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Review

Organic Amendments for Sustainable Agriculture: Effects on Soil Function, Crop Productivity and Carbon Sequestration Under Variable Contexts

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Abstract

Soil amendments play a critical role in improving soil health and supporting sustainable crop production, especially under declining soil fertility and climate-related stress. However, their impact varies because each amendment influences the soil through different biogeochemical processes rather than a single universal mechanism. This review synthesizes current knowledge on a wide range of soil amendments, including compost, biosolids, green and animal manure, biochar, hydrochar, bagasse, humic substances, algae extracts, chitosan, and newer engineered options such as metal–organic framework (MOF) composites, highlighting their underlying principles, modes of action, and contributions to soil function, crop productivity, and soil carbon dynamics. Across the literature, three main themes emerge: improvement of soil physicochemical properties, enhancement of nutrient cycling and nutrient-use efficiency, and reinforcement of plant resilience to biotic and abiotic stresses. Organic nutrient-based amendments mainly enrich the soil and build organic matter, influencing soil carbon inputs and short- to medium-term increases in soil organic carbon stocks. Biochar, hydrochar, and related materials act mainly as soil conditioners that improve structure, water retention, and soil function. Biostimulant-type amendments, such as algae extracts and chitosan, influence plant physiological responses and stress tolerance. Humic substances exhibit multifunctional effects at the soil–root interface, contributing to improved nutrient efficiency and, in some systems, enhanced carbon retention. The review highlights that no single amendment is universally superior, with outcomes governed by soil–crop context. Its novelty lies in its mechanism-based, cross-amendment synthesis that frames both yield and carbon outcomes as context-dependent rather than universally transferable. Within this framework, humic substances and carbon-rich materials show potential for climate-smart soil management, but long-term carbon sequestration effects remain uncertain and context-dependent.

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1. Introduction

Global warming is attributed to the significant amount of methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) emissions through the diverse types of agricultural management systems [1,2]. Agriculture contributes approximately 12% of global anthropogenic greenhouse gas (GHG) emissions [3]. Increasing pressure on land, driven largely by population growth and intensive agriculture, has been responsible for a decline in soil fertility and the large-scale release of anthropogenic GHGs, promoting severe acceleration of global warming and climate change [3,4]. Yet, the total global food demand is expected to increase by 35% to 56% before the year 2050 [5]. According to FAO [6], a 60% increase in food production compared to current levels is required, with 80% of this additional output expected to come from existing arable land. Meeting the global demand for nutritious and safe food for the continuously growing population, both now and in the future, presents a significant problem. This intensification places significant pressure on soils and ecosystems. While the use of inorganic fertilizers may initially boost crop yields, excessive utilization can reduce soil microbial biomass, cause soil acidification and degradation, pollute water bodies, contribute to greenhouse gas emissions, and ultimately threaten both flora and fauna ecosystems [7].

To address these problems, the application of organic amendments has been advocated as a viable tool for sustainable food production [7,8]. A prevalent belief exists that a comprehensive transition from conventional to organic farming may provide the world with safe and nutritious food while preventing environmental deterioration. The incorporation of organic amendment into agricultural soils offers numerous benefits, serving both as a source of essential plant nutrients and as a means of enhancing soil organic carbon (SOC) levels [9]. Benefits such as enhanced soil structure, improved nutrient cycling, and increased SOC must be weighed against important trade-offs, including variable nutrient release patterns, potential nitrogen losses, greenhouse gas emissions during decomposition or composting, and challenges related to scalability, transport, and application costs. Moreover, the agronomic performance of organic amendments is strongly context-dependent, influenced by feedstock quality, processing method, soil type, and climate. Recognizing these limitations is essential for evaluating their realistic role in sustainable agriculture and climate mitigation strategies.

Although these inputs are widely recognized for their multiple agronomic and environmental benefits, their use is not without challenges, with ongoing controversies regarding their effectiveness in mitigating greenhouse gas emission through enhanced soil carbon (C) sequestration. Other concerns include the possibility of harboring pathogens and soluble salts, low nutrient concentration requiring high application rates, and slow nutrient release that may not align with crop demand [10–12]. Environmental implications also arise from composting, where C and nitrogen (N) losses reduce agronomic value and contribute to emissions, particularly when management is inadequate. Additionally, questions persist as to whether all organic matter inputs, irrespective of their source, exert the same influence on soil properties [13,14].

Several reviews have examined individual amendment types or focused on specific outcomes such as nutrient cycling or carbon sequestration. However, few synthesize the full breadth of both traditional and emerging organic amendments while integrating mechanistic insights across physical, chemical, and biological soil processes. This review provides a comprehensive, cross-comparative assessment of amendments ranging from compost and manure to biochar, hydrochar, algae, humic substances, and engineered materials. By emphasizing the distinct mechanisms through which each amendment influences soil function and crop performance, this work offers a more integrated framework for selecting amendment strategies tailored to specific agronomic and environmental goals.

2. Types of Organic Amendments

Organic amendments encompass a wide range of materials of biological origin that are added to soil to improve its physical, chemical, and biological properties, enhance crop productivity, and contribute to C sequestration [15,16]. These amendments can be broadly classified according to their primary source into plant-derived and animal-derived materials. Plant-derived amendments originate from fresh biomass, crop residues, or processed plant products such as compost, biochar, green manure, algae, seaweed, and bagasse. They often supply organic matter and nutrients while influencing soil structure and microbial activity. Animal-derived amendments, on the other hand, include biosolids and biopolymer-based materials like chitosan. These typically provide concentrated nutrient inputs, enhance soil biological health, and may offer additional benefits such as pathogen suppression [17]. Understanding the origin, composition, and decomposition dynamics of each category is essential for evaluating their role in soil improvement, sustainable crop production, and long-term C storage.

2.1. Importance of Source-Based Classification

Recent findings highlight the contrasting effects of plant- and animal-derived organic amendments on soil C dynamics and fertility, which can be interpreted through both their biological origin (plant- vs. animal- derived) and their functional composition (nutrient-rich vs. carbon-rich). Xie et al. [18] observed that animal-derived fertilizers rapidly increased total organic carbon (TOC) by 139.25% and particulate organic carbon (POC) by 215.25%, reflecting the high proportion of readily mineralizable organic inputs typically associated with animal manures. In contrast, plant-derived fertilizers contributed to a more stable accumulation of POC, indicating stronger potential for long-term fertility. Rahman et al. [19] reported that organic amendments, including animal manures, improved soil aggregate stability and enhanced C sequestration in wetland paddy soils, underscoring their role in short- to medium-term biological and structural improvements.

While organic amendments can be broadly grouped into plant-derived and animal-derived categories, these classifications inevitably overlap. For example, compost may contain both plant residues and animal manures, and biosolids can be further processed into composted or pelletized forms. The purpose of the source-based classification used here is not to impose rigid boundaries but to highlight dominant compositional and functional characteristics. Acknowledging these overlaps is important, as the agronomic behavior of an amendment often reflects both its origin and its degree of processing.

These contrasting responses illustrate that amendment origin alone does not fully explain soil outcomes; rather, functional composition plays a critical role. Plant-derived materials generally supply higher proportions of lignocellulosic C and contribute to structural improvements and long-term C storage, particularly when in processed or pyrolyzed forms such as compost and biochar [20]. By contrast, animal-derived amendments often contain higher concentrations of readily mineralizable N and P, leading to more immediate effects on crop yield and soil microbial activity [21,22]. Importantly, exceptions to this general pattern exist. Algae and green manures are plant-derived yet nutrient-rich, while lignocellulosic residues and biochar represent carbon-rich materials with limited short-term nutrient release. These examples illustrate that amendment origin and functional composition are complementary, rather than competing, classification criteria.

In addition to conventional materials, several emerging or engineered amendments, such as chitosan, algae extracts, and metal–organic framework (MOF) composites are increasingly explored for their biostimulant or soil-conditioning properties. However, many of these materials remain at an experimental or early development stage, with limited field validation and uncertain scalability. Their inclusion in this review is intended to highlight future directions rather than to imply readiness for widespread agricultural deployment.

Furthermore, decomposition dynamics, potential contaminants, and functional roles differ markedly across amendment types. For example, animal-derived amendments may pose greater risks of nutrient losses or contaminants, whereas some plant- or bio-based materials provide ancillary benefits such as disease suppression, as observed with chitosan [23–25]. This classification therefore provides a practical framework for evaluating the suitability of different organic amendments under specific agronomic and environmental conditions, facilitating targeted soil management strategies that balance short-term productivity with long-term soil health and C sequestration goals.

2.2. Plant-Derived Amendments

2.2.1. Algae

Algae are unicellular or multicellular photosynthetic autotrophs occurring in a wide range of aquatic and terrestrial habitats [26]. They include microalgae, such as green algae (*Chlorella* spp.) and cyanobacteria (*Arthrospira platensis*), as well as macroalgae, or seaweeds, including brown, red, and green varieties. Owing to their rich composition of organic matter, essential nutrients, and bioactive compounds such as phytohormones, polysaccharides, and amino acids [27,28], algae have gained increasing attention as organic amendments for enhancing soil fertility and crop productivity. When incorporated into soil, algae can improve nutrient availability, stimulate beneficial microbial activity, and promote plant growth and stress tolerance.

Several studies have shown that microalgae and seaweed amendments enhance soil nutrient status and crop performance. Short-term laboratory and pot experiments provide mechanistic insights into nutrient dynamics following microalgal amendments. In laboratory incubations, manure enriched with *Chlorella vulgaris* increased SOC mineralization by 16.2–35.9%, boosted available potassium by 40–50%, and enhanced nitrate-N by 20–30% compared with control treatments [29]. Similarly, a pot experiment conducted by Garbowski [30] on sandy soils amended with *C. vulgaris* suspension reported increases of approximately 26% and 10% in total N and P, respectively, while also reducing nutrient leaching and stabilizing SOC. Consistent with these findings, microalgae-based fertilization has been shown to substantially reduce N losses, with only 7% of N leached compared to 50% under synthetic fertilizer and 24% with liquid digestate [31]. Collectively, these short-term studies highlight the capacity of microalgae to improve nutrient retention and use efficiency, although responses vary with soil type, amendment rate, and management practices.

