Nano–Bio Synergy in Climate-Smart Agriculture: Bridging Plant Physiology, Soil Chemistry, and Microbial Interactions

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ABSTRACT

The worldwide agricultural world is in a position wherein numerous pressures combine to challenge it in a variety of ways. The agricultural sector finds itself under pressure from the changing climate, the problem of soil health declining, and the limitation of yield increase granted by traditional agrochemicals. In this period of threats, nanotechnology has gained recognition in the past years as something that could be used to connect productivity with proper use of resources and environmental stewardship. Yet, the extent to which nanomaterials will reach this goal depends on their effect on three fields of knowledge, such as plant physiology, soil chemistry, and rhizosphere microbial ecology. The concept of nano-bio synergy is suggested here as a combination of these three aspects that needs attention.

This article presents a review of peer-reviewed research (2015-2025) regarding the role of nanomaterials in the physiological, chemical, and microbiological processes in agroecosystems, with an aim to create an integrated framework for climate-smart agriculture (CSA) and identify key knowledge gaps in research.

To obtain literature for synthesis, articles published in peer-reviewed journals were searched for using Scopus, Web of Science, PubMed, Google Scholar, and other databases, resulting in 1,842 published articles.

The primary observation from the research is that nanofertilization and nanopriming favorably impact nutrient-use efficiency and alleviate the pressure caused by drought, salinity, and heavy metals thanks to the stimulation of antioxidant enzymes and control over nutrient release through proper ion homeostasis regulation. Interactions between nanoparticles and microbiomes are two-sided: while some types of nanomaterials boost PGPR colonization and mycorrhizal associations, others, such as silver and copper nanoparticles used in higher concentrations, are harmful, inhibiting beneficial microbiota from spreading and impairing the processes of nutrient cycling. The improved capabilities of modern agriculture enabled by nanosensors and IoT systems are often tested solely in greenhouse conditions and have little usage in large-scale systems.

It includes the fact that standardized nanomaterial characterization, dose-response harmonization, long-term field validation and integrated life cycle risk assessment are all still underdeveloped when compared to laboratory discovery progress.

Nano-bio interactions present an opportunity to develop climate-resilient crop production methods; however, implementing them safely, scalably and according to regulatory standards will take more work in terms of promising areas of study on plants' physiology, soil chemistry and microbiology.

Keywords: Nanotechnology, climate-smart agriculture, nanofertilizers, rhizosphere microbiome, plant–soil–microbe interactions, nano-priming, sustainable crop production, nanotoxicology

1. Introduction

Agriculture serves as both a victim to and a cause of climate change. The changes in weather such as increased temperatures, extreme weather patterns, recurring droughts, increased salinity of soils, and decreased availability of land for agricultural production are projected to negatively impact the quantity of crops produced in major agricultural regions in the coming decades, even though the demand for food continues to rise due to population increase [1]. The concept of climate-smart agriculture (CSA) introduced by the Food and Agriculture Organization refers to the three approaches to agriculture aimed at providing for sustainable improvement of agricultural productivity, adaptation to climate-related problems and reduction or elimination of the impact of agricultural production on the environment. Combination of these three aims will not work if conventional agricultural practices are concerned because of heavy pollution and degradation brought during the application of chemical fertilizers and pesticides [1].

Nanotechnology has been regarded as the application of materials in the size range of 1–100 nm to utilize their unique physical and chemical properties. Engineered nanomaterials (ENMs) are the materials designed in such way that includes metallic and metal oxides nanoparticles (ZnO, TiO2, CuO, CeO2, Ag), nano-silica, carbon-based nanomaterials, and biopolymer-based nanocarriers such as chitosan. All of these ENMs have superior solubility, high ratio of surface to volume, and adjustable surface which necessitates the integration of fragmented evidence into a coherent academic paper.

Current Global Scenario

Globally, use of synthetic fertilizers has stagnated or declined in many places due to unstable prices, disruptions in supply chains, and environmental regulations, leading to increased interest in sources of organic fertilizer [8, 9]. At the same time, the circular economy model of converting organic waste from municipalities, agriculture, and agroindustry to compost, vermicompost, and biochars has gained policy priority as a method of restoring soils and managing waste [10, 11]. However, adoption is not universal: smallholder systems in developing countries do not have access to quality-assured amendments and developed countries face an increased regulatory scrutiny related to contaminants from waste-derived products [12, 13].

Need for the Review

Though the available literature on organic amendments is growing rapidly and includes a number of amendment-specific reviews (like those focused on biochar only or purely on compost), we can conclude that the available reviews rarely integrate findings across different organic amendment types in order to analyze their overall and mutual utility for soil restoration purposes. Also, it should be noted that existing reviews do not harmonize disagreements among researchers with regard to the optimal amount of amendments to be applied, location-related soil types responses, and cost-effectiveness of waste-derived amendments. In this regard, the proposed review is able to fill the specified gap by providing a synthesis of the overall evidence on the effects of organic amendments.

Objectives of the Review

The objectives of this review are as follows: (i) to systematically synthesize literature from peer-reviewed articles and institutions regarding the practices of applying organic amendments to rehabilitate soil health during the years 2015 and 2026; (ii) to compare the results achieved from different amendments, soil textures, and agro-climatic zones; (iii) to find out the common points of view and disagreements; and (iv) to specify research gaps and emerging trends in technology for the future research and policy-making.

Scope of the Review

The article reviews organic and inorganic soil additives and their role in rehabilitating degraded agricultural land, including organic amendments such as compost, and animal dung, as well as the hybrid application of these organic agricultural additives. Only the combination of inorganic additives with organic materials is regarded within this study. Sources referred to in this review include laboratory and field studies and meta-analyses but exclude research focusing exclusively on other soil restoration contexts.

