



REVIEW ARTICLE

Soil-centred organic amendments for sustainable vegetable cropping systems: Mechanisms and future prospects

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Abstract

Organic soil amendments have gained increasing attention as sustainable tools for improving soil health and enhancing vegetable crop productivity in intensive agricultural systems. This systematic literature review synthesises current evidence on the effects of organic amendments, including farmyard manure (FYM), compost, vermicompost, green manures, crop residues and biochar, on soil quality and vegetable production. Relevant literature published between January 2000 and April 2026 was retrieved from Scopus, Web of Science (WoS), ScienceDirect, PubMed and Google Scholar following the PRISMA 2020 guidelines using predefined inclusion and exclusion criteria. The findings demonstrate that organic amendments significantly improve soil physical, chemical and biological properties by enhancing soil structure, aggregate stability, water-holding capacity, nutrient availability, microbial activity and organic carbon (C) accumulation. These improvements promote efficient nutrient cycling, greater nutrient-use efficiency (NUE) and improved crop resilience under diverse environmental conditions. Evidence further indicates positive effects on seed germination, plant growth, yield, quality attributes and nutrient uptake in a wide range of vegetable crops. The combined application of organic amendments with inorganic fertilisers through integrated nutrient management (INM) may complement organic amendments in specific production systems; however, this review primarily focuses on the mechanisms, applications and sustainability benefits of organic soil amendments, resulting in higher productivity and improved soil fertility compared with the use of either source alone. In addition to agronomic advantages, organic amendments contribute to C sequestration, reduced dependence on synthetic fertilisers, enhanced environmental sustainability and improved economic returns for farmers. Despite challenges such as labour requirements, variable nutrient release patterns and storage constraints, organic amendments remain essential components of sustainable vegetable production systems. Future research should focus on region-specific management strategies, long-term field evaluations and optimisation of amendment combinations to maximise soil health and crop productivity.

Keywords: integrated nutrient management; organic soil amendments; soil fertility; soil health; sustainable agriculture; vegetable cropping systems

Introduction

Vegetable-based cropping systems are among the most nutrient-intensive agricultural systems due to their rapid growth rates, shallow root architecture and high nutrient demand during their relatively short growth cycles. Unlike cereal crops, vegetables extract large quantities of nutrients from soils within a limited time, making them particularly sensitive to nutrient imbalances and soil fertility constraints (1, 2). Essential nutrients play critical roles in enzyme activation, photosynthesis, chlorophyll synthesis and metabolic regulation in vegetable crops. However, nutrient deficiencies and declining soil fertility are widespread in vegetable-growing soils, particularly in alkaline, calcareous and intensively cultivated regions where nutrient availability is often limited due to unfavourable soil chemical conditions (3).

Continuous reliance on high-analysis chemical fertilisers with limited organic inputs has further aggravated soil degradation by reducing soil organic carbon (SOC), weakening nutrient buffering capacity and disrupting soil biological activity (4, 5). This imbalance in soil fertility frequently results in poor plant growth, reduced leaf expansion, impaired root development and significant yield and quality losses in vegetable crops. Therefore, improving soil health has become a key priority for sustaining productivity in vegetable-based farming systems.

Organic soil amendments such as farmyard manure (FYM), compost, vermicompost, green manures, crop residues and biochar play a crucial role in improving soil health and maintaining long-term soil fertility. These amendments influence soil properties through multiple interacting mechanisms, including pH buffering, enhancing

cation exchange capacity, improvement of soil structure, stimulation of microbial activity and gradual release of nutrients (6).

In addition, increased microbial activity in organically amended soils promotes nutrient mineralisation, organic matter decomposition and rhizosphere interactions that improve nutrient uptake efficiency in vegetable crops (7). These biological processes contribute to the restoration of soil fertility and create a more balanced and resilient soil ecosystem capable of sustaining crop growth under intensive cultivation.

Accordingly, this review critically evaluates the role of organic amendments as a soil-health-centred approach for enhancing vegetable crop productivity by integrating evidence on improvements in soil physical, chemical and biological properties. The review further identifies key limitations, knowledge gaps and future research priorities.

Unlike previous reviews that focused on individual organic amendments, this review provides an integrated soil-centred framework linking compost, vermicompost, biochar, green manures and FYM with soil-health indicators and vegetable productivity. The review further synthesises evidence on amendment mechanisms, environmental benefits and implementation challenges to identify future research priorities for sustainable vegetable production systems.

Materials and Methods

Review design

This study was conducted as a systematic literature review following the PRISMA 2020 statement for reporting systematic reviews. The review aimed to critically evaluate and synthesise scientific evidence regarding the effects of organic soil amendments on soil health indicators, nutrient dynamics, crop productivity, environmental sustainability and economic performance in vegetable-based cropping systems.

Inclusion and exclusion criteria

Inclusion criteria

Studies published in English between January 2000 and April 2026 that evaluating the effects of organic soil amendments on soil health, nutrient dynamics and vegetable crop productivity were included. Peer-reviewed research articles, review articles, conference proceedings and technical reports were considered.

Exclusion criteria

Duplicate records, non-English publications, studies unrelated to vegetable-based cropping systems or organic soil amendments, editorials, abstracts without full text and publications with insufficient scientific information were excluded.