Longer-term greenhouse and field studies further support the agronomic relevance of these amendments under more realistic growing conditions. Alobwede et al. [32] evaluated *Arthrospira platensis* (Spirulina), *Chlorella* sp., the red seaweed *Palmaria palmata*, and the brown seaweeds *Laminaria digitata* and *Ascophyllum nodosum* in greenhouse-grown garden peas and field-grown spring wheat. In the greenhouse, application of *Chlorella* sp. and Spirulina both at 1.9 g kg^{-1} increased soil N concentration by 12%, while *Chlorella* sp. and *P. palmata* significantly increased soil C concentrations by 17%. Under field conditions, amendments with *Chlorella* sp., Spirulina, *P. palmata*, and *L. digitata* consistently increased soil inorganic N, demonstrating that microalgae and seaweed amendments can enhance nutrient cycling and crop performance beyond controlled experimental settings. Benefits accumulate gradually, particularly in coarse-textured or degraded soils, where organic inputs contribute to aggregate formation and long-term structural stabilization. Stańczyk-Mazanek [33] reported that the repeated application of algal biomass to initially low-fertility sandy soils over a 3-year period led to substantial improvements in soil chemical properties. Relative to the unfertilized control and baseline soil conditions typical of sandy soils (low organic matter and nutrient contents), hydrolytic acidity decreased by 29%, while soil P and N contents increased by 43% and 17%, respectively. Marked increases were also observed in soil organic carbon (66.3%) and organic matter (62%) at a fertilization dose of 2% algal biomass, indicating a pronounced enhancement of soil quality over the study period. Similarly, Ali et al. [34] found that *Ascophyllum nodosum* seaweed extract enhanced tomato yield by 51–63% compared with control plants.

Certain species, particularly cyanobacteria, are capable of biological N fixation, contributing 20–40 kg N ha^{-1} yr^{-1} in rice paddies [35,36] and, under favorable conditions, up to 80 kg N ha^{-1} [37]. Importantly, their application can reduce the reliance and costs on chemical N fertilizers by approximately 25–50% [38,39]. Inoculation with cyanobacteria has also been shown to enhance crop performance by improving yield and microbial activity (5–25%), while also promoting plant growth and seed germination across a wide range of cereal and vegetable crops [40,41]. Furthermore, *Lupinus termis* seeds treated with cyanobacterial filtrates (*Anabaena flos-aquae* and *Nostoc muscorum*) and bacterial suspensions (*Azotobacter chroococcum* and *Azospirillum brasilense*) showed markedly higher germination rates, with increases ranging from 53% to over 200% compared with untreated controls [42].

Algal biomass positively influences the physical and chemical properties of soil by improving its water retention capacity, soil structure, and microbial activity [43]. For example, application of microalgae fertilizer increased soil moisture content by 20%, 67%, and 75% under low (25%), medium (75%), and high (100%) application rates, respectively, compared to the control, with the highest dose maintaining moisture for a longer period [44]. Similarly, seaweed-derived products have been reported to enhance aggregate stability by 85%, 130%, and 160% in sandy loam, loam, and silty clay loam soils, respectively [36]. Algal additions also stimulate microbial activity. Stimulation of microbial activities by algal additions expressed by increases in dehydrogenase and phosphatase activity, microbial biomass C, and higher Shannon diversity index values have been reported under *Chlorella* application [28,45]. The ability of algae to reduce metal availability and uptake in contaminated soils has also been established. Their effectiveness is attributed to high surface area-to-volume ratios that facilitate metal absorption, the production of phytochelatins for detoxification, and the ability to thrive under diverse metabolic conditions [46]. Genetic modifications have further enhanced tolerance and metal removal efficiency. Incorporation of dried *Ulva* and *Gelidium* biomass at 0.95 t ha^{-1} in pot trials reduced DTPA-extractable Zn, Pb, Mn and Cu by 28%, 27%, 40% and 33%, respectively, compared to the control [47]. Similarly, a mixture of *Ulva fasciata* and *Sargassum lacerifolium* reduced soil Pb, Cu, Zn and Ni to tolerable levels of 40.2, 49.3, 43.8 and 1.1 mg kg^{-1}, respectively, while increasing plant bioaccumulation factors (e.g., Cd BAF = 7.45, Ni BAF = 26.6) in radish roots [48]. In another pot study, application of *Ascophyllum nodosum* extract enhanced sorghum growth by 22–100% and increased Cd and Pb uptake [49], demonstrating that algae can promote either immobilization or phytoextraction depending on the form of amendment.

Furthermore, algae play a significant role in climate change mitigation by capturing atmospheric CO_2 through photosynthesis and addressing SOC depletion [39,50]. Inoculation of soils with living microalgae has been proposed as a viable strategy to simultaneously restore soil C stocks and reduce CO_2 emissions. Algal biomass can influence soil C dynamics by supplying labile organic C that supports microbial metabolism and more recalcitrant fractions that contribute to long-term C sequestration [51]. Microalgae are highly efficient carbon-rich amendments, capturing CO_2 at rates 10–50 times greater than terrestrial plants [52], corresponding to 1.8–2.5 kg CO_2 m^{-2} yr^{-1} compared with 0.1–0.3 kg CO_2 m^{-2} yr^{-1} by terrestrial vegetation [53]. This high C fixation potential distinguishes microalgae from nutrient-rich synthetic fertilizers, which primarily supply readily available N, P, and K but contribute little to soil C sequestration.

Despite these benefits, several challenges limit the widespread adoption of algae-based amendments. Regulatory gaps and the lack of standardized quality control result in inconsistent product efficacy and low awareness among farmers [54]. Practical constraints include limited storage and transportation facilities, the inaccessibility of suitable algal strains, and the tendency of some strains to lose effectiveness over time [55]. Soil and climatic factors, such as salinity, toxicity, or extreme weather, may further reduce field performance [56]. Economically, algae-based fertilizers generally contain lower nutrient concentrations (1–10% N, 0.05–3.3% P, and 1.2–3% K) than synthetic fertilizers (15–20% N) [31,39], requiring larger application rates of 4–8 t ha^{-1} to achieve equivalent yield effects, thereby increasing production and application costs by 2–3 times compared with conventional fertilizers.

Repeated or unscreened applications of algal materials are known to concentrate trace elements (As, Cd, Pb, Hg and others) and can contain substantial salt loads depending on species and harvest location. *Saccharina latissima* (*Sugar kelp*) and Greenland seaweed species have been found to contain arsenic at levels up to 61 mg kg^{-1} dry weight (dw) [57,58]. Reviews and case reports caution that applying seaweed from contaminated sources may increase soil and plant pollutant loads and that anaerobic decomposition of seaweed may produce sulfides that oxidize to sulfates [59,60], altering soil chemistry. Therefore, routine testing of algal feedstocks for salinity and trace-metal concentrations and careful management of application rates are recommended to avoid long-term salinization or accumulation of contaminants in amended soils. Given the ability of algal amendments to provide nutrients, enhance microbial activity, remediate pollutants, and sequester carbon, they present a promising, multifunctional solution for enhancing soil fertility, crop productivity, and environmental sustainability as a unique bioresource. However, addressing logistical, regulatory, and agronomic constraints is crucial to fully harness their potential in modern agriculture.

2.2.2. Compost

Compost is a stabilized organic amendment produced through the controlled aerobic decomposition of plant- and/or animal-derived residues [61,62]. Its maturity and stability are commonly assessed using indicators such as temperature decline, C/N ratio, respiration indices, germination index, humification indices, and electrical conductivity [63]. Mature compost is typically characterized by a C/N ratio < 20, respiration rate < 2 mg CO_2–Cg^{-1} OM d^{-1}, germination index $> 80\%$, and electrical conductivity < 4 dS m^{-1} [62,64,65]. The feedstocks used, such as crop residues, manures, or food wastes, along with process parameters including moisture, aeration, and curing time, strongly influence the nutrient profile, pH, salinity, and the relative proportions of labile versus humified C in the final product [62]. Reported compost nutrient compositions span 0.5–3.0% total N, 0.2–2% P, 0.5–3% K, 20–50% organic C, and a pH of 6.5–8.5, with moisture contents ranging 25–50% depending on feedstock [66–68].

When applied to soil, compost improves soil quality through multiple mechanisms. Physically, it increases aggregate stability (15–50%), lowers bulk density (by 0.1–0.5 g cm^{-3}), and improves infiltration and plant-available water (25–60%), particularly in coarse-textured or degraded soils [69–71]. These changes translate into better root penetration and water storage capacity. Compost contributes to the gradual release of N and P, enhances base saturation and cation exchange capacity (CEC gains of 2–6 cmolc kg^{-1}), and often exerts a partial liming effect depending on its ash content [63]. Chen et al. [72] reported that compost application for 3 years led to an increase in soil pH by 0.54, 0.75 and 0.49 units at rates of 15, 30, and 45 t ha^{-1}, respectively. Compost also immobilizes trace metals in contaminated soils through organic ligands [63]. According to Al Mamun et al. [73], addition of 2.5% (dry weight) municipal compost to soils reduced Cd concentrations in onions, spinach, and lettuce by up to 60%. Depending on compost type and application rates, reductions ranging from 20% to over 80% in Cd and Pb concentrations have also been reported [72,74]. Mechanisms include increased organic matter, enhanced microbial activity, and the formation of stable metal–organic complexes. Biologically, compost addition stimulates microbial biomass C and N (increases of 20–80% over unfertilized control) [75,76], boosts enzymatic activity, and enhances the diversity of beneficial microbial communities [77], thereby improving rhizosphere functioning and nutrient cycling [62]. Disease suppression is a further benefit, with tomato Fusarium wilt incidence reduced by 40–60% in soils receiving compost compared to synthetic fertilizer treatments [78].