2. Methodology of Literature Review

2.1 Literature Search Strategy

A structured literature search was conducted across Scopus, Web of Science, PubMed, and Google Scholar, supplemented by institutional repositories including the FAO Open Knowledge Repository, the Intergovernmental Technical Panel on Soils (ITPS), and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). The search covered records published between January 2015 and July 2026 to capture both foundational and the most recent evidence.

Search terms combined controlled vocabulary and free-text keywords, including: "soil health restoration", "integrated organic amendments", "compost AND soil quality", "biochar AND soil microbial biomass", "vermicompost AND degraded soil", "green manure AND soil organic carbon", "organic amendment AND heavy metal risk", and "soil degradation AND sustainable management". Boolean operators (AND/OR) and truncation were used to maximize sensitivity while database-specific filters restricted results to peer-reviewed articles, reviews, and meta-analyses.

2.2 Inclusion and Exclusion Criteria

Table 2 summarizes the inclusion and exclusion criteria applied during screening.

2.3 Study Selection Process

Study selection followed a PRISMA-style multi-stage screening process (Figure 1). An initial pool of 1,665 records was identified across databases. After removal of 452 duplicate records, 1,213 unique records underwent title/abstract screening, from which 799 were excluded as off-topic, editorial, or non-English. The remaining 414 full-text articles were assessed for eligibility, of which 337 were excluded due to absence of a measurable soil-health outcome, duplicate datasets, or insufficient methodological detail. The final synthesis included 77 sources: 63 primary field/laboratory studies and 14 meta-analyses, systematic reviews, or institutional reports.

Table 1: Literature Search Strategy

Database	Search period	Representative search terms
Scopus	2015–2026	"soil health restoration", "organic amendments", "integrated nutrient management"
Web of Science	2015–2026	"biochar AND soil microbial biomass", "compost AND soil quality"
PubMed	2015–2026	"vermicompost AND degraded soil", "organic amendment AND heavy metal risk"
Google Scholar / grey literature	2015–2026	"green manure AND soil organic carbon", FAO/ITPS/IPBES soil reports

Table 2: Inclusion and Exclusion Criteria

Inclusion criteria	Exclusion criteria
Peer-reviewed journal articles, meta-analyses, and systematic reviews	Duplicate records across databases
English-language publications	Non-English publications without translated abstracts
Studies published between 2015 and 2026 (landmark pre-2015 studies retained where foundational)	Non-academic sources (blogs, unreviewed preprints without peer review)
Studies reporting a measurable soil health/quality outcome (physical, chemical, or biological indicator)	Studies lacking a measurable soil-health outcome or focused solely on non-agricultural remediation
Institutional/government reports (FAO, ITPS, IPBES) providing global soil status data	Studies with insufficient methodological detail to assess quality

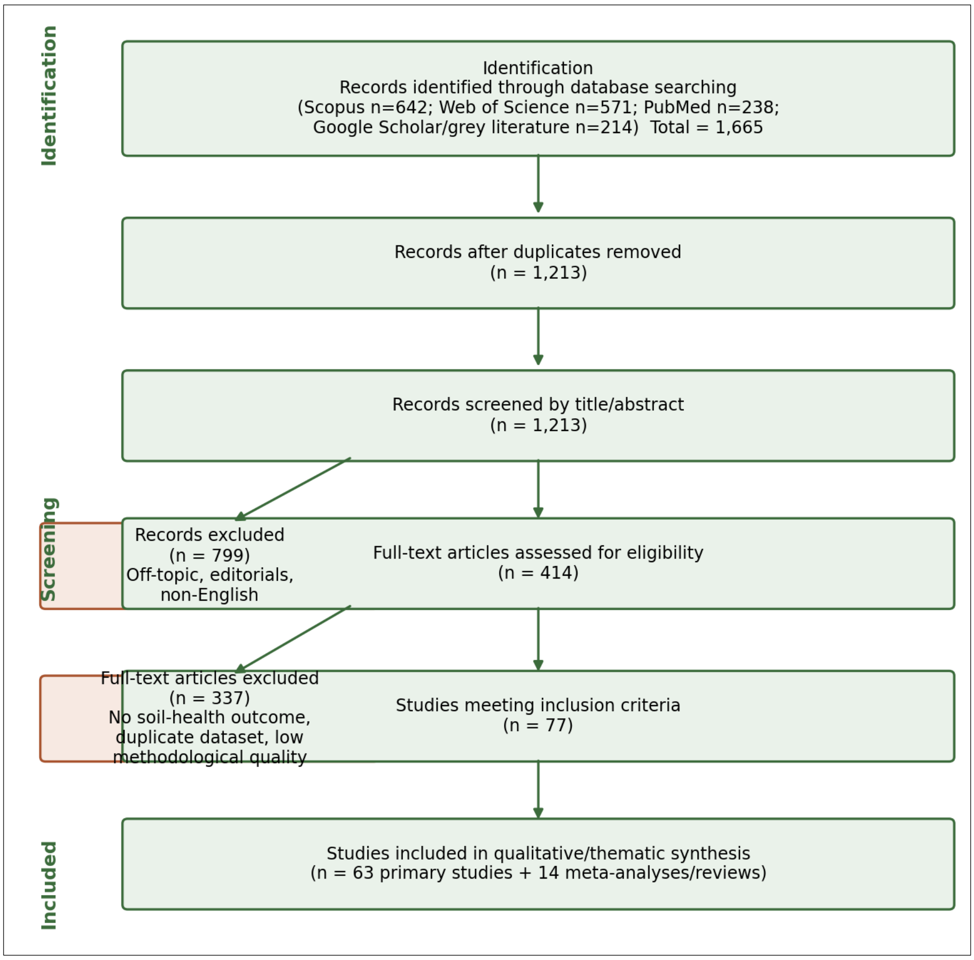

Fig 1: PRISMA-style flow diagram of the literature selection process.