Search strategy

Preferred reporting items for systematic reviews and meta-analyses (PRISMA 2020) was used for searching. The literature search was conducted in April 2026 using Scopus, Web of Science, ScienceDirect, PubMed and Google Scholar. The following search string was used: ("organic amendments" OR compost OR vermicompost OR biochar OR farmyard manure OR green manure) AND ("soil health") AND ("vegetable crops" OR horticultural crops) AND ("sustainable agriculture").

Screening process

Two reviewers independently screened titles, abstracts and full-text articles. Any disagreements were resolved through discussion until consensus was achieved.

Quality assessment

Since the objective of this review was qualitative synthesis rather than quantitative meta-analysis, a formal risk of bias assessment was not conducted. Instead, studies were evaluated based on relevance, methodological quality, experimental design and completeness of reported outcomes. The complete study selection processes are depicted in Fig. 1.

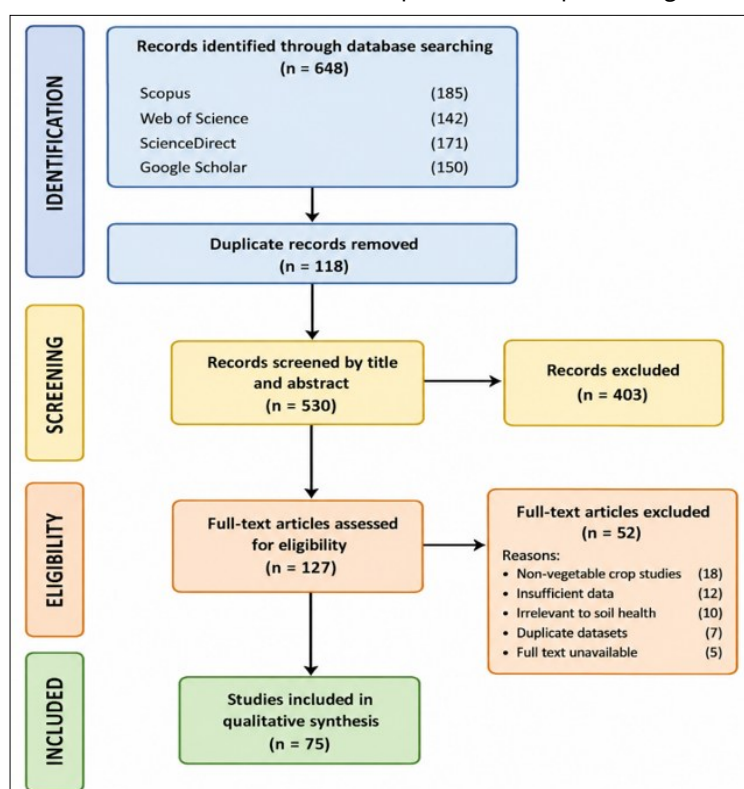


Fig. 1. PRISMA flow diagram showing the identification, screening, eligibility assessment and inclusion of studies used in this systematic literature review on organic soil amendments and sustainable vegetable production.

In total, 648 records were identified through database searching. After removing 118 duplicates and screening 530 titles and abstracts, 127 full-text articles were assessed for eligibility. Based on predefined inclusion and exclusion criteria, 75 studies were finally included in the qualitative synthesis used for this review. The search included peer-reviewed articles, review papers, conference proceedings and technical reports published from January 2000 to April 2026.

Organic fertilisers

Sources and types

Organic fertilisers are derived from plant and animal materials such as FYM, compost, crop residues, green manures, biosolids, peat moss and biochar. These amendments improve soil fertility by increasing soil organic matter (SOM), enhancing microbial activity, improving soil structure and water-holding capacity and reducing dependence on synthetic fertilisers. Appropriate crop rotation and diversified cropping systems further enhance the benefits of organic amendments. They improve soil fertility, stimulate microbial activity and reduce environmental pollution compared with the exclusive use of inorganic fertilisers. Excessive chemical fertiliser has caused serious nitrogen (N) and phosphorus (P) contamination in aquatic ecosystems (8). The major types and sources of soil organic amendments are summarised in Table 1.

Nutrient composition and functional differences

Organic soil amendments differ widely in their nutrient composition depending on their source materials, degree of decomposition and method of processing. Common organic amendments such as FYM, compost, green manure, crop residues and biochar provide essential macro and micronutrients (N, P, potassium (K), calcium (Ca), magnesium (Mg), sulphur (S), iron (Fe), zinc (Zn), etc.) in varying proportions. Manures and composts generally serve as balanced

nutrient sources, whereas materials like biochar contribute less directly to nutrient supply but significantly enhance nutrient retention and soil structure (18).

The functional differences among these amendments arise from their chemical composition, carbon-to-nitrogen (C : N) ratio and decomposition rates. Amendments rich in readily decomposable organic matter (e.g., green manures, vermicompost) release nutrients more rapidly, promoting immediate plant uptake and microbial activity (19, 20). In contrast, materials with high lignin and stable C content (e.g., biochar, matured compost) improve long-term soil fertility by enhancing cation exchange capacity, water retention and C sequestration (18, 21). Overall, understanding the nutrient composition and functional variability of organic amendments is crucial for selecting suitable materials that align with specific crop and soil requirements, ensuring both short-term productivity and long-term soil health improvement (3, 4).

Mechanisms of soil health improvement

Organic soil amendments such as FYM, compost, vermicompost, crop residues and biochar improve soil physical, chemical and biological functions by enhancing SOM, nutrient cycling, aggregate stability and water-holding capacity (Fig. 2) (22).