The benefits of compost for crop productivity have been confirmed in diverse systems. Across multiple cereals, compost improves yields by 10–40% [79,80], while in vegetable systems such as tomato, fruit yield rose by 20–35% compared with unfertilized or mineral-only treatments [81,82]. Yield responses are most pronounced in nutrient-poor soils or when compost is used in combination with mineral fertilizers to synchronize N supply with crop demand [79,83]. Recent greenhouse experiments by Oueld Lhaj et al. [84] on sweet basil (*Ocimum basilicum* L.) further illustrate these effects: in sandy loam soil typical of arid and semi-arid regions, compost applications significantly improved soil fertility, structure, and plant performance, with 30-t ha^{-1} treatment producing the most notable results. Soil organic matter increased to 13.71%, while shoot length, essential oil content, and 100-seed weight rose to 42 cm, 0.83%, and 0.32 g, respectively, compared to the control. Importantly, these benefits were achieved without exceeding heavy metal thresholds, underscoring the potential of compost to boost horticultural productivity, reduce reliance on chemical fertilizers, and promote circular economy principles through organic waste recycling. Similarly, long-term field trials in corn-tomato rotations showed that continuous poultry manure compost applications enhanced soil aggregation, C storage, and microbial biomass compared to mineral fertilizers, which reduced aggregate stability and C storage [85]. Unlike biochar, which showed limited effects, compost delivered microbial-driven ecosystem services such as macroaggregate formation, improved nutrient cycling, and long-term C sequestration.

In terms of C sequestration, compost contributes to both short- and long-term soil C pools. Labile fractions feed soil microorganisms, while more humified fractions contribute to stable SOC [86]. On average, compost amendments increase SOC stocks by 0.3–0.8 Mg C ha^{-1} yr^{-1} [87,88]. Compost can also influence greenhouse gas emissions by reducing nitrous oxide release by 15–25% compared to fresh manures [89], due to its stabilized N forms and improved soil aeration. Co-application with biochar has shown even greater reductions in nitrous oxide emissions (up to 50%) while enhancing C sequestration potential [90,91].

Despite these benefits, compost use is not without setbacks. The quality of compost is highly variable, and immature compost can cause phytotoxicity, N immobilization, or salinity stress [62]. Immature products have been reported to reduce seed germination by 20–50% due to volatile fatty acids and ammonia [62]. Repeated applications could lead to nutrient imbalances, such as P accumulation and runoff risks, while N release may not coincide with crop demand without supplemental mineral N [92]. Salinity risks are also reported, as food-waste composts can reach 5–10 dS m^{-1} EC, suppressing growth of salt-sensitive crops [12,93]. Depending on feedstock, compost may also contain contaminants such as plastics (up to 536 kg ha^{-1} yr^{-1}), pathogens, or trace metals, underscoring the importance of careful feedstock selection and process monitoring [86,94]. Additionally, Compost is bulky and expensive to move and apply at agronomic rates. Practical case studies in Northern and Central Europe show full costs (purchase + haulage + spreading) around £300–350 ha^{-1} at moderate application rates [95,96]. Surveys across Northwestern Europe highlight transport, machinery, and labor as the most common barriers to adoption, consistent with the observation that compost's benefits accrue gradually and may require incentives to encourage long-term use. Policy instruments in Italy, for example, offer €155–220 ha^{-1} subsidies to help farmers offset application costs for 25 t DM ha^{-1} rates [97].

Compost represents one of the most widely studied and utilized organic amendments, with clear benefits for soil health, crop productivity, and climate change mitigation through C sequestration. However, consistent outcomes require careful attention to compost quality, application rate, and integration with other nutrient sources. Best practices include applying mature, stable compost at context-appropriate rates, balancing with mineral fertilizers to meet crop nutrient demands, and monitoring salinity or potential contaminants in manure- or waste-derived composts. When combined with complementary practices such as biochar addition or cover cropping, compost offers an effective strategy for sustaining soil fertility and building resilient agroecosystems [91].

2.2.3. Biochar

Biochar is a carbon-rich material produced through the thermal decomposition of biomass under limited or no oxygen, a process known as pyrolysis [98]. Depending on feedstock type (e.g., crop residues, wood, manure, or nutshells) and pyrolysis conditions (temperature, heating rate, and residence time), biochar can exhibit a wide range of physico-chemical properties such as pH (3.5–12.9), porosity, surface area, ash content (<5% to >50%), and C stability [99,100]. These inherent variations strongly influence their interactions with soil and plants. In particular, the hydrogen-to-carbon (H/C) and oxygen-to-carbon (O/C) ratios serve as quality/stability indicators [101]. A controlled greenhouse study on lettuce testing 10 biochars and 9 non-pyrogenic organic amendments showed effects ranging from strongly inhibitory to highly stimulatory depending on material chemistry; biochars with low H/C were generally least inhibitory and often growth-promoting [101]. Lower ratios indicate higher aromaticity and greater chemical recalcitrance; the International Biochar Initiative (IBI) recommends targets such as $H/C < 0.7$ and $O/C < 0.4$ for chars intended for long-term soil application [20,101]. Thus, production conditions largely dictate biochar's agronomic performance and environmental applications.

Biochar functions primarily as a soil conditioner rather than a direct nutrient source. Biochar improves water retention, aeration, cation exchange capacity (CEC) and adsorptive nutrient retention [102]. Meta-analysis finds available water (AW) increases approximately 30% in coarse soils, 21% in medium soils and 12% in fine soils [103] with effects depending strongly on texture, biochar dose and particle size. Improved field water content and reduced drought stress after biochar application had also been reported [104]. Coarse, high-ash biochars can supply base cations (Ca, Mg, K) and generate a liming effect [99,105], with typical field application rates that show clear liming or CEC effects often in the order of 5–20 t ha^{-1}. Conversely, very high application rates (>50 t ha^{-1}) can cause adverse outcomes such as salinity rise, reduced biological N fixation or N immobilization, unless balanced with N-rich inputs [106]. Biochar can capture mineral N (nitrate/ammonium) in its pore structure and organic coatings; field-aged biochar has been shown to retain plant-available nitrate and reduce leaching in several studies. Meta-analyses and field syntheses report reduced nitrate leaching (often in the range of 26–32%) and improved nutrient-use efficiency when biochar is combined with fertilizers [107]. Biochar application has also been reported to reduce soil N_2O emissions, although magnitudes vary with rate, feedstock and soil. Reported central values range from 19% (global analysis at 20 t ha^{-1} average application) to 38–54% reduction in many meta-analyses and reviews; mitigation is often larger in sandy or paddy soils and at higher biochar application rates [108,109].

Biochars strongly sorb cationic heavy metals (e.g., Pb, Cd, Cu, Ni) and many hydrophobic organic contaminants (HOCs) through a combination of high surface area/pore-filling, π–π and hydrophobic interactions, surface complexation with oxygenated functional groups, and pH/ash-driven precipitation [110]. Meta-analytic evidence indicates average reductions in plant tissue concentrations of Cd, Pb, Cu and Zn of roughly 38%, 39%, 25% and 17%, respectively, following biochar addition [111]. Laboratory adsorption experiments demonstrate that adsorption capacities vary widely with feedstock and treatment conditions. For example, Pb sorption ranges from tens up to >150–200 mg g^{-1} in modified, alkali-activated, or straw-derived biochars [112], while Cd sorption can be less than 1 mg g^{-1} in some wood-based biochars but reach 50–100 mg g^{-1} in manure or straw-derived biochars [113]. Co-composted (activated) biochars commonly outperform biochar alone at reducing extractable metal fractions and plant uptake, likely because composting generates organo-mineral complexes and coatings on biochar that increase nutrient retention and metal stabilization. Biochar also provides a habitat for soil microbes, stimulating plant growth–promoting organisms and mycorrhizal fungi, which improve nutrient cycling and crop resilience [91].

Crop responses to biochar are highly variable and context specific. In temperate agroecosystems, many studies reported limited or even negative yield effects when biochar is applied alone [114], underscoring the importance of soil type, crop species, and amendment strategy. When combined, mixtures exhibited non-additive interactions: synergistic effects were most common when biochar was paired with N-rich, lignin-poor amendments, whereas antagonistic outcomes occurred with woody or leaf litter materials. Mixture performance was governed primarily by the chemical quality of the accompanying organic amendment rather than the specific biochar type, indicating that the functional interactions between biochar and organic substrates play a decisive role in determining productivity outcomes. Field evidence reinforces this principle. In a continuous cotton system in Xinjiang, the combined application of organic manure and biochar significantly improved root morphology and physiology through better nutrient availability [115]. While manure alone enhanced root enzyme activities such as glutamine synthetase and nitrate reductase, the combined application of 6% manure with 1% biochar yielded the greatest improvements in root traits and overall soil fertility. Notably, higher biochar rates without manure were less effective, likely due to N immobilization under excess C input. This highlights the importance of balancing biochar with N-rich inputs to avoid short-term nutrient deficiencies and to optimize agronomic outcomes. Another strategy with strong potential is co-composting biochar with organic wastes, producing “activated biochars.” Co-composted biochar not only stabilizes organic matter but also capture mobile nutrients such as nitrate during the composting process, which are later released gradually in soil. This enhances nutrient availability, improves soil structure, and stimulates beneficial microbial communities, often outperforming biochar or compost alone [116]. Such synergies demonstrate how biochar is best deployed in integrated soil management systems rather than as a standalone amendment.

Beyond crop productivity, biochar offers significant environmental co-benefits. Its stable aromatic C structure enables persistence in soils for centuries to millennia, making it a proven strategy for long-term C sequestration and climate change mitigation. However, its persistence and functional effects in soil are not uniform and remain context dependent. Biochar stability varies with feedstock characteristics, production conditions, soil type, and post-application aging processes, which can alter surface chemistry and susceptibility to decomposition over time. Biochar amendments can also reduce greenhouse gas emissions by lowering nitrous oxide fluxes through improved soil aeration and altered microbial pathways [109]. Moreover, biochar's high sorption capacity, micro- and mesoporosity, and ion-exchange properties make it useful for soil remediation, wastewater treatment, and nutrient recovery from waste streams [117,118]. Nevertheless, limitations remain. Biochar responses are highly site-specific, and depending on biochar properties, soil type, and crop species, yield benefits are negligible or negative. Poorly produced biochars may introduce harmful compounds such as polycyclic aromatic hydrocarbons or heavy metals [117]. In addition, high application rates can increase soil salinity or immobilize N if not balanced with nutrient-rich inputs. Moreover, biochar production and transport remain costly and energy-intensive, limiting widespread adoption without policy incentives or integration into waste valorization and circular economy models [99]. Overall, biochar represents a multifunctional amendment with strong potential to enhance soil quality, improve crop productivity, and mitigate climate change through C sequestration. Yet, its success depends on production quality, co-application strategies, appropriate feedstocks, and site-specific management, emphasizing the need for tailored approaches rather than blanket application.