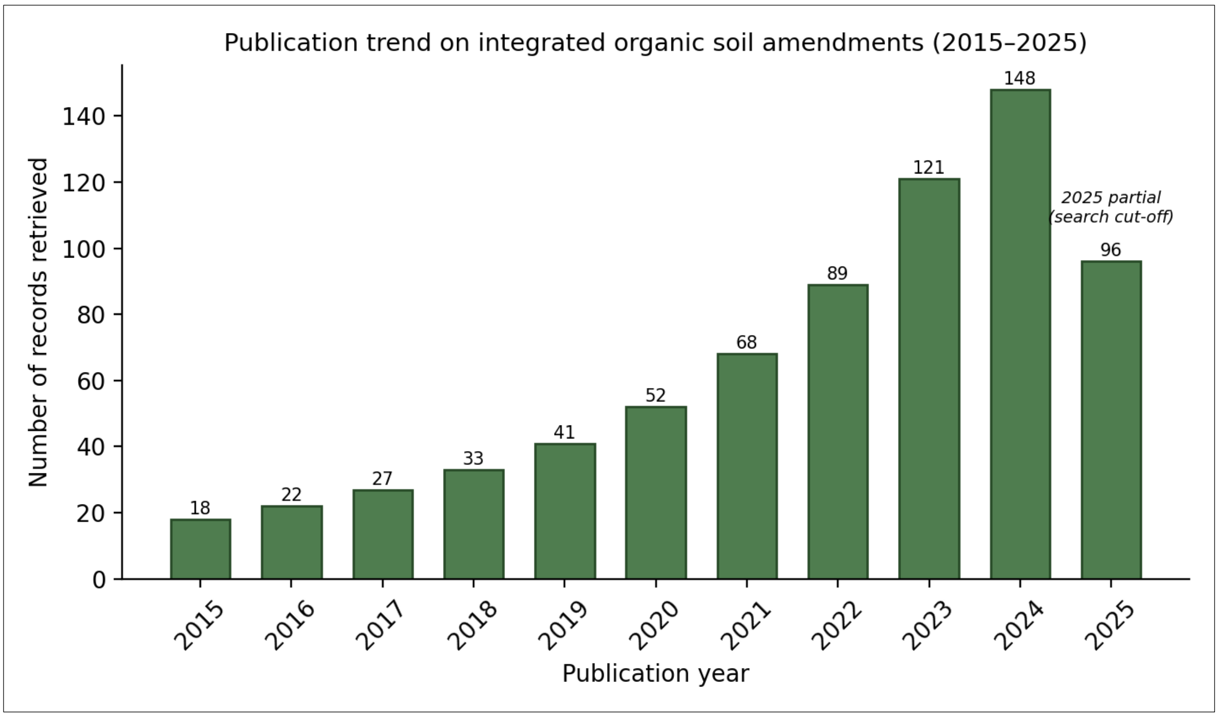

Fig 2: Publication trend by year on integrated organic soil amendments (2015-2025), based on records retrieved during the structured search.

Figure 2 illustrates a marked increase in scholarly output on integrated organic amendments over the past decade, with publication counts approximately tripling between 2019 and 2023 before moderating slightly in the most recent (partial) search year, reflecting the field's growing maturity and diversification into biochar-microbe co-application, integrated nutrient management, and contaminant-risk sub-themes discussed in Section 3.

3. Literature Review and Thematic Analysis

The reviewed literature clusters into six major thematic areas (Figure 4): compost and manure-based amendments, biochar and biochar-compost combinations, vermicompost applications, green manure and cover cropping, integrated nutrient management, and contaminant/risk assessment. Each theme is critically examined below.

3.1 Compost and Manure-Based Amendments

Compost and animal manure remain the most widely studied organic amendments for soil restoration. A comprehensive narrative synthesis covering studies published through December 2023 concluded that compost, vermicompost, biochar, and industrial pomace amendments consistently increase soil organic matter content and improve short-term aggregate formation and soil structure across diverse soil types and climatic conditions [13]. Comparative work on animal manure versus vegetable-waste-derived compost found both effective at restoring polluted or degraded soils and supporting maize growth, though manure-based composts tended to release nutrients more rapidly while vegetable-waste composts contributed more stable, humified organic matter [14].

Long-term biosolids application studies in semi-arid dryland systems similarly reported improvements in key soil health functions, including water-holding capacity and microbial activity, though the magnitude of benefit was strongly moderated by application history and native soil texture (14). A recurring point of agreement across this sub-theme is that compost/manure amendments improve short- to medium-term soil physical and biological properties; a point of disagreement concerns their capacity to produce durable, long-term structural change without repeated application, since the more labile organic fractions they supply decompose relatively quickly [13].

3.2 Biochar and Biochar-Compost Combinations

Biochar has attracted sustained research interest as a stable, high cation-exchange-capacity soil conditioner and climate mitigation tool. A field-based meta-analysis found that biochar application in combination with compost or manure produced a substantially higher effect size on soil microbial biomass carbon (37.2%) than biochar alone or any other single management practice, attributing this synergy to biochar's capacity to retain and stabilize nutrients supplied by co-applied organic matter [3].