Effects on physical properties

Organic soil amendments are essential for improving the structure, porosity and water-holding capacity of soil. Stable soil aggregates are facilitated by the addition of organic elements including biochar, compost, FYM and green manures.

Soil porosity: By establishing a balanced network of micro- and macropores, more organic matter from these additions increases soil porosity. This improves gas exchange, drainage and water infiltration in the soil profile (23).

Table 1. The major sources, functions and limitations of soil organic amendments

Organic amendment	Major benefits	Limitations	References
Animal manures	Supply nutrients, improve soil structure, CEC and microbial activity	Bulky to transport and apply	(9)
Farmyard manure (FYM)	Enhances organic matter, nutrient availability, microbial biomass and soil structure	Benefits mainly confined to surface soil; dose-dependent effects	(9)
Compost	Mature compost slowly mineralises nutrients while increasing soil organic carbon (SOC), aggregate stability and microbial diversity.	Slow nutrient release	(9)
Cover crops and crop residues	Reduce erosion, conserve moisture, suppress weeds and add organic matter	Occupy land that could be used for cash crops	(10)
Biochar	Biochar possesses a porous structure and high surface area, increasing cation exchange capacity, retaining nutrients, improving water storage and providing habitats for beneficial microorganisms.	Difficult handling due to dusty nature; effectiveness depends on application method	(11)
Vermicompost	Vermicompost contains readily mineralisable organic matter and beneficial microorganisms that accelerate nutrient mineralisation and enzymatic activity, resulting in faster nutrient availability.	Limited production and scalability	(12)
Blood meal	Rich nitrogen source; promotes vegetative growth and microbial activity	Strong odour may attract animals	(13)
Green manure	Increases soil nitrogen, fertility and subsequent crop yields	Nutrient release varies with species and management	(14)
Poultry manure	Improves soil fertility, nitrogen, phosphorus and crop productivity	Excess application may cause salinity and yield reduction	(14, 15)
Press mud	Improves soil structure, nutrient availability and crop yield	Excessive use may cause nutrient imbalance and salinity	(16)
Fly ash	Low-cost amendment for pollutant adsorption and soil improvement	Requires activation; potential environmental concerns	(17)

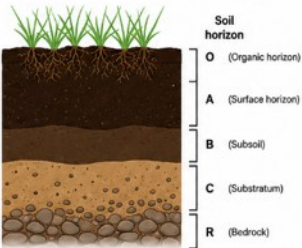
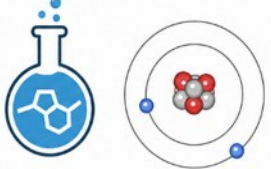
Physical properties	Chemical properties	Biological properties
Indicators: • Aggregate stability • Soil structure and porosity • Bulk density • Water infiltration • Water holding capacity 	Indicators: • Cation exchange capacity • Organic and inorganic N • Organic and inorganic P • Organic and inorganic K • Soil pH 	Indicators: • Earthworms • Soil microorganisms • Particulate organic matter • Soil respiration • Soil enzymes 

Fig. 2. The major soil health indicators influenced by organic amendments.

Water holding capacity: Additionally, by enhancing the soil's sponge-like qualities, organic components improve the soil's ability to hold water; this is especially advantageous in sandy or degraded soils (4). Better plant development and stress tolerance are supported by this increased water-holding capacity, which sustains ideal moisture conditions for microbial activity and nutrient availability. Continuous application of organic amendments increases soil tilth, strengthens resistance to erosion and supports agricultural soils long-term physical stability and sustainability (24).

Effects on chemical properties

Organic matter contains numerous carboxyl and phenolic functional groups that increase cation exchange capacity and nutrient retention. As organic amendments decompose, nutrients are gradually mineralised, improving nutrient availability while reducing losses through leaching and volatilisation.

Soil pH and cation exchange capacity (CEC): Numerous functional groups found in organic matter, such as carboxyl and phenolic hydroxyls, raise the soils CEC and enhance nutrient retention. Macronutrients and micronutrients are released gradually throughout the breakdown of organic amendments, improving nutrient utilisation efficiency and lowering nutrient losses from leaching and volatilisation (25).

Extended field studies conducted in Tamil Nadu have demonstrated that using FYM and composted coir pith boosts SOC levels, as well as the availability of N, P and K, while keeping the soil pH close to neutral (26). These amendments also enhance microbial activity, which promotes nutrient cycling and helps stabilise soil chemical properties, thereby preserving soil fertility and productivity in vegetable-based and rice-pulse cropping systems.

Effects on biological properties

Microbial biomass: Soil organic matter is a vital feature of soil quality, which directly influences soil microbial dynamics. Many important functions (including nutrient mineralisation, nutrient cycling and decomposition and formation of SOM) are mediated by the microbial biomass in soils as they are the main reservoirs of enzymes in soils. Soil nutrients by the microbial biomass and flux of soil nutrients through the microbial fraction can be significant

(27). The quality and quantity of the biological amendment can further modify the richness and functionality of the biota and microbial community (28).

Effect on nutrient availability on chelation

Chelating agents that are found naturally include:

- Fulvic acid:** This naturally occurring chelating agent attaches itself to micronutrients like copper (Cu), Zn and Fe. It has the added advantage of enhancing soil structure and water retention and it works well across a broad pH range.
- Another naturally occurring chelating agent that attaches to micronutrients like Fe, Cu and Zn is humic acid. It works well in alkaline soils and has the extra advantage of enhancing water retention and soil structure.
- Amino acids:** These naturally occurring chelating agents attach themselves to micronutrients including Zn, Cu and Fe. They have the extra advantage of enhancing plant growth and development and are effective in a broad range of pH values (29).