2.2.4. Bagasse

Bagasse, the fibrous residue produced after sugarcane juice extraction [119], is generated in large quantities, about 300 kg per ton of cane, and represents one of the most abundant agro-industrial by-products in the tropics and subtropics [120]. It is composed mainly of cellulose (45–55%), hemicellulose (20–30%), and lignin (18–24%) [121,122], with a high organic matter content of approximately 95%, low bulk density (0.10 g cm^{-3}), moderately low pH (4.0), and a wide C:N ratio of around 66 [123,124]. It also contains appreciable amounts of nutrients, including K up to 1.0 g kg^{-1}, N ranging 0.25–2.7%, and P between 0.05 and 0.26 g kg^{-1} [125,126]. These properties give bagasse a unique capacity to improve soil structure and nutrient dynamics when applied as an organic amendment. Its fibrous nature reduces soil bulk density, enhances porosity, and increases water-holding capacity, particularly in coarse-textured, leaching-prone soils. Field studies in Florida demonstrated that incorporation at rates of 85–170 t ha^{-1} significantly lowered bulk density, decreased soil pH, and increased organic matter, porosity, and water-holding capacity compared with unamended soils [124]. Although the acidic nature of bagasse can modestly reduce pH in neutral and alkaline soils, this effect is often buffered in calcareous systems, suggesting that its main contribution lies in enhancing organic matter and cation exchange properties rather than driving major pH shifts [126].

Beyond its influence on physical properties, bagasse also plays an important role in nutrient cycling. Long-term soil column studies revealed that bagasse incorporation reduced cumulative leaching of organic C, N, P, and K by 25–50% compared with unamended controls [126]. The mechanisms underpinning these reductions include greater sorption capacity, improved aggregation, microbial immobilization, and calcium-mediated P stabilization in calcareous soils. Nevertheless, due to its wide C:N ratio, bagasse can temporarily immobilize N during decomposition [125,127], highlighting the importance of supplying supplemental mineral N when bagasse is used at high rates. Positive effects of bagasse on crop productivity have also been documented. In controlled pot trials, incorporation of bagasse at 2–10% (w/w) significantly enhanced the growth of Chinese cabbage seedlings [128]. Seedling emergence was faster, with the time to 50% emergence decreasing from 5 days in control to 3 days at 10% bagasse, representing a 40% faster emergence. Plant height increased from 5.3 cm (control) to 15.3 cm at 10% bagasse, root length increased from 2.2 cm to 6.2 cm, and number of leaves rose from 3.6 to 8.7. Biomass accumulation was also enhanced, with root dry weight increasing from 0.096 g to 0.203 g and shoot dry weight from 0.402 g to 2.632 g. Additionally, bagasse-amended soils improved relative water content from 57.3% to 73.2%, with optimal growth observed at 10% incorporation [128]. Field-scale studies in sugarcane production further highlight its potential: incorporation of thick bagasse layers (85–170 t ha^{-1}) improved soil fertility indicators and supported higher biomass and sugar yields, with cane yields rising by 9% when combined with N fertilization [126]. These findings suggest that bagasse can promote crop establishment and productivity, particularly in sandy soil where its contributions to water and nutrient retention are most beneficial.

The decomposition of bagasse is accompanied by rapid humification, which contributes to short-term C sequestration [125,128]. In incubation studies, sugarcane bagasse undergoes rapid decomposition of its labile C fraction, while humic acid concentration increased nearly fifty-fold within thirty days of incorporation, supported by FTIR spectra showing rising carboxyl and carbonyl groups alongside declining aliphatic signals [128]. These changes indicate the transformation of labile C into more stable humic substances, which contributes to the buildup of SOC. The presence of both readily decomposable and lignin-rich fractions means that bagasse provides an initial pulse of labile C followed by slower stabilization of more recalcitrant fractions. This process is mediated by microbial communities, as bagasse has been shown to stimulate microbial biomass and fungal activity by 1.7-fold, supporting decomposition, nutrient cycling, and aggregation [125,129]. The contribution of bagasse to C sequestration is significant in the short term, as it supplies substantial organic C inputs, promotes humification, and reduces dissolved organic C losses through leaching [123,130,131].

However, its relatively labile composition means that it decomposes rapidly under warm and moist conditions, limiting its long-term persistence. Repeated applications or integration with management strategies such as reduced tillage, composting, or co-application with calcium-rich amendments may be necessary to ensure durable C storage. Recent studies also point to the potential of converting bagasse into biochar through pyrolysis, which increases its stability and enhances soil properties such as organic C, nutrient content, and water-holding capacity. For example, bagasse biochar application increased available water capacity by 60%, and CEC by 42%, relative to unmodified soil [132]. Economic modeling from Brazilian sugarcane systems indicates that the financial viability of bagasse biochar depends strongly on carbon credit valuation and residue availability. Sensitivity analyses suggest that biochar production generally becomes economically feasible at carbon credit prices above US $120 per tCO_2e and when sugarcane bagasse availability exceeds 60% of total residue generated, particularly for medium- to large-scale farms (20,000–50,000 hectares) [133].

Despite these benefits, several limitations constrain the widespread use of bagasse as a soil amendment. Its wide C:N ratio leads to N immobilization, which can reduce crop yields if not managed properly. This challenge may be addressed through the co-application of mineral N fertilizers or nutrient-rich organic materials to balance nutrient supply [124]. Rapid decomposition under warm and moist tropical conditions also limits its persistence in soil, requiring repeated applications for sustained benefits. Composting or pyrolyzing bagasse into biochar can mitigate this limitation by stabilizing organic matter, slowing decomposition, and enhancing long-term C sequestration [130]. Another challenge is the high application rates, often 85–170 t ha^{-1}, required to observe significant improvements in soil properties at the field scale. Such rates may not be practical for small-holder farmers due to costs associated with transport and application. Partial solutions include localized use in high-value cropping systems, on-farm composting to reduce volume, or the development of densification technologies that improve handling efficiency [133]. Furthermore, bagasse is inherently acidic (pH ~4.0), and although its effect on soil pH is moderated in calcareous soils, repeated application in neutral or slightly acidic soils may exacerbate soil acidity and potentially affect nutrient availability [126]. The nutrient profile of bagasse also presents challenges. While it is relatively rich in K, its N and P concentrations are low, making it an unbalanced nutrient source if applied alone. In nutrient-demanding systems, this imbalance can limit its effectiveness unless it is integrated with mineral fertilizers or nutrient-rich organic amendments such as animal manures, rock phosphate, or lime [125].

In addition, freshly applied bagasse is structurally fibrous and can take time to decompose, with some studies reporting 40–70% mass persistence after 130 days [120,134], which may initially interfere with soil-seed contact, germination, or tillage operations if not adequately incorporated. Lastly, there are management and environmental considerations. Stockpiling large amounts of fresh bagasse near fields risks generating anaerobic decomposition, odors, and greenhouse gas emissions (methane), particularly under waterlogged conditions. Without proper management, this can offset some of its environmental benefits. Converting bagasse to compost or biochar mitigates these risks but requires additional processing, infrastructure, or investment, which may not be accessible to all farming systems [130,133].

Overall, bagasse is a valuable organic amendment that improves soil structure, enhances nutrient use efficiency, stimulates microbial activity, and supports crop productivity while contributing to short-term C sequestration. Although its rapid mineralization and tendency to immobilize N present management challenges, these can be mitigated through integrated nutrient management and repeated or stabilized applications. As a circular pathway for recycling sugarcane residues, bagasse aligns well with sustainable agriculture objectives, offering both agronomic and environmental benefits when appropriately managed.

2.2.5. Green Manure

Green manures (GM), annual or perennial species grown primarily to be returned to the soil, are a cornerstone of low-input, sustainable nutrient management because they add organic matter, enhance biological N inputs, and regulate multiple soil functions without relying solely on mineral fertilizers. Practical guidance emerging from temperate organic systems underscores the strategic integration of green manures (e.g., clovers, vetches, brassicas, cereals) into rotations to supply 40–120 kg N ha^{-1} of biologically fixed N [135,136], recover residual nutrients, improve soil structure, suppress weeds (typically 30–60% weed biomass reduction) [137,138], and reduce erosion. Integrating cover crops into maize rotations typically reduces soil erosion losses by 20–40% depending on rainfall, slope, and management intensity [139,140]. The modeling evidence indicates that species selection and termination timing are the main levers modulating productivity benefits and trade-offs like N immobilization or volunteer regrowth [141]. At the soil process level, GM residues act as fresh C and nutrient substrates that stimulate microbial activity, enzyme pools, and aggregation, thereby improving structure, water infiltration, and cation exchange over time. In legume GMs, symbiotic N fixation supplies protein-rich residues that mineralize relatively quickly, whereas non-legumes such as grasses contribute more recalcitrant C that stabilizes organic matter and can temper nitrate loss. Recent field and pot studies show GM-driven shifts in microbial community composition toward taxa linked to C and N cycling such as increases in bacterial α-diversity (7–38%) and functional guilds for cellulose/xylan degradation and N transformations [142]; these shifts translate to higher microbial biomass C (29.8–72.9%) and improved soil pH by 0.2–0.5 units where initial acidity is a constraint [143,144]. Agronomically, GM use tends to raise or stabilize yields in subsequent crops by synchronizing N release with early crop demand. Meta-analyses and field experiments report that incorporating legume green manures into maize systems can increase yields by around 11–22%, largely due to improved nitrogen availability and soil health benefits [145–147]. In both paddy and upland systems, integrating GMs with reduced mineral N rates often sustains crop yields while improving nitrogen use efficiency (NUE). For example, in rice systems, yield parity has been reported when 50–60% of the recommended mineral N was combined with green manure, compared with 100% mineral N alone, with NUE increasing by 12–25% under the integrated practice [148,149].