However, the literature reveals important moderating factors. A separate meta-analysis reported that biochar's effect on microbial biomass was significant in acidic and neutral soils but not detected in alkaline soils, indicating that soil pH context substantially conditions amendment efficacy (15). Complementary evidence from metagenomic studies of biochar-compost co-application in urban soils demonstrated enrichment of specific microbial taxa (e.g., Acidobacteria, Nitrospira) associated with carbon-fixation gene abundance, alongside a 27% increase in soil moisture content and a 45% increase in available phosphorus at particular dose combinations (16). These findings collectively support the conclusion that biochar's benefits are dose-, feedstock-, and pyrolysis-temperature dependent rather than universal, a nuance often lost in generalized claims about biochar's soil health benefits (17,18).

Emerging work combining biochar with functional microbial inoculants reported even larger gains — shoot dry weight increased by 51.8% and soil organic carbon by 49.4% relative to controls when biochar was paired with selected microorganisms, particularly when low-pyrolysis-temperature (≤500 °C), wood-based biochar was used (19). This points to microbial co-inoculation as a promising but still under-standardized extension of biochar-based restoration.

3.3 Vermicompost Applications

Vermicompost — produced through earthworm-mediated decomposition of organic waste — is consistently reported to improve cation exchange capacity, micronutrient availability, and microbial biomass carbon more effectively than conventional compost of equivalent feedstock, owing to its higher porosity and humic substance content (20,21). Texture-specific studies in dryland agroecosystems found vermicompost reduced bulk density and dispersible clay while raising soil organic carbon and friability index across clay loam and sandy soils, though electrical conductivity increases were also observed in clay loam soils, warranting salinity monitoring under repeated application (22).

In acidic soils, combined lime and vermicompost applications significantly raised soil pH and phosphorus availability relative to either amendment alone, illustrating a broader pattern in the literature: vermicompost performs best as a component of an integrated amendment strategy rather than as a stand-alone intervention, particularly in chemically constrained soils (23). Vermicompost has also demonstrated value in phytostabilization contexts, supporting plant performance in manganese-contaminated mining-degraded soils while preserving arbuscular mycorrhizal fungal (AMF) functionality even at reduced root colonization rates (24).

3.4 Green Manure and Cover Cropping

Green manure incorporation and cover cropping represent lower-cost, biologically driven alternatives (or complements) to externally sourced amendments. Mechanistic reviews indicate that green manure integration reduces soil organic carbon mineralization, increases carbon inputs, and promotes soil aggregation and microbial biomass accumulation through combined physical, chemical, and microbial stabilization pathways (25). Field evidence from the Eastern Himalayan foothills demonstrated that green manuring and crop residue management increased soil organic carbon stock and aggregation while sustaining system productivity in cereal-based cropping systems (26).

A notable controversy in this sub-theme concerns interactions between green manure and soil inorganic carbon (SIC) in calcareous soils: a nine-year Loess Plateau field experiment found that while green manuring reliably enhanced SOC sequestration, it simultaneously increased the risk of SIC loss, with the magnitude of this trade-off depending on the specific green manure species used (27). This finding complicates a straightforward endorsement of green manuring as universally carbon-positive and underscores the need for site-specific carbon accounting that considers both organic and inorganic pools.

Pot- and field-based studies combining green manure with reduced chemical fertilizer rates found that green manure incorporation mitigated the nutrient-availability penalty of fertilizer reduction, supporting its role within integrated nutrient management systems aimed at reducing synthetic input dependency without compromising yield (28).

3.5 Integrated Nutrient Management and Synergistic Practices

A growing body of literature examines organic amendments not in isolation but as one component of integrated management systems alongside conservation tillage, crop rotation, and soil microbiome management. A 2025/2026 synthesis argued that the integration of these four strategies yields benefits that substantially exceed their individual contributions, with organic amendments serving as the primary lever for replenishing soil organic matter and stimulating biological activity within the broader system. This meta-analytic evidence indicated that long-term organic amendment increases topsoil organic carbon by approximately 24% on average and that a 2023 meta-analysis found consistent increases in soil bacterial diversity and enzyme activities linked to nitrogen and phosphorus cycling following organic amendment.

This integrative framing represents an important shift in the field: rather than asking which single amendment performs best, recent research increasingly investigates which combinations and sequencing strategies produce the greatest synergistic soil health gains under specific pedoclimatic conditions.

3.6 Contaminant and Risk Assessment

A critical, sometimes underemphasized, strand of the literature examines risks associated with organic amendments, particularly those derived from municipal or industrial waste streams. Reviews note that organic amendments can harbor human pathogens, heavy metals, persistent organic pollutants, and emerging contaminants such as antibiotic-resistance genes and microplastics, creating potential trade-offs between soil fertility benefits and environmental or public health risk.

Field studies on poultry waste, press mud, and farmyard manure applied to soil-vegetable systems found that while these amendments reduced heavy metal mobility in some cases, they also elevated metal concentrations in edible tissue under certain conditions, with implications for food-chain exposure. Similarly, composting has been shown to concentrate rather than eliminate microplastic contamination, with one study reporting high ecological risk indices for microplastic content across all sampled composting facilities, and organic fertilizer increasingly recognized as a vehicle for microplastic entry into agricultural soils. These findings introduce a necessary caveat to enthusiasm for waste-derived organic amendments: their soil-restorative benefits must be weighed against contaminant loading, particularly where feedstock quality is not verified or regulated.