By creating stable Fe-HS complexes, humic substances (HS) function as natural chelators that improve plant iron nutrition by raising Fe availability and solubility in the rhizosphere. These complexes increase internal Fe distribution and promote physiological Fe-uptake systems in addition to giving plants an easily available Fe supply. Humic substances are an environmentally friendly substitute for manufactured iron chelates for enhancing crop Fe nutrition due to their chelating capacity and beneficial effects on root activity and metabolism (30).

One of the environmental elements necessary for crop growth and development is plant nutrients. For commercial crop production to be as productive as possible, nutrient management is essential. Micronutrients, which include Fe, Zn, Cu, manganese (Mn), boron (B), chlorine (Cl), molybdenum (Mo) and nickel (Ni), are those nutrients found in plant tissues at concentrations of less than 100 parts per million (ppm). Because micronutrients like Fe, Mn, Zn and Cu are rapidly oxidised or precipitated in soil, their usage is inefficient. To improve the efficiency of micronutrient utilisation, chelated fertilisers have been created (Fig. 3) (31).

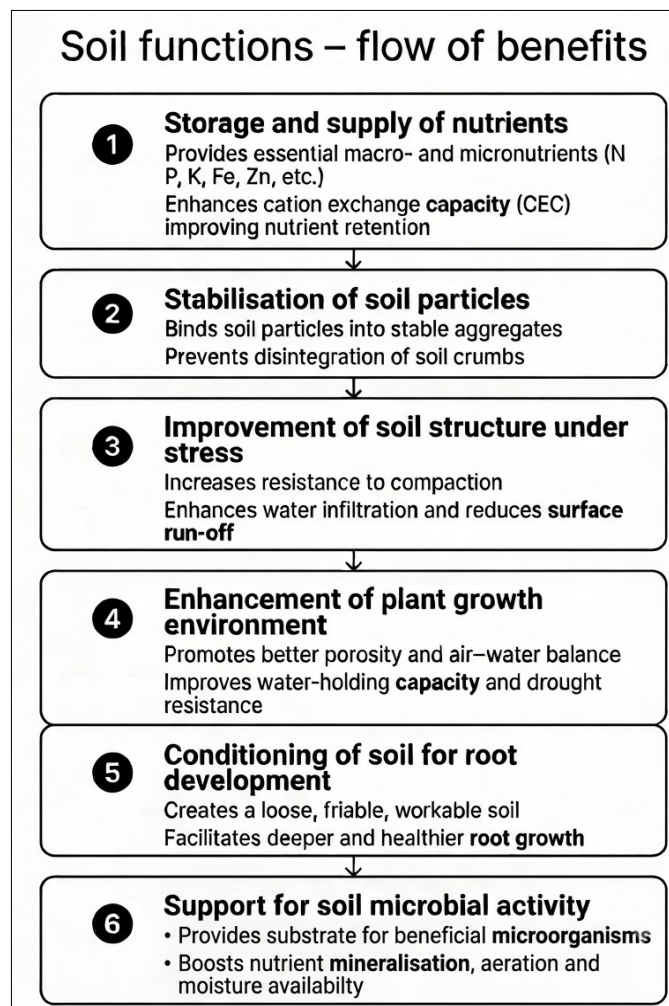


Fig. 3. The contribution of soil organic matter to soil quality (32).

Impact on vegetable crop growth and productivity

Organic soil amendments improve vegetable crop growth through enhanced nutrient availability, improved soil physical properties, increased microbial activity and better root development. These changes promote seed germination, vegetative growth, flowering, fruit development, yield and crop quality across a wide range of vegetable species. Currently, there is a greater demand than supply for certified organic products, especially vegetables, which drives up market prices (33).

Influence on seed germination and early establishment

One of the most dependable, effective and widely used methods for growing seedlings is propagation by seeds. A key component of successful plant multiplication is the generation of robust, healthy rootstocks within the necessary time frame. To produce rootstocks that are uniform and healthy, the right media or substrate must be used. The quality of seedlings produced in a nursery is influenced by the growing medium and this has an impact on the transplant establishment and survival in the main field (34). Ensuring high germination rates and robust early growth is one of the main goals of organic seed selection. High-vigour seedlings establish rapidly, reducing weed competition and improving nutrient uptake. Studies have revealed that high germination rates of organic seeds result in seedlings with 25 % higher biomass, enhancing total plant productivity and resilience (35).

Yield improvement in vegetables

Using a mix of organic materials on chilli crops, like half FYM and half poultry manure or half vermicompost and half poultry manure,

plus combinations of FYM with neem cake and poultry manure at a rate of 7.5 t ha⁻¹ led to noticeably taller plants, more branches per plant and larger leaf areas (36).

In soybeans, using a mix of crop residues at 5 t ha⁻¹ along with FYM at the same rate led to greater plant height, more branches, increased leaf area index and more dry matter compared to just using FYM alone. For chilies, key growth factors such as plant height, number of branches, leaf area and dry matter in different parts of the plant improved significantly when both organic compost and FYM were used together. Additionally, the growth of chilies was also enhanced by adding beneficial N-fixing bacteria like *Azospirillum* and *Azotobacter* (37).