Field evidence indicates that incorporating legume green manures into maize–oilseed rape rotations can maintain or even enhance rapeseed yields under reduced nitrogen input. Corn yields were significantly higher following leguminous GM: white clover (*Trifolium repens* L.) produced 7.2 Mg ha^{-1} and red clover (*Trifolium pretense* L.) produced 6.7 Mg ha^{-1}, compared with 5.7 Mg ha^{-1} in plots without cover crops [150]. In a multi-year study, lablab–maize intercropping buffered the yield penalty (21%) otherwise observed under reduced N fertilization, while also improving soil N availability and uptake [151]. Similarly, a complementary study showed that intercropped green manure returned to the soil allowed a 25–35% reduction in chemical N fertilizer without compromising yield, while raising agronomic NUE by 48–21% and improving soil organic matter and available N [152]. A meta-analysis of green manure effects on soil properties in Northern China demonstrated significant improvements in soil quality: bulk density decreased by approximately 5.6%, microbial biomass C increased by about 28%, and soil enzyme activities were enhanced by 14–39%, depending on the enzyme type [146]. In tea and other perennial systems, GM groundcovers boosted peroxidase and cellulase activity, raised SOM, and lifted soil pH [143]. As a nutrient management tool, GMs directly supply plant-available N via symbiotic fixation (50–150 kg N ha^{-1} yr^{-1} in legumes) [136,153] and indirectly to non-legumes via nutrient scavenging [154]. They also improve P dynamics through rhizosphere mobilization and residue-driven microbial processes. Notably, field studies in paddy soils show alfalfa GM increased P use efficiency by an average of 66% and reduce P losses [155,156], illustrating how GM can be paired with P-smart strategies to counter legacy deficiencies or high Ca–P precipitation environments. Practical guidelines suggest that growers can achieve near-optimal outcomes by combining green manures with reduced mineral N inputs. Several studies indicate that using green manures alongside 50–75% of the normal N fertilizer rate often maintains yields and improves NUE, especially when baseline soil fertility is moderate [157,158].

Systematic evidence on greenhouse gases and C outcomes is increasingly nuanced. A 2024 meta-analysis across rice systems reports that co-returning straw with GM generally increases yields (7–10%) and soil C (0.3–0.6 Mg C ha^{-1}) while not uniformly elevating methane [159]. Complementary syntheses indicate SOC accrual under cover crops/green manures ranging from 0.32 Mg C ha^{-1} yr^{-1} over 50 years [160], 0.56 Mg C ha^{-1} yr^{-1} across global cropland [161], and 0.88 Mg C ha^{-1} yr^{-1} in surface soils [162]. These C gains occur through increased belowground inputs and residue-derived particulate organic matter, though tillage intensity and soil texture can attenuate sequestration at depth. These suggest GM as a credible component of a climate-smart amendment strategy, provided water and residue management minimize CH_4 pulses in flooded systems and avoid inadvertent N_2O spikes from poorly synchronized N release.

There are, however, trade-offs. Short-term N immobilization can depress yields by up to 5% when residues have high C/N (>25:1) [163,164]. Green manure incorporation can inadvertently increase CH_4 emissions under waterlogged or flooded conditions [165,166]. In drylands, poorly timed cover crop termination can deplete soil moisture by approximately 10 mm for every 1000 kg ha^{-1} of cover crop biomass produced [167] or cause volunteer regrowth in subsequent crops [168]. Emerging evidence warns that some co-applied organic amendments offset SOC gains, with reduction in net sequestration [169]. These risks are manageable: selecting legume–grass blends, terminating at early bloom, and pairing with reduced tillage can safeguard benefits [170].

2.3. Animal-Derived Amendments

2.3.1. Biosolids

Biosolids, the stabilized organic by-products of municipal wastewater treatment, are increasingly positioned as circular, soil-building inputs that can recover nutrients, rebuild SOM, and bolster climate resilience when applied judiciously within agronomic systems. Across soil processes, a consistent pattern emerges: thoughtfully treated and well-matched biosolids additions tend to enrich C and N pools, improve water relations, and stimulate biological functioning, with crop responses that are often positive, particularly where soils are degraded or nutrient-limited, while risk management hinges on product quality, rate, site, and regulatory compliance.

Recent experimental work underscores the capacity of biosolids to rebuild SOM and enhance biological fertility. For instance, Nicholson et al. [171] documented 10–17% increases in SOM, and a two-fold rise in earthworm populations following 20 years of annual biosolid applications at 250–500 kg N ha^{-1}. In California, long-term biosolid amendments led to significantly higher SOC across all sites, with SOC increasing by 0.2–0.5 Mg C ha^{-1} yr^{-1} to 100 cm depth, even under low application rates (74 Mg $biosolids_{dry}$ ha^{-1} [172]. Similarly, in Illinois, soils retained 554–1001 mg kg^{-1} microbial biomass C within 2 years of biosolid treatments compared to 315 mg kg^{-1} in the control, and 150–500% higher potentially mineralizable N up to eight years after cessation of biosolid treatments [173]. In a six-month microcosm comparison of biosolids (stabilized via constructed wetlands) against other amendments (biochar, compost, microalgae, digestate), biosolids significantly increased total organic C and total N stocks reaching up to 18.1 Mg ha^{-1} and 1.8 Mg ha^{-1}, respectively, boosted microbial biomass C (76% increase vs. control), and exhibited a low C mineralization rate (k: 0.006 d^{-1}, compared with compost k = 0.013 d^{-1} and digestate k = 0.023 d^{-1}), signals of both fertility gains and potentially favorable C retention dynamics [174]. In field contexts, available water is often the limiting factor linking soil function to yield. A rangeland study showed that a single application of composted biosolids increased SOM content by 32%, and soil moisture throughout the growing season, a practical bridge from C inputs to plant-available water and drought buffering [175]. These findings align with broader agronomic observations that biosolids' organic matter improves aggregate stability, porosity, and infiltration, thereby enhancing water-holding capacity. Nicholson et al. [171] reported increase of up to 10% in available water capacity and numerical increases in water infiltration rate and aggregate stability (33% reduction in % dispersion ratio) under long-term biosolid additions. Similarly, in desert rangelands, biosolid application rate of 7 Mg ha^{-1} reduced erosion by 40% and increased infiltration after five years [176], underscoring their hydrological benefits.

Vegetation responses are particularly evident in restoration and reclamation settings where soils are severely depleted. A synthesis of 59 studies across global grassland restoration sites demonstrated that biosolid amendments increased aboveground plant productivity by an average of 256% relative to untreated controls. Similarly, total vegetative cover rose by approximately 222%, underscoring biosolids' strong positive influence on biomass accumulation and vegetation establishment in degraded soils [177]. These vegetation benefits are reinforced by moisture-related gains from composted biosolids, suggesting that structure- and water-mediated pathways are important complements to direct nutrient supply. For instance, in semi-arid grasslands, one-time surface application of 20 Mg ha^{-1}

biosolids resulted in about 100% higher aboveground plant biomass than untreated controls 14 years after treatment [178]. Similarly, long-term plots in semi-arid Colorado receiving infrequent high biosolids rates (21–30 Mg ha^{-1}) showed persistent gains in plant biomass and soil microbial activity over 12 years [179].

Nutrient dynamics and risk mitigation benefit from blending and co-amendment strategies. Combining biosolids with complementary organic materials, such as green waste composts, can mitigate nitrate leaching, dilute trace contaminant concentrations, and enhance the stabilization of organic N, while maintaining agronomic benefits. For example, sawdust/biosolid mixtures reduced nitrate leaching by 40–80% [180], while co-application with green waste compost lowered Cd, Cu, Pb and Zn concentrations in amended soils by 50–80% [181]. More recently, Badewa et al. [182] reported that biosolids favor C residue stabilization and slower N turnover compared with mineral fertilizer. These outcomes highlight the importance of careful product specification, application rate, and site-specific management in minimizing environmental trade-offs while optimizing soil fertility. Practical guidance for the safe and effective use of biosolids in agriculture is strongly shaped by regulatory standards that define product classes and management conditions. Extension publications note that classification into Class A, Class B, or Exceptional Quality (EQ) depends on meeting thresholds for pollutant concentrations (particularly heavy metals), demonstrating adequate pathogen reduction, and reducing vector attraction levels [183]. The U.S. regulatory benchmarks for pollutant-concentration threshold for Cd, Pb, and Zn are 39, 300, and 2800 mg kg^{-1}, respectively [184]. These criteria, established under the U.S. Environmental Protection Agency's 40 CFR Part 503 rule, serve as safeguards to ensure both environmental protection and agronomic utility. Notably, biosolids that meet Class A or EQ requirements are suitable for broad agricultural use, as they pose minimal risk to human health or the environment and therefore carry fewer site restrictions compared to Class B materials, which are typically subject to more limited application conditions and extended setbacks [184]. Recent guidance from the Alabama Cooperative Extension System, in alignment with EPA summaries, further underscores this framework while clarifying the available management pathways, which include land application, land reclamation, and composting [183]. This regulatory clarity is especially valuable for producers and municipalities planning large-scale recycling initiatives, as it helps balance agronomic opportunities with compliance and public safety considerations.

From a climate perspective, biosolids can enhance soil C sequestration by supplying relatively stable organic matter fractions and promoting aggregation, which protects C within micro- and macro-aggregates. Observations from constructed-wetland biosolids indicated recalcitrant organic C fractions increment by 48–57%, suggesting long-term stabilization potential [174]. At the field scale, Morgan [172] reported SOC sequestration rates of 0.2–0.5 Mg C ha^{-1} yr^{-1}, comparable to compost and higher than synthetic fertilizers. The persistence of biosolids-derived C at the field scale, however, depends on stabilization method (e.g., composted, digested, or alkaline treated), soil texture, climate, incorporation depth, and cropping intensity. Beyond C retention, biosolids also influence water-mediated ecosystem services: increased soil water can reduce irrigation demands and buffer soils against heat and dry spells, amplifying resilience benefits [175].