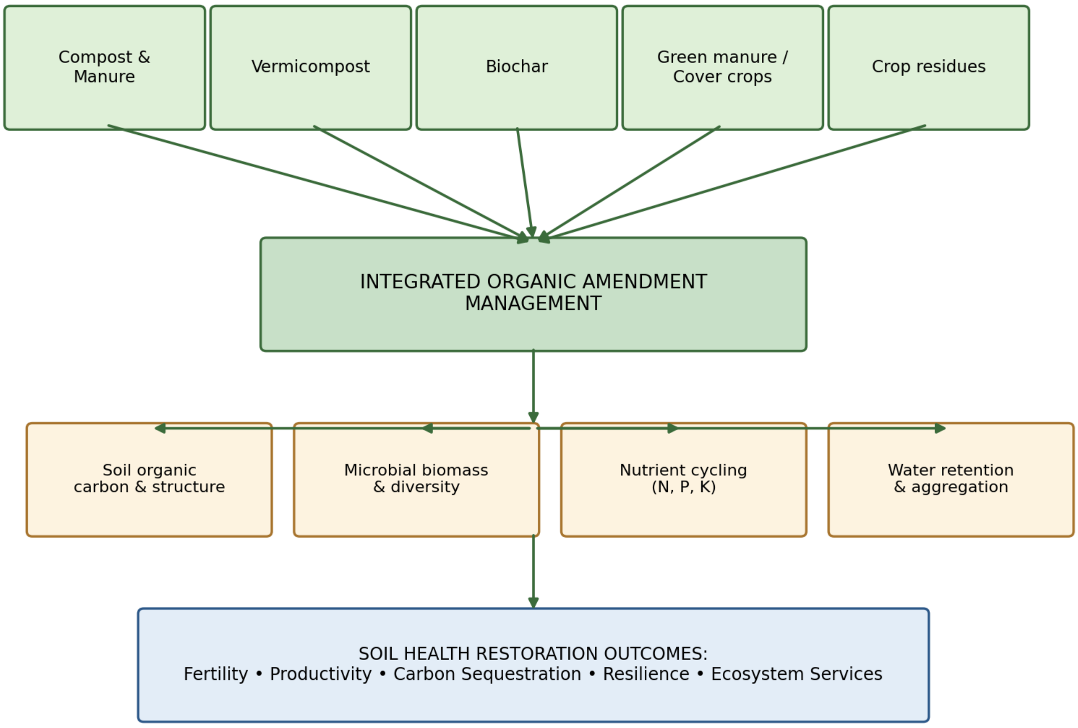

Fig 3: Conceptual framework linking organic amendment inputs, soil mechanisms, and soil health restoration outcomes.

Figure 3 depicts the conceptual pathway synthesized from the reviewed literature: diverse organic amendment inputs act through overlapping mechanistic channels — organic carbon and structural change, microbial biomass and diversity, nutrient cycling, and water dynamics — that collectively converge on multidimensional soil health restoration outcomes, reinforcing the rationale for integrated rather than single-input amendment strategies.

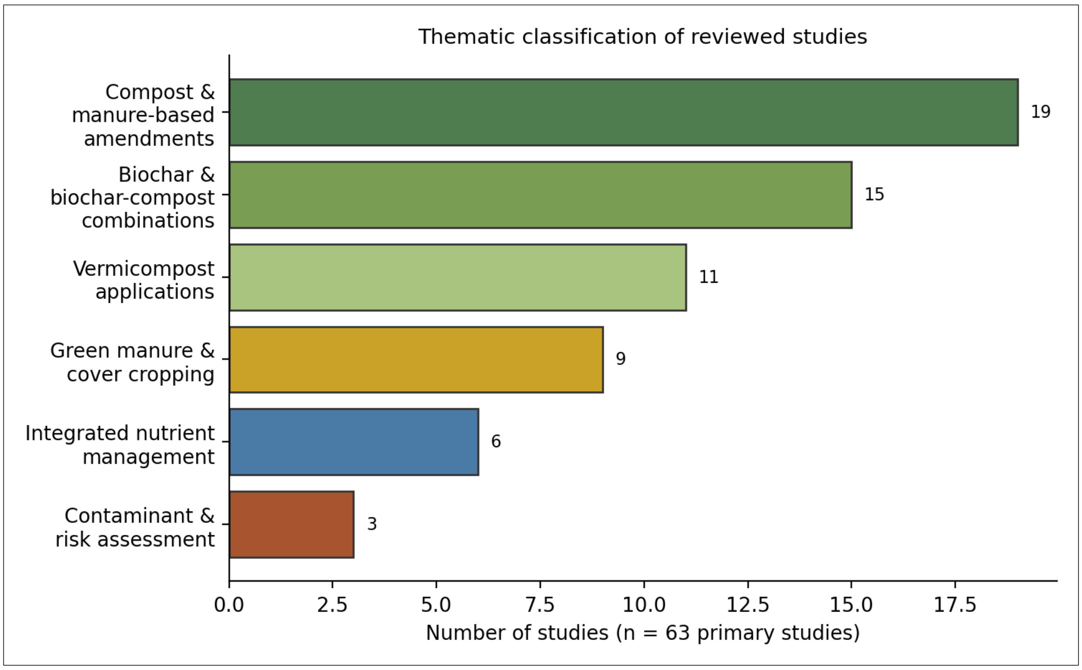

Fig 4: Thematic classification of the 63 primary studies included in the review.

As shown in Figure 4, compost/manure-based amendments and biochar/biochar-compost combinations together account for more than half of the primary studies reviewed, reflecting their long research history, while contaminant and risk-assessment studies remain comparatively scarce despite their policy relevance — a disparity discussed further in Section 5.

4. Comparative Analysis of Previous Studies

Table 3 and Table 4 present a structured comparison of key studies reviewed, summarizing study location, methodological approach, principal findings, and stated limitations. This comparative structure highlights both convergence (e.g., consistent SOC gains from long-term organic amendment) and divergence (e.g., variable biochar efficacy across soil pH classes) across the evidence base.