Yield was also enhanced by higher vermicompost application rates, with 6 t ha⁻¹ showing the highest results. Vermicompost generated high-quality veggies like *Solanum melongena* when combined with chemical fertilisers. When 50 % NPK was replaced with vermicompost made from cow manure, *Azolla* and *Eichhornia*, the plant's height, leaf count, fruit characteristics and blooming time were all improved (38).

In addition to being a rich source of micronutrients, vermicompost also functions as a chelating agent, controls the availability of metallic micronutrients to plants and boosts plant growth and output by supplying nutrients in the form that is available and according to crop demand. Compared to recommended dose of fertilisers (RDF) alone, the application of organics, specifically FYM at 10 t ha⁻¹, increased fruit output and nutrient uptake, including N, P, K, Ca, S and Fe (37).

Nutrient uptake and plant growth enhancement

Numerous factors, such as plant type, environmental conditions and microbes connected to plant roots, influence how well plants absorb nutrients. Nutrient uptake is mostly dependent on root development and function, particularly in organic farming where nutrients are frequently available in soil solution in comparatively small amounts (39). The macronutrient (N, P and K) concentrations in commonly used organic soil amendments, compiled from previous studies are illustrated in Fig. 4.

Two important characteristics of biochar are its strong affinity for water and nutrients, which lowers nutrient losses and off-site pollution from feed leaching. Biochar has a half-life in soil of several centuries, in contrast to compost or manure. In the past, applying biochar to barley by itself did not significantly affect yield, but when combined with N fertiliser, it had a substantial interaction impact. According to other research, applying compost and biochar together may boost soil fertility, plant development and the capacity to sequester C (40).

Many crops, such as tomatoes, eggplant, okra, lettuce, cabbage, coriander, cucumber, strawberries and pistachios are positively impacted by vermicompost. It also enhances the growth of ornamentals like marigold. Compared to inorganic fertilisers, it frequently yields higher overall output. As shown in Fig. 5, soil nutrient status directly influences human nutrition through its effects on crop nutrient composition and food quality. The vermicompost greatly improved biochemical characteristics like protein and fat content, yet chemical fertiliser-amended soils produced more leaves, a larger stem circumference and a better marketable output than vermicompost alone (41).

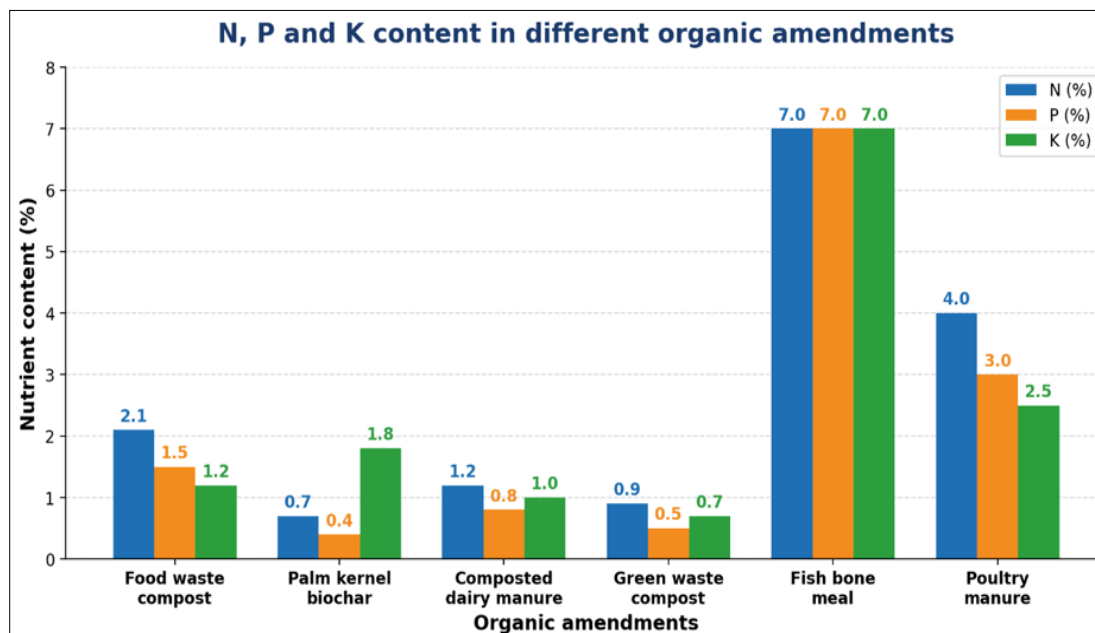


Fig. 4. Macronutrient (nitrogen (N), phosphorus (P) and potassium (K)) concentrations in commonly used organic soil amendments.

