mechanisms can improve consumer confidence, traceability and market access, although certification costs, documentation requirements, conversion periods and limited awareness may remain barriers for small and marginal farmers. Strengthening crop-specific extension, farmer training, access to approved organic inputs and market linkages in sesame-growing regions could therefore support wider adoption of certified organic sesame production.

Farmer adoption factors

Adoption of organic sesame farming is influenced by economic, technical and institutional factors. Higher labour requirements, availability and cost of organic inputs, the time required for nutrient release, conversion periods and uncertainty about yield during the transition can discourage farmers from adopting organic practices. Conversely, access to organic inputs, technical knowledge, extension services, certification support, premium markets and farmer groups can facilitate adoption. These factors may vary among regions according to farm size, availability of livestock and biomass, market access and local production conditions. Therefore, improving farmer training,

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strengthening extension services, facilitating certification and developing reliable market linkages are important for promoting wider adoption of organic sesame production.

Challenges

- Slow and inconsistent nutrient release from organic amendments makes synchronisation with crop demand difficult.
- Bulky nature of organic manures
- Variability in nutrient composition of organic manures results in inconsistent field performance
- Most reported improvements in soil health are based on short-term, location-specific studies, limiting their wider applicability.
- Botanical pesticides and biological control agents provide variable efficacy and generally require repeated applications.
- Organic weed management relies heavily on labour-intensive hand weeding, while living mulches and allelopathic extracts alone often provide inadequate weed suppression.
- Low productivity, transition-period yield penalties, inadequate certification and poor marketing infrastructure restrict large-scale adoption of organic sesame farming

Research needs

- Long-term, multi-location studies on integrated organic nutrient management and nutrient release dynamics.
- Nutrient use efficiency and the role of alternative green manures
- Long-term changes in soil carbon fractions, microbial diversity, enzyme activities, biochar optimisation and PGPR-soil microbiome interactions
- Economic threshold levels, long-term natural enemy dynamics and compatibility between botanicals and biological control agents in sesame
- Variety-specific weed competition periods, long-term weed seedbank dynamics, optimised intercropping systems
- The influence of organic management on sesame lignans (sesamin, sesamolin and sesamol), oil quality and physiological mechanisms
- Life cycle assessment, carbon footprint, energy-use efficiency, economics and crop rotation-based organic sesame production systems.

Conclusion

Organic farming offers a sustainable approach to sesame cultivation by improving soil health, nutrient availability, biodiversity and seed quality while reducing dependence on synthetic agrochemicals. The integrated use of organic manures, biofertilisers, botanicals and biological control agents enhances crop productivity and supports environmentally sustainable production systems. However, challenges related to nutrient synchronisation, weed management, pest and disease management and inconsistent field performance continue to limit the widespread adoption of organic sesame cultivation. Addressing the identified research gaps through long-term, multi-location studies and the development of standardised, region-specific organic production packages is essential. Future advances in organic sesame production will depend on the integration of precision nutrient management, resilient microbial

Authors' contributions

KH was responsible for the literature review, synthesis of information, manuscript preparation and editing. KR contributed to the conceptualisation of the review, critical review of the manuscript, discussion and drafting of the conclusions and supervision. ACB contributed to the literature review, discussion on weed management and editing. SS has contributed to the critical review of the manuscript and discussion.

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

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