Table 3: Summary of Selected Studies

Author(s)	Year	Study location	Methodology	Major findings
Chen *et al.* [4]	2025/2026	Global synthesis	Meta-analysis of integrated management practices (rotation, tillage, amendments, microbiome)	~24% increase in topsoil SOC with long-term organic amendment; amplified benefits from integration
Ali/Bashir group [13]	2024	Multi-region narrative review	Literature synthesis, studies through Dec. 2023	Compost, vermicompost, biochar, pomace amendments improve SOM and short-term aggregation
Springer/Biochar journal [3]	2025	Global field meta-analysis	Meta-analysis of field experiments	Biochar + compost/manure raised microbial biomass carbon effect size to 37.2%
Frontiers Soil Science [16]	2025/2026	Urban green space, China	Metagenomic sequencing, 8 treatment gradients	BC8 compost combo raised soil moisture 27%; BC4 combo raised available P by 45%
ScienceDirect biochar-microbe study [19]	2025	Global meta-analysis	Meta-analysis, biochar + microbial inoculants	Shoot dry weight +51.8%, SOC +49.4% vs. control
Drylands vermicompost study [22]	2025	Semi-arid drylands	Field/soil-texture comparative study	Reduced bulk density and dispersible clay; raised SOC and friability across textures
Ethiopia lime-vermicompost [23]	2025/2026	Sayo District, Ethiopia	Pot-based incubation, factorial design	Combined lime + coffee husk vermicompost raised pH and P availability in acidic soils
Loess Plateau green manure study [27]	2025	Loess Plateau, China	9-year field experiment	SOC sequestration increased but SIC loss risk also increased under green manuring
Eastern Himalaya study [26]	2022	Eastern Himalayan foothills, India	Long-term field trial	Green manuring + residue management increased SOC stock, aggregation, productivity
Organic amendment risk review [12]	2019	Global review	Narrative review of contaminant risk	Organic amendments can harbor pathogens, heavy metals, ARGs, and microplastics

Table 4: Comparative Analysis of Previous Research by Amendment Category

Amendment category	Key strengths (evidence)	Key limitations / risks
Compost/Manure	Improves SOM, aggregation, short-term structure across soil types (13,14)	Benefits often transient without repeated application; nutrient release variable by feedstock
Biochar (+ compost/manure)	Synergistic microbial biomass gains (37.2% effect size); stabilizes co-applied nutrients (3,16)	Efficacy pH-dependent (limited in alkaline soils); feedstock/pyrolysis variability (15,17)
Vermicompost	Superior CEC, micronutrient availability, structure improvement across textures (20–23)	EC increases observed in clay loam soils; salinity monitoring needed (22)
Green manure/Cover crops	Low-cost SOC and N-cycling gains; supports reduced fertilizer regimes (25,26,28)	Trade-off with soil inorganic carbon loss in calcareous soils (27)
Integrated/INM systems	Amplified, synergistic benefits exceeding single-practice effects (4,6)	Few studies isolate the marginal contribution of each component practice
Waste-derived amendments (risk)	Valorizes organic waste; circular-economy potential (10,11)	Heavy metal, ARG, and microplastic contamination risks require feedstock quality control (12,29–31)

5. Research Gaps and Emerging Trends

5.1 Unresolved Issues and Knowledge Gaps

Despite substantial convergence on the general soil-restorative value of organic amendments, several issues remain unresolved. First, the durability of soil health gains beyond 3–5 years is inadequately documented; most primary studies reviewed here report outcomes from single or short-sequence growing seasons, leaving open questions about whether observed improvements in SOC, aggregation, and microbial biomass persist, plateau, or regress without sustained input (13,26). Second, the field lacks a standardized, universally adopted soil health index, resulting in studies reporting disparate indicator sets (enzyme activities, microbial biomass carbon, aggregate stability, CEC) that resist direct comparison or formal meta-analytic pooling (4,20).

5.2 Methodological Limitations in Previous Studies

A recurring methodological limitation is the confounding of amendment type with application rate, feedstock source, and co-management practices (e.g., tillage, irrigation), which complicates attribution of observed effects to the amendment itself versus the broader management system (3,15). Many studies, particularly those addressing biochar, do not adequately report pyrolysis temperature or feedstock characteristics, despite evidence that these parameters materially alter soil microbial and chemical responses (17,18). Additionally, contaminant-risk studies are frequently short-term and site-specific, limiting extrapolation to the diversity of waste streams used in practice (12,29,30).

5.3 Emerging Technologies and Future Developments

Several emerging directions are visible across the recent literature (Table 6, Figure 6). Precision and sensor-guided amendment dosing, informed by real-time soil monitoring and decision-support algorithms, offers the potential to optimize amendment type and rate to site-specific soil conditions rather than relying on blanket recommendations (4). Co-formulation of biochar or compost carriers with selected functional microbial consortia is emerging as a means of enhancing and stabilizing biological soil health gains beyond what either component achieves alone (19). Circular-economy models for converting municipal and agricultural waste into quality-assured amendments are gaining policy traction, particularly where linked to carbon-credit or agri-environmental incentive schemes (6,10,11).

5.4 Areas Requiring Further Investigation

Priority areas for future research include: long-term (>5-year), multi-site field trials spanning diverse agro-climatic zones; development and validation of standardized soil health indices; expanded representation of tropical and smallholder farming contexts; quantitative risk assessment frameworks for microplastic and antibiotic-resistance gene contamination in waste-derived amendments; and socioeconomic research examining adoption barriers and cost-effectiveness for resource-constrained farmers (12,22,29–31).