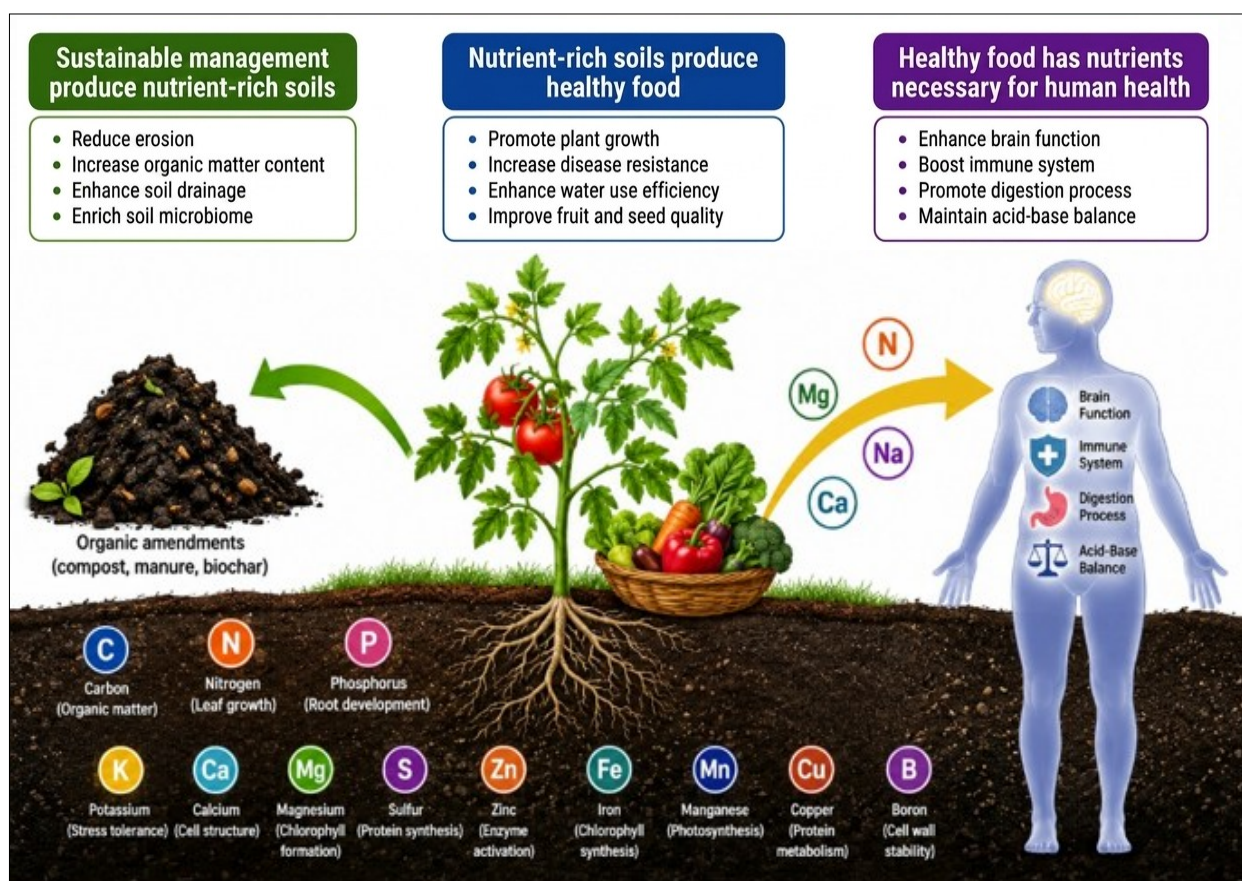


Fig. 5. Relationship between soil nutrient status and human nutrition.

Cropping systems

A key requirement for sustained crop production and soil fertility restoration is the strategy of integrated plant nutrients using appropriate methods with balanced doses of fertilisers and organic manures. Intensive vegetable production systems rapidly deplete soil nutrient reserves because of their high nutrient demand and frequent cropping cycle (42).

Combined use with inorganic fertilisers (integrated nutrient management)

The fundamental idea behind INM is to lower fertiliser input costs while simultaneously maintaining soil fertility for long-term

agricultural output. Crop residues, organic manures, chemical fertilisers and N_2 -fixing crops like pulses, gram and other legumes must all be properly combined. Soil health and partial factor productivity have declined as a result of the intensive cropping system's uneven application of chemical fertilisers (42).

Application of vermicompost with 75 % recommended NPK improved plant growth and micronutrient uptake in vegetables compared with mineral fertilisation alone (43). Nutrient synchronisation is essential in protected cultivation and combining organic and inorganic use improves production and quality (44).

Crop rotation and amendment scheduling

Crop rotation increases soil health, lessens insect pressure and promotes nutrient cycling. Rotations with legumes boost soil biological activity and increase N availability. Rotating vegetables with pulses or green manure crops (such as French beans or cowpeas) is very beneficial. Vegetable rotations with legumes enhanced soil N, P and microbial activity (45). In order to balance crop demand and fertiliser supply, amendment scheduling is crucial. When inorganic fertilisers are administered in divided doses, organic manures are applied when the soil is being prepared. Fertiliser splitting combined with pre-season organic amendment application improves nutrient synchronisation, nutrient uptake efficiency and vegetable yield stability (45).

Conservation tillage

Increased crop diversity enhances microbial diversity, improves nutrient cycling and supports soil fertility (46). Long-term studies demonstrated that reduced tillage combined with cover crops and proper fertilisation positively influences microbial activity and community structure, promoting soil fertility (47). Additionally, organic amendments like compost not only improve soil health but also provide plant protection benefits during the winter season, reinforcing the advantages of conservation-focused soil management (48).

Environmental implications

There are major economic and environmental advantages to vegetable-based farming systems that use both organic and inorganic fertiliser sources. While inorganic fertilisers guarantee timely nutrient supply, organic amendments improve soil quality, lessen environmental degradation and increase nutrient-use efficiency (NUE). The sustainable nutrient management enhances system resilience against climate unpredictability, lowers production costs over time and lowers ecological risks. These integrated solutions can decrease greenhouse gas (GHG) emissions, boost soil C storage, lessen reliance on chemicals and increase farmer profitability in vegetable production, particularly under intensive and protected agriculture (49).