Despite these benefits, concerns remain regarding the potential accumulation of heavy metals and pathogens in soils treated with biosolids. While the U.S. EPA Part 503 framework addresses metals and pathogens, emerging organic contaminants, especially per- and polyfluoroalkyl substances (PFAS), have become an active regulatory frontier [185]. PFAS are synthetic chemicals widely used in nonstick coatings, stain- and water-resistant products, firefighting foam, and food packaging. Their average concentrations in biosolids were reported to be 161 μg kg^{-1}, with perfluorooctane sulfonate (PFOS) most abundant [186].

They are highly persistent in the environment, can migrate through soil and groundwater, and bioaccumulate in living organisms, posing potential risks to human and ecological health [187]. U.S. policy attention has intensified, with utilities and practitioners monitoring EPA risk assessment updates and PFAS rulemakings that could influence monitoring, allowable concentrations, and land-application. In the meantime, practical risk-reduction strategies include using higher-quality (Class A/EQ) biosolids, verifying metal and PFAS testing where available, applying agronomically appropriate rates, incorporating rather than surface-applying biosolids, avoiding overly vulnerable sites, and blending with complementary organic amendments. These approaches help retain the agronomic benefits of biosolids while minimizing environmental and health risks [183,188].

2.3.2. Chitosan

Chitosan, a deacetylated derivative of chitin primarily obtained from crustacean shells, has emerged as a multifunctional organic amendment with promising applications in sustainable agriculture. Its biodegradable, non-toxic nature and inherent N content make it particularly suited to improving soil quality, stimulating plant growth, and contributing to C sequestration in agroecosystems. Recent studies indicate that the addition of chitosan to soil enhances nutrient cycling, microbial activity, and overall soil structure, creating conditions conducive to both plant productivity and long-term soil health [24,25].

When incorporated into soil, chitosan interacts with soil particles and microbial communities in ways that improve physical and biological soil properties. Chitosan treatment improved soil structure and moisture retention, increasing aggregate stability by 200% and adjusting field capacity and permanent wilting point to 0.38 and 0.23 $cm^3\ cm^{-3}$, compared with 0.39 and 0.24 $cm^3\ cm^{-3}$ in the reference soil [189]. Moreover, chitosan acts as a substrate for beneficial soil microorganisms, stimulating populations of nitrogen-fixing bacteria (1.8-fold increase) and phosphate-solubilizing microbes (30–100% increase) [23]. Chitosan applications have been observed to significantly reduce pathogen incidence. For example, in tomato infected with *Fusarium oxysporum* f. sp. *lycopersici*, chitosan treatment led to 70% reduction in disease incidence and 91% reduction in disease severity [190]. Similarly, in rice seedlings challenged with *Rhizoctonia solani*, chitosan caused 31–84% lower disease incidence and substantial reduction (66–91%) in lesion size [191].

The influence of chitosan on crop productivity is equally compelling. Chitosan functions as a natural elicitor, stimulating plant defense responses, improving seed germination, and promoting robust root and shoot development. In maize, soil drench applications of 0.5% chitosan solution increased shoot fresh weight by 31% [192], while tomato plants treated with foliar sprays showed higher fruit set and 16.8% higher marketable yield [193]. In turmeric (*Curcuma longa* L.), foliar application of chitosan (20 mg L^{-1}) under water-deficit conditions mitigated growth reductions caused by drought stress [194]. Chitosan-treated plants maintained higher leaf area, pseudostem dry weight, and rhizome biomass compared with untreated controls. Under 45 days of water withholding, rhizome fresh and dry weights in untreated plants declined by over 40%, whereas chitosan application substantially alleviated these losses, sustaining growth performance closer to that of well-watered plants [194]. Physiologically, chitosan applications have been associated with increased chlorophyll content (19–40% increase in chlorophyll a, and 25–42% in chlorophyll b), enhanced photosynthetic efficiency, and overall plant vigor [195,196]. These findings demonstrate that its benefits extend beyond soil conditioning to direct enhancement of plant physiological performance. Beyond immediate agronomic advantages, chitosan contributes to carbon sequestration. Repeated application of chitosan has been shown to modestly increase soil organic carbon, thereby improving the soil's capacity to store carbon and supporting broader greenhouse gas mitigation goals [197]. Evidence from incubation and plot-level studies suggests that chitosan can both promote formation of more recalcitrant, humic-like soil C pools and slow short-term C mineralization. Reported increases in humic fractions typically fall in the range of 5–30%, while reductions in CO_2 emissions from amended soils are commonly modest (5–15%) [198,199]. Moreover, chitosan's interactions with microbial communities can modulate nitrogen and carbon cycling in soils, further reinforcing its role in enhancing agroecosystem sustainability.

The practical effectiveness of chitosan depends on application method, dosage, and integration with other amendments. Soil drenching, foliar spraying, and incorporation into composts or organic blends are commonly employed approaches, with dosages tailored to crop type, soil condition, and environmental context [192,193]. Optimal results have been observed at dosages between 0.5 and 1.0% w/w for soil incorporation and 0.2–0.5% for foliar sprays [200,201]. Combining chitosan with complementary organic amendments has been shown to produce synergistic effects. For example, maize treated with Zn-chitosan nanoparticles in field trials showed grain yield increases of 20–40% compared with conventional treatments; chitosan-enriched composts and chitosan-biochar composites have also been reported to increase crop performance relative to compost or biochar alone [198,202]. Despite the agronomic benefits of chitosan, its adoption has been constrained by several factors. Cost is often higher than for conventional chemical inputs due to extraction, purification, and formulation processes. Variability in molecular weight, degree of deacetylation, and purity of chitosan leads to inconsistent efficacy across studies [203]. Moreover, there is a lack of standardized application protocols, regarding dosage, timing, and mode of application, limiting comparability and farmer confidence in results. Chitosan represents a versatile organic amendment capable of simultaneously improving soil structure, enhancing microbial and nutrient dynamics, boosting crop productivity, and contributing to carbon sequestration. While its efficacy has been demonstrated across diverse crops and soils, further research is required to optimize application strategies, quantify long-term soil and carbon impacts, and integrate chitosan effectively into large-scale sustainable agricultural practices. By addressing these challenges, chitosan has the potential to play a key role in transitioning toward resilient, productive, and environmentally sustainable farming systems.

2.3.3. Vermicompost

Vermicompost is a nutrient-rich organic amendment produced through the bio-oxidation and stabilization of organic wastes by the combined action of earthworms and microorganisms [204]. Unlike conventional composting, which is primarily thermophilic, vermicomposting is a mesophilic process that results in a fine, granular, humus-like product rich in plant-available nutrients, microbial biomass, and biologically active substances [205]. Earthworms speed up the mineralization rate and transform manures into castings with a higher nutritional content and level of humification [204]. The process reduces the C:N ratio of organic waste from about 40:1 to 15:1 and increases total N content by 25–50% compared to the initial substrate [205,206]. The chemical composition of vermicompost varies with feedstock and worm species. Typically, mature vermicompost contains 1–3% total N, 0.4–2.55% available P, and 1.61–2.25% exchangeable K, alongside 30–50% organic carbon and pH values between 6.5 and 7.5 [205,206]. Earthworms fragment and aerate the organic material, increasing microbial activity and accelerating mineralization. Earthworm casts are enriched with humic substances, microbial enzymes such as dehydrogenase and phosphatase, and phytohormones like auxins, gibberellins, and cytokinins, all of which stimulate root growth and plant development [207]. Comparative studies indicate that vermicompost exerts stronger effects on soil biochemical activity than conventional compost. For example, soils amended with animal-derived vermicompost showed 85.8% higher dehydrogenase activity, compared to 80.6% for plant-based vermicompost and 75.9% for cotton compost, relative to the control [208]. At equivalent application rates, vermicompost also enhanced β-glucosidase, phosphatase, urease, and arylsulfatase activities by 22–48%, 16–27%, 3–4%, and 10–14%, respectively, over compost-amended soils.

Vermicompost significantly improves soil physicochemical and biological properties. Field and pot studies show that vermicompost application can increase SOC stocks by 18–52%, and boost soil CEC by 20–57% depending on soil type, rate, and management context. For example, application of vermicompost at 10 t ha^{-1} raised SOC by 40.3% in a lettuce pot study [209], while a bean crop trial recorded a 20% increase in CEC at 5 t ha^{-1} [210]. Importantly, these SOC gains reflect an increase in labile and intermediate organic matter fractions following organic input addition, rather than confirmed long-term C sequestration. During the vermicomposting process itself, organic C losses of 12.7–28% and reductions in the C:N ratio of 42.4–57.8% have been reported, accompanied by marked increases in total N (50.6–75.8%), available P (42.5–110.4%), and exchangeable K (36.0–78.4%) contents [211]. These transformations indicate accelerated decomposition and stabilization of organic substrates into more nutrient-enriched, biologically active forms. Earthworm activity during application contributes to increased macroaggregate stability and infiltration rate, resulting in improved aeration and reduced compaction.