Table 5: Research Gaps Identified

Gap category	Description	Consequence
Temporal scope	Predominance of short- to medium-term (1–3 year) trials	Limits confidence in durability of soil health gains and long-term risk accumulation
Indicator standardization	Wide variability in soil health metrics used across studies	Impedes cross-study comparison and meta-analytic synthesis
Geographic representation	Underrepresentation of tropical smallholder and resource-limited systems	Findings from temperate, mechanized systems may not generalize
Contaminant quantification	Limited quantitative risk data on microplastics and ARGs in field settings	Risk-benefit trade-offs remain poorly characterized for policy guidance
Mechanistic resolution	Limited coupling of microbial community data with functional soil outcomes	Restricts mechanistic understanding of why synergies occur
Socioeconomic dimension	Sparse cost-benefit and adoption-barrier research for smallholders	Limits translation of technical findings into scalable policy

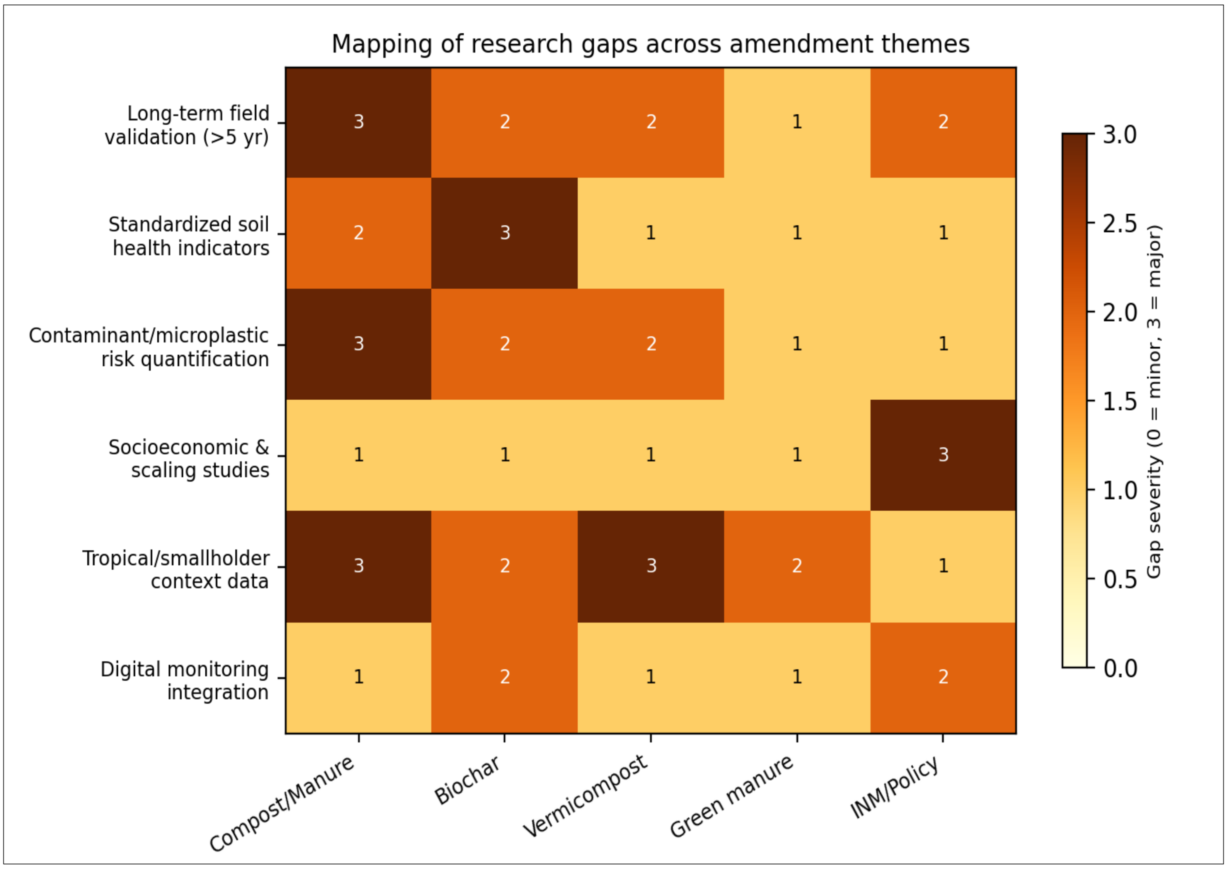

Fig 5: Research gap mapping across amendment themes, illustrating the relative severity of each gap category by theme.

Figure 5 highlights that long-term validation and standardized indicators represent the most pervasive gaps across nearly all amendment categories, whereas socioeconomic and scaling research gaps are comparatively concentrated within the integrated nutrient management/policy theme, suggesting where future funding and research prioritization could yield the greatest marginal benefit.

Table 6: Emerging Trends in the Field

Emerging trend	Description
Precision/sensor-guided amendment dosing	Integration of soil sensors and decision-support algorithms to tailor amendment type, rate, and timing to site-specific conditions
Microbial inoculant co-formulation	Combining biochar or compost carriers with selected functional microbial consortia to enhance and stabilize soil biological gains
Standardized soil health indices	Development of harmonized, multi-indicator soil health scoring frameworks to enable cross-study and cross-region comparison
Circular-economy waste valorization	Systematic conversion of municipal, agro-industrial, and livestock waste into quality-assured amendments under regulatory oversight
Carbon-credit and policy integration	Linking verified soil organic carbon gains from organic amendment practices to carbon markets and agri-environmental policy incentives
Contaminant screening technologies	Rapid, field-deployable methods for detecting heavy metals, antibiotic-resistance genes, and microplastics in amendment feedstocks