Reduction in chemical input dependence

By partially replacing chemical fertilisers with organic resources like FYM, compost, vermicompost, biochar and green manures, integrated nutrient management (INM) lessens the need for chemical fertilisers. According to a previous study combining 50 % RDF with organic inputs improved NUE while maintaining vegetable yields comparable to full chemical fertiliser doses (50).

Soil acidification, salt accumulation and N leaching are common issues in vegetable systems are lessened when there is less reliance on chemical inputs. According to a previous study organic and inorganic combinations also increase residual soil fertility, which lowers the amount of fertiliser needed for subsequent crops (51).

Carbon sequestration and greenhouse gas mitigation

One of the most important methods for raising SOC and lowering emissions of GHGs including CO₂, N₂O and CH₄ is the application of organic amendments. Long-term application of manure and compost greatly increases SOC stores, which helps mitigate climate change (52). Cover crops are an effective strategy for C sequestration in agricultural soils. Meta-analysis findings show that adding cover crops steadily increases SOC at about 0.32 Mg ha⁻¹ yr⁻¹, with soils reaching a new steady state over long-term cultivation. On average,

cover crops can add about 16.7 Mg ha⁻¹ of SOC in the top 22 cm of soil, making them a highly efficient C-input practice. Globally, they have the potential to sequester around 0.12 Pg C yr⁻¹, offsetting roughly 8% of annual agricultural GHG emissions (53).

Global adoption of best management practices are capable of creating a positive soil and ecosystem. Carbon budget could sequester an estimated 178 Pg C in soils and 155 Pg C in biomass between 2020 and 2100, providing a total terrestrial C drawdown potential of 333 Pg C and reducing atmospheric CO₂ by approximately 157 ppm. Key techniques for enhancing SOC sequestration include system-based conservation agriculture, agroforestry, biochar application and integrated crop-tree-livestock systems (54).

Economic benefits

The adoption of organic soil amendments and INM practices provide substantial economic benefits by reducing input costs, improving NUE, increasing crop productivity and enhancing long-term farm profitability. In debates about fixing these difficulties, most of the attention has concentrated on the design of farm financial safety net programs, the compression on pricing associated with USA and European Union (EU) subsidies, global market pressures and the need for even greater productivity. Reducing input costs and entering price-premium environmental markets have received relatively little attention (55).

Cost-benefit analysis and farmer adoption issues

By lowering fertiliser expenditures, boosting yield stability and improving soil health, INM can increase profitability. According to a previous study, INM in vegetables increased benefit-cost ratios (B : C) because of increased nutritional efficiency and decreased reliance on external inputs (56). Farmers frequently deal with issues such poor access to high-quality organic materials, labour-intensive composting, delayed nutrient release from organics and a lack of technical expertise. Adoption rises when farmers receive market incentives for sustainably cultivated produce, training and demonstrative support (57).

Challenges and limitations

Organic farming has many advantages, but there are a number of obstacles that could prevent its widespread use and efficacy.

Yield limitations in organic farming

The fact that organic farming usually yields less than conventional farming is one of its main drawbacks. Organic farming practices frequently lead to lower productivity. Because of the lack of artificial pesticides and fertilisers, which may have an impact on food security and profitability. Furthermore, organic farming is more vulnerable to weather, pests and illnesses due to its production variability. Farmers may face significant hazards as a result of this fluctuation, especially in areas with erratic weather patterns or severe pest pressure (58).

Cost and market barriers in organic agriculture

Research on organic farming techniques and their optimisation remains significantly limited. Therefore, there is a need for the development of novel techniques and technologies to improve the efficiency, productivity and sustainability of organic farming. In addition, lower-income consumers often have limited access to organic products due to their higher prices. Since organic foods are generally more expensive than conventional alternatives, their consumption may be largely restricted to higher-income

demographics. Additionally, organic producers frequently struggle to integrate into conventional supply chains and markets due to market access issues. Their sales prospects and financial sustainability may be hampered by this challenge, especially for businesses that operate in areas with underdeveloped organic marketplaces (59).

May be hampered by inadequate funding and attention to organic agriculture research. Furthermore, farmers frequently receive insufficient information from research organisations, which makes it difficult to spread best practices and knowledge about organic farming. Farmers may not be able to completely benefit from organic farming practices because of this mismatch (60).

Handling, storage and labour constraints

Even in recent studies conducted after 2010, organic farming still faces significant labour and post-harvest issues. Organic produce typically has a shorter shelf life and is more vulnerable to microbial deterioration and pest infestation during storage because synthetic preservatives, ripening agents and chemical fumigants are prohibited. According to an earlier study, in order to minimise spoilage losses, organic fruits and vegetables need to be handled with more stringent procedures, such as quick cooling and storage in a controlled environment (61). The lack of post-harvest chemical treatments and higher respiration rates cause organic fresh produce to deteriorate more quickly (62).

Labour requirements are also significantly higher in organic farming. Operations such as hand weeding, compost preparation,

pest surveillance and selective harvesting demand increased manual effort. Organic farms require 20–30 % more labour, significantly raising production costs and limiting scalability for smallholders (63). Furthermore, it was found that labour scarcity and high-wage costs are major barriers to the expansion of organic systems in developing countries.