Vermicompost applications have been shown to dramatically enhance microbial-biological activity in soils. Nsiah-Gyambibi et al. [212] reported microbial biomass C increases of 75–160%, while Wu et al. [213] found that urease enzyme activity rose by over 220% when vermicompost was applied. Vermicompost harbors dense microbial population, comprising beneficial species such as *Azotobacter*, *Pseudomonas*, *Bacillus*, actinomycetes, and arbuscular mycorrhizal fungi [214]. These organisms contribute to nutrient mineralization, enzyme activation, and enhanced plant health through symbiotic and antagonistic interactions. Vermicompost and its derivatives have been shown to enhance plant growth substantially, often yielding 50–100% higher growth than conventional compost and 30–40% more than chemical fertilizers [205,215]. The degree of this improvement, however, varies according to several factors, including the type of feedstock, vermicomposting conditions, soil characteristics, crop species, application technique, and rate. Across diverse cropping systems, the use of vermicompost has consistently been associated with improvements in seed germination, plant growth, yield, and quality have been reportedly enhanced as a result of vermicompost application. For instance, Arancon et al. [216] observed a 35–40% increase in strawberry yield following vermicompost amendment at 10 t ha^{-1} compared to mineral fertilizer controls. Comparable yield enhancements were reported in tomato and pepper under similar vermicompost treatments [217,218]. In cereal crops, applications of 5–6 t ha^{-1} vermicompost increased rice and maize yields by 18–30%, primarily due to improved nutrient uptake efficiency [219,220]. In lettuce, vermicompost derived from cattle manure has been shown to significantly enhance biomass production under greenhouse conditions [221]. Beyond growth promotion, vermicompost also alleviates salt stress by improving leaf relative water content, stomatal conductance, chlorophyll a, and carotenoid concentrations, thereby supporting better physiological performance under saline conditions [222]. In olive groves, vermicompost application increased yield by 35.5%, and the nutrient content of the olive fruits was significantly improved compared to the control, outperforming composts derived from municipal solid waste and sheep manure [208].

Vermicompost application not only enhances crop growth but also improves nutritional quality. Reported benefits include increases in leaf chlorophyll by 15–30%, grain protein by 10–18%, and vitamin C content by up to 20% in vegetable crops [222,223]. When combined with mineral fertilizers, vermicompost exhibits synergistic effects, allowing for 25% reductions in NPK fertilizer use while sustaining or even enhancing crop yields [224].

In addition, the high organic matter content and CEC of vermicompost create abundant binding sites for heavy metal adsorption [205]. In a related study, 10–20% soil amendment with vermicompost reduced Pb accumulation in plant leaves and roots by about 65%, while plant biomass increased four- to fivefold and flowering occurred earlier compared with unamended control plants [225]. Vermicompost harbors a diverse community of pathogen-suppressive microorganisms that enhance plant defenses against soil-borne diseases [207]. Its application has been shown to stimulate secondary metabolite production, up-regulate defense-related genes, and improve overall plant vigor, while also modifying soil properties such as pH, EC, and microbial activity, in ways that further suppress pathogen proliferation [226,227].

Vermicomposting contributes to soil C sequestration by stabilizing organic C in humic fractions. Studies indicate that a substantial portion of C (29.6–41 g kg^{-1}) in vermicompost exists as stable humic substances resistant to microbial degradation [224,228]. Field and greenhouse applications of 2.5–10 t ha^{-1} vermicompost have been shown to increase SOC by 24–44% [209,229]. Additionally, vermicomposting reduces GHG emissions by diverting organic waste from landfills, lowering CH_4 and N_2O emissions by up to 18–40% compared to unmanaged decomposition [230,231]. Similarly, Ducasse et al. [206] and Lleó et al. [232] reported that emissions of NH_3, CH_4, and N_2O from vermicomposting are up to three times lower than for domestic composting.

Despite its benefits, vermicompost use is constrained by several limitations, one of which is the lack of awareness and poor control of operational variables. Successful production depends on maintaining optimal environmental conditions, typically 60–80% moisture, temperatures between 20 and 30 °C, and a near-neutral pH (6–8) to sustain earthworm activity and organic matter processing [233,234]. Maintaining a continuous supply of organic waste, water, temperature, and moisture are major hurdles that complicate the process of vermicomposting. Scaling up production remains labor-intensive, with application rates of 10–20 t ha^{-1} required to achieve comparable field responses. Moreover, feedstock contamination with heavy metals and plastics can compromise vermicompost safety and agronomic value, and the absence of harmonized quality control standards contributes to wide variability in product composition and field performance. Excessive application rates may also lead to negative effects. Application of vermicompost (40 t ha^{-1}) derived from organic municipal waste and cow manure increased root disease incidence in *Panax ginseng*, whereas moderate rates (around 10 t ha^{-1}) enhanced root growth and overall plant health [235]. These findings underscore the need for balanced application strategies, as nutrient surpluses from overuse can harm crops and potentially impact the surrounding environment.

2.3.4. Animal Manure

Animal manures from livestock operations such as cattle, poultry, pigs, sheep, goats, and mixed-animal systems, are one of the most widely used organic amendments in sustainable agriculture, providing both nutrient inputs and organic matter to improve soil fertility and structure [236]. They are applied to soil either in raw (e.g., fresh manure, slurry), semi-processed (e.g., farmyard manure with bedding, poultry litter), or fully stabilized forms (e.g., composted manure, anaerobic digestate). The type of manure, its moisture content, and its handling characteristics depend on the animal source, bedding material, feeding system, and storage method [237]. When properly managed, manures serve as effective nutrient sources and organic matter inputs that support crop productivity while promoting soil health and biological activity.

The nutrient composition of animal manure varies widely among species and production systems. Fresh manures generally contain substantial amounts of N, P, K, and organic carbon (OC), with typical concentrations ranging from 1 to 8 g N kg^{-1}, 1.2–8 g P kg^{-1}, and 15–35 g K kg^{-1} [238,239]. This variability is influenced by feed composition, manure storage, and environmental conditions. Processing methods such as composting, anaerobic digestion, and pelletization alter nutrient availability and reduce environmental and sanitary risks [237]. Composting, for example, reduces pathogen load and stabilizes organic matter, while anaerobic digestion produces a nutrient-rich digestate and renewable biogas. However, because nutrient composition can differ substantially between batches, regular laboratory analysis of manure before field application is essential for accurate nutrient budgeting and effective fertilizer management.

When incorporated into soil, animal manure affects several physical, chemical, and biological properties simultaneously. Repeated manure applications have been shown to increase SOC (by 20% in 10-year trials) and labile C fractions relative to unfertilized controls [240]. Another review observed that long-term farmyard manure additions increased SOC compared to unfertilized or solely mineral-fertilized soils and prevented SOC decline [236]. Physically, manure-derived organic matter enhances aggregation, porosity, and macropore formation, which improves water infiltration and retention and can reduce bulk density. Manure also provides both readily mineralizable and slow-release nutrient fractions, ensuring sustained nutrient supply throughout the cropping season [240,241]. At the same time, it stimulates microbial biomass (18–53% MBC under high-manure substitution) [242], increases enzymatic activity and alters fungal and bacterial community structure. In a rice system, manure plus fertilizer increased SOC by 55.4% and microbial biomass [243]. These biological effects, via microbial exudates, fungal hyphae and aggregate binding, further improve soil aggregation, enhance nutrient cycling and support greater soil biodiversity and resilience. Over the long term, continual manure applications lead to durable improvements in SOC stocks. A long-term study by Xiang et al. [244] reported an increase of 8.12 Mg ha^{-1} in POC following continuous manure application and, when integrated with conservation practices (such as cover cropping or reduced tillage), contribute to more stable soil structure and greater resistance to degradation.

A substantial body of evidence shows that applying animal manure can enhance crop productivity and contribute to yield stability, especially in nutrient-depleted or degraded soils, though the magnitude of benefit depends strongly on crop, soil, climate and management. A meta-analysis of Chinese field trials found that substituting mineral nitrogen fertilizer with manure increased wheat, maize and rice yields by 3.3–4.8% [245]. The favorable response is attributed to improved nitrogen availability, enhanced soil organic matter and moisture-holding capacity, and better root growth under improved soil structure. In another study, the combined use of manure with chemical fertilizer sustained higher crop yields through improved soil fertility and ^{15}N recovery (38.2–49.7%) [246]. At regional scales, the effects of manure application on SOC and ecosystem services depend on baseline fertility, climate, and management intensity. Modeling and field syntheses report typical SOC accumulation rates of 0.3–0.6 Mg C ha^{-1} yr^{-1} under repeated manure inputs in forage/arable systems [241]. Strategically recycling manure within integrated farm systems not only enhances nutrient circularity but also contributes to climate change mitigation and resource efficiency. Meanwhile, long-term studies document that manure additions can raise SOC stocks by around 10.7 Mg ha^{-1}, an average of 35% increase across global sites [247]. Manure-derived amendments in forage and crop systems likewise have been shown to boost SOC and crop performance under a variety of soils and climatic zones [241]. Zhu et al. [248] found that manure-amended rice systems exhibited improved resilience under extreme temperature stress, reducing yield losses from 33.6% to 25.1% through increased net photosynthetic rate and plant physiological resistance to extreme temperatures.

However, despite these agronomic benefits, manure use also poses environmental and food-safety risks when mismanaged. Raw animal manures may harbor pathogens (e.g., *E. coli* O157:H7, *Salmonella*) and for fresh-produce systems many standards require a waiting interval (e.g., 90 or 120 days) between raw manure application and harvest [249,250]. Excess or improperly timed manure applications can lead to nitrate leaching, phosphorus-driven eutrophication and ammonia loss; for instance, incorporation or injection of manure can reduce NH_3 volatilization by 50–90% compared to surface application [251]. Manure management is a notable source of agricultural greenhouse gases, mainly CH_4 and N_2O. Methane is produced during anaerobic decomposition in liquid or slurry storage systems, while N_2O arises through nitrification and denitrification during handling and after applications under moist or compacted soil conditions. Globally, manure management contributes about 5–10% of agricultural CH_4 and 16% of agricultural N_2O emissions [252]. Liquid systems emit more CH_4 than solid or composted manures, whereas surface-applied manure increases N_2O losses [253,254]. Mitigation practices such as reduced storage time, use of impermeable covers for lagoons, solid–liquid separation with composting of solids, and injection of manure into soil have been shown to reduce CH_4 and NH_3 emissions from manure management but may lead to increases in N_2O or ammonia losses under some conditions [253,255]. Intensive livestock manures have been shown to introduce elevated concentrations of trace metals (e.g., Cu, Zn) into soils with long-term use (e.g., Cu and Zn increased by 204% and 107%, respectively, after 10 years of high-rate pig manure application) [256,257]; meanwhile, veterinary antibiotics, hormones and microplastics have been detected in manures (e.g., 50,000 microplastic n/kg in manure) and thus pose emerging risks to soil, plant and human health when applied to land [258,259].