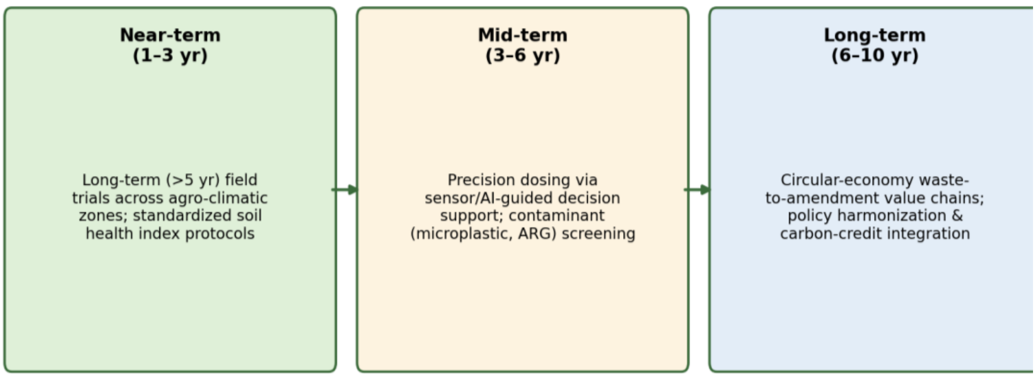

Fig 6: Projected trajectory of research and technology adoption in integrated organic amendment management over near-, mid-, and long-term horizons.

6. Discussion

Synthesizing across the six thematic areas reviewed, the literature demonstrates a consistent and mechanistically coherent case that organic amendments — particularly when integrated rather than applied as single inputs — restore multiple dimensions of soil health simultaneously: physical (aggregation, bulk density, water retention), chemical (organic carbon, cation exchange capacity, nutrient availability), and biological (microbial biomass, diversity, enzyme activity) [3, 4, 13, 16]. The magnitude of reported effects is often substantial: topsoil organic carbon increases averaging approximately 24% under long-term organic amendment, and microbial biomass carbon effect sizes reaching 37% under combined biochar-compost application, represent gains of practical agronomic significance rather than marginal statistical effects [3, 4].

At the same time, the review surfaces important sources of heterogeneity that qualify any universal recommendation. Soil pH context substantially moderates biochar efficacy, with alkaline soils showing attenuated or absent microbial biomass responses relative to acidic and neutral soils [15]. Soil texture likewise conditions vermicompost outcomes, with electrical conductivity increases observed specifically in clay loam soils that were not evident elsewhere [22]. These findings collectively argue against one-size-fits-all amendment prescriptions and in favor of soil-diagnostic, context-specific recommendations — a conclusion consistent with the broader shift toward precision and integrated nutrient management approaches identified in the emerging-trends literature [4, 6].

A further tension evident in the literature concerns the carbon accounting boundary. While green manure incorporation reliably increases soil organic carbon, at least one long-term calcareous-soil study found this occurs alongside increased soil inorganic carbon loss, meaning that SOC-only reporting may overstate net soil carbon benefit in specific soil chemistries [27]. This suggests that future carbon-sequestration claims tied to organic amendment practices — including those underpinning carbon-credit schemes — should account for total (organic plus inorganic) carbon pools where calcareous soils are involved.

The risk dimension of the evidence base deserves particular emphasis because it is frequently underweighted relative to the fertility and productivity benefits emphasized in agronomic literature. Waste-derived amendments — compost, manure, biosolids — supply valuable nutrients and organic matter, but multiple studies document the co-introduction of heavy metals, pathogens, antibiotic-resistance genes, and microplastics, with at least one study reporting high ecological risk indices for microplastic contamination across all sampled composting facilities [12, 30, 31]. This is not an argument against organic amendment use, but rather evidence that amendment quality assurance, feedstock screening, and regulatory oversight should be treated as integral components of soil health restoration programmes rather than afterthoughts.

Finally, the concentration of rigorous field evidence in temperate, mechanized agricultural systems — relative to sparser data from tropical smallholder contexts — raises legitimate questions about the generalizability of current recommendations to the farming systems where soil degradation pressures and food security stakes are often greatest [2, 22]. Bridging this evidence gap is arguably the single most consequential step needed to translate the substantial scientific progress synthesized in this review into globally equitable soil health outcomes.

7. Conclusion

This review incorporates the insights gleaned from 77 peer-reviewed and institutional sources spanning from 2015 to 2026 to assess the significance of integrated organic amendments in improving the quality of soils. Thus far, the evidence supports the notion that composts, manure, vermicompost, biochar and green manure can have a lasting impact on improving soil organic carbon and the soil's physical, chemical and biological attributes, especially when applied in the framework of integrated management of various amendments.

What makes this synthesis notable is the fact that it allows identifying the key areas of research where agreement between scientific researchers exists (general thermal and microbial impact of organic amendments) and the key names of active research, with some improvements in soil quality depending on such criteria as the pH level.

This review suggests that researchers should prioritize conducting long-term and multi-venue field trials, creating and implementing standardized indices for assessing soil health, and improving quantitative assessment of risks from contamination caused by waste-based amendments. On the other hand, practitioners and policymakers need to follow a contextual approach and introduce amendment prescriptions taking into account results from soil diagnostics; waste-based amendment production should be regulated with regulations; and policies should favor circular economics — and should contain guidelines for carbon credit systems and risk assessment for integrated amendment production process.

Researchers must pay attention to the integration of precision monitoring systems, co-formulation microbial techniques, and expanding representation of tropical and smallholder agricultural systems for the purpose of achieving equitable and sustainable application of integrated organic amendment techniques on a global scale.

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