Crop-specific research gaps

A major limitation in the organic farming literature is the uneven distribution of research across crop types. Most existing studies concentrate on a narrow set of staple and high-value crops such as cereals (wheat, rice, maize) and select vegetables, while many minor crops, region-specific varieties and perennial or tree crops remain understudied (64). This imbalance means that agronomic recommendations, pest management protocols and yield-optimisation strategies developed for well-researched crops cannot be reliably extrapolated to less-studied ones. Consequently, farmers cultivating underrepresented crops often lack evidence-based guidance on organic input substitution, soil fertility management, or pest control, increasing production risk and discouraging conversion to organic methods. The scarcity of long-term, multi-location trials further limits understanding of how crop-specific organic performance varies across soil types, climatic zones and cropping systems, restricting the generalisability of existing findings (65).

The effects of different organic amendments on vegetable crop growth and productivity, along with their economic benefits, returns and associated labour requirements are presented and compared in Tables 2–4.

Table 2. Organic amendment type × mechanism of action

Organic amendment	Major components	Mechanism of action	Soil health benefits	Crop productivity benefits	References
Compost	Stabilised organic matter, nutrients	Improves nutrient cycling and organic matter accumulation	Enhanced aggregation, water retention, microbial activity	Increased soil organic carbon (SOC) by 15–28 %, microbial biomass by 20–35 % and vegetable yield by 18–30 %	(66)
Vermicompost	Earthworm-processed organic residues	Releases plant-available nutrients and beneficial microbes	Increased enzyme activity and microbial diversity	Enhanced nutrient uptake and productivity	(66)
Farmyard manure (FYM)	Animal excreta and bedding materials	Supplies macro- and micronutrients gradually	Improved soil structure and biological activity	Sustained crop growth	(67)
Green manure	Leguminous or non-leguminous cover crops	Biological nitrogen fixation and organic matter addition	Increased soil fertility and biodiversity	Higher yields and reduced fertiliser requirement	(68)
Biochar	Carbon-rich pyrolysed biomass	Enhances cation exchange capacity and carbon sequestration	Improved moisture retention and microbial habitat	Better nutrient-use efficiency and stress tolerance	(69)

Table 3. Amendment × vegetable crop × yield response

Amendment	Vegetable crop	Reported yield response	Major observations	References
Compost	Cabbage	15–30 % increase	Improved head weight and nutrient uptake	(68)
Vermicompost	Tomato	20–40 % increase	Fruit yield increased by 28 %, average fruit weight by 18 %, total biomass by 22 %.	(70)
Biochar	Lettuce	10–25 % increase	Better water-use efficiency	(69)
Vermicompost + Biochar	Tomato	25–50 % increase	Synergistic improvement in soil biological activity	(67, 69)
Farmyard manure (FYM)	Okra	15–35 % increase	Increased pod production	(71)
Compost + green manure	Spinach	15–30 % increase	Enhanced nutrient availability and biomass	(68, 72)

Table 4. Economic return and labour requirement

Amendment	Approximate cost (₹ t ⁻¹)	Labour requirement (person-days ha ⁻¹)	Nutrient release pattern	Typical benefit: cost ratio (B : C)	References
Vermicompost	₹4000–8000	15–20	50–70 % nutrients available within 30–60 days	2.0–3.0	(66, 68)
Compost	₹2000–4000	10–15	30–50 % nutrients released during the first year	1.5–2.2	(73)
Farmyard manure (FYM)	₹800–1500	8–12	20–30 % nutrients released during the first cropping season	1.3–1.8	(74)
Biochar	₹15000–35000	4–8	< 10 % immediate nutrient release; stable in soil for >10 years	1.8–2.8 (long-term)	(69, 71)
Green manure	₹1000–3000	12–18	40–60 % N mineralised within 4–8 weeks after incorporation	1.6–2.3	(72, 75)

Conclusion

By enhancing the physical, chemical and biological properties of soil, organic soil amendments are essential for maintaining and restoring soil health in vegetable-based cropping systems. Unlike previous reviews focusing on individual amendments, this review integrates soil physical, chemical and biological processes within a soil-centred framework to compare the complementary roles of compost, vermicompost, biochar, farmyard manure (FYM) and green manures for sustainable vegetable production. The review also identifies conflicting evidence and highlights region-specific management strategies for future research. A key finding is that integrating organic amendments with balanced inorganic fertilisation often provides greater benefits than either approach alone.

Future prospects and research needs

Future research on organic soil amendments should focus on developing region-specific application strategies, improving amendment quality standards and understanding long-term impacts on soil health under vegetable-based systems. More studies are needed to explore microbial and enzymatic responses using advanced analytical tools, as well as the combined use of organic amendments with biofertilisers and climate-resilient practices. Research on nutrient release dynamics, economic feasibility and farmers adoption will also help strengthen the practical use of organic amendments for sustainable vegetable production.

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Authors' contributions

RS conceptualised the study, conducted the literature review and prepared the original manuscript draft. SS supervised the work, contributed to conceptualisation and reviewed and edited the manuscript. PSP contributed to the literature review and manuscript editing. MLM contributed to the interpretation of scientific information and manuscript review. KP contributed to critical review, editing and refinement of the manuscript. All authors have read and approved the final manuscript.

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During the preparation of this work the authors used ChatGPT and Claude in order to the preparation of the manuscript, mainly for improving language, grammar, clarity and readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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