2.4. Other/Engineered Sources

2.4.1. Hydrochar

Hydrochar, the solid carbonaceous product of hydrothermal carbonization (HTC), has emerged as a promising soil amendment derived from the treatment of wet biomass under moderate temperatures (typically 180–280 °C) in water-saturated conditions. Unlike pyrolysis biochar, hydrochar retains higher amounts of labile organic C, oxygenated functional groups, and mineral nutrients due to its lower carbonization temperature and water-mediated reaction environment. These physicochemical characteristics make it a potentially valuable amendment for improving soil fertility and structure, though they also confer higher degradability and, in some cases, short-term phytotoxicity. The composition of hydrochar varies significantly with feedstock type and HTC conditions. Studies have shown that nutrient-rich feedstocks such as biogas digestate, sewage sludge, and food waste yield hydrochars containing substantial quantities of plant-available P and K. Hydrochar produced from sewage sludge has been found to contain up to 8% P, significantly higher than unmodified char, which typically contains less than 0.5% phosphorus [260]. Also, de Jager and Giani [261] reported that digestate-derived hydrochar contained approximately 6544 mg PO_4-P kg^{-1}, while the native soils used in their experiments contained only 30–200 mg kg^{-1} PO_4-P. When applied to soil, this significant increase in available P and K concentrations were observed within weeks, especially at moderate application rates (5–10% w/w). Hydrochar pH, commonly ranging from 6.0 to 7.5, can also shift soil pH toward neutrality [261]. Experimental application rates of hydrochar vary widely. In controlled pot trials, researchers have used 0.5–30% w/w hydrochar in soil mixtures, equivalent to approximately 30–150 t ha^{-1} depending on incorporation depth and bulk density [262]. Lower rates (1–5%) often yield measurable improvements in soil nutrient status and structure without adverse effects, while higher rates can result in salinity or oxygen-demand issues, especially in fine-textured or poorly drained soils. Quantitative evidence indicates that hydrochar improves soil physical properties by increasing aggregate stability and water-holding capacity, particularly in sandy or degraded soils. Studies consistently report higher plant-available water and improved seedling emergence following amendment with hydrochar produced from agricultural residues or digestate.

The effects of hydrochar on plant performance are highly variable. A meta-analysis by Luutu et al. [263] synthesizing data from 43 studies found that hydrochar application reduced mean seed germination by 38% and shoot biomass by 10% across experiments, reflecting the influence of soluble organic compounds formed during HTC. These compounds can be phytotoxic in freshly produced hydrochars. However, when hydrochar undergoes post-treatments such as washing or co-composting, its agronomic performance improves substantially. Laboratory washing has been shown to remove up to 90% of volatile fatty acids and small polar organics, raising germination indices by approximately 18% compared with unwashed material [262]. Similarly, co-composting hydrochar with green waste for several weeks effectively reduces phytotoxicity while stabilizing nutrient content and enhancing microbial activity in soil. Hydrochar's impact on carbon cycling differs markedly from that of biochar. Incubation studies show that 13–16% of hydrochar-derived C is mineralized within eight weeks, demonstrating that hydrochar C is relatively labile [264]. While this limits its long-term sequestration potential, hydrochar can still increase short-term SOC through both direct addition and indirect stimulation of plant growth. In some soils, a priming effect occurs, in which the labile C in hydrochar accelerates the decomposition of native SOC, indicating that hydrochar is more suitable for fertility enhancement over short and medium time periods rather than for long-term C storage.

Overall, hydrochar offers immediate agronomic benefits through nutrient enrichment and physical improvement of degraded soils, but these advantages must be balanced against potential phytotoxicity and limited C stability. Evidence indicates that nutrient-rich hydrochars (from digestate or sludge) can partially replace mineral fertilizers due to their high P and K content, whereas hydrochars from lignocellulosic feedstocks are better suited for soil-structure enhancement. To ensure safe and effective application, hydrochar should be characterized for pH, electrical conductivity, dissolved organic C, and heavy metals before use. Field application should commence at $\leq$5% w/w (about 30 t ha^{-1}) with gradual scaling following soil-specific studies. For long-term C sequestration goals, hydrochar may be best used in combination with compost or more recalcitrant biochar forms [265].

2.4.2. Metal–Organic Framework Composites

Metal–organic framework (MOF) composites are emerging as purpose-built soil amendments that bridge the gap between conventional organic inputs and precision materials for nutrient delivery, contaminant immobilization, and stress mitigation. As crystalline, highly porous coordination networks, MOFs can host and exchange ions and molecules with exceptional selectivity; when they are combined with biochar, polymers, clays, or biogenic carriers, their stability and function in soils improve markedly, opening routes to use them not only as sorbents in remediation but also as controlled-release carriers for fertilizers and crop-protection agents. Rojas et al. [266] mapped the agricultural potential of MOFs across three fronts; remediation, controlled agrochemical delivery, and detection, highlighting the promise of Zr-based frameworks (UiO family), zeolitic imidazolate frameworks (ZIFs), and Fe/MIL series for robust performance under variable pH and moisture regimes that typify field soils. MOFs themselves do not add stable organic carbon to soil; however, when integrated with carbonaceous carriers such as biochar, hydrochar, or lignin, the resulting composites combine the persistent carbon fraction of the carrier with the functional reactivity of the MOF. The MOF fraction plays the "active" role by supplying chemically precise functionalities for sorption, catalysis, and nutrient hosting, thereby enhancing fertilizer efficiency and immobilizing contaminants [266,267].

Across soil functions, MOF-biochar composites have been the most intensively studied "soil-ready" platform to date, because biochar buffers pH swings, offers mechanical protection against framework collapse, and adds redox-active, sorptive carbon that interacts synergistically with MOF nodes and linkers. MOF-biochar hybrids consistently outperform either component alone for capturing heavy metals and multi-contaminant mixtures, with adsorption gains 25 times higher than pristine biochar [267,268]. These improvements were traced to larger accessible surface area (up to 950–1200 $m^2 g^{-1}$ vs. 12–500 $m^2 g^{-1}$ for biochar alone), cooperative complexation sites, and improved electron/ion transport at MOF-carbon interfaces [269–271]. Polyakov et al. [272] demonstrated that decorating wheat-straw biochar with MIL-100 (Fe) increased its BET surface area by about six-fold and doubled sorption capacity for Cu^{2+} and Pb^{2+} in contaminated soil, with XAFS and SEM-EDX confirming complexation/cation-exchange as dominant mechanisms. These results make a practical case for MOF-biochar as an amendment to reduce plant-available metal pools and alleviate toxicity in the root zone. Complementary studies functionalizing biochar with MIL-101 further showed that MOF-decorated biochars can operate as "advanced amendments" in real soils, exhibiting more than a threefold increase in sorption efficiency over raw biochar, with retention capacities of 15.70 $\mu g g^{-1}$ for polycyclic aromatic hydrocarbons compared to 4.86 $\mu g g^{-1}$ for the unmodified biochar, thereby reinforcing their translational potential from materials science to field-scale remediation [273].

Beyond immobilizing legacy contaminants, MOF composites offer a tunable path to nutrient management that conventional organic amendments cannot easily achieve. Early demonstrations with oxalate-phosphate-amine metal–organic frameworks (OPA-MOFs) as fertilizers showed that these materials can provide slow-release nitrogen and phosphorus in weathered Ferralsols.

Urea hydrolysis from OPA-MOFs was rapid, but conversion to nitrate was slower than with conventional urea, while P was released gradually and was partially bioavailable, leading to higher plant biomass and P uptake compared to unfertilized controls, though less than with conventional TSP + urea fertilization [274]. Since then, ZIF-8 and UiO-type carriers have been engineered to release P, Mg, and agrochemicals in pH-responsive or light-triggered fashions, with composites such as ZIF-8@hydroxyapatite acting simultaneously as a slow-release nutrient source and antibacterial agent. Emerging studies have begun to quantify the agronomic benefits of MOF composites, particularly regarding yield enhancement. A novel Mg-based, controlled-release MOF (GR-MOF-27) demonstrated significant improvements in plant growth metrics, specifically, enhancements of 10.5% in shoot weight, 11.0% in root weight, and 13.1% in dried biomass compared to control treatments under similar fertilization regimes [275]. ZIF-8@hydroxyapatite demonstrated a great fertilizer effect, increasing shoot (9.4%) and root length (27.1%) of wheat seeds and reduced bacterial wilt incidence by 80% [276]. In greenhouse tomato trials, CMC/PVA-ZIF-8-coated TSP (c-TSP) consistently outperformed uncoated TSP (uc-TSP) and the control across all growth parameters [277]. Compared to uc-TSP, c-TSP increased leaf number, plant height, stem diameter, and chlorophyll content by 12–18%, and enhanced fresh and dry biomass by 38–50%. Relative to the control, these gains were even greater, ranging from 29 to 43% for growth traits to over 70% and 150% for fresh and dry weight, respectively [276]. Despite these promising results, large-scale, replicated field trials remain scarce, leaving a degree of uncertainty about yield consistency across soil types and climatic conditions. Stimuli-responsive ZIF-8 systems have been employed for the delivery of fungicides and nematicides, providing effective disease suppression with lower active ingredient requirements and prolonged soil persistence due to reduced photodegradation [278,279].

From an economic standpoint, widespread adoption faces significant cost barriers. Industrial-scale techno-economic assessments reveal that production costs of MOFs presently range between $35–71 per kilogram, depending on the type and synthesis route used [280]. More recent estimates focusing on MIL-100 (Fe) syntheses suggest that costs could potentially be lowered to under $30/kg, provided synthesis methods rely on aqueous, ambient-pressure processes and use affordable iron precursors [281]. For context, conventional NPK fertilizers cost between $0.5–2.0/kg, underscoring the disparity [282,283]. This cost structure makes MOFs economically viable primarily in niche applications or high-value cropping systems, rather than broad land-applied scenarios. Bridging the gap between performance gains and economic practicality may be possible in high-margin or stress-sensitive systems. For example, if MOF carriers enable reductions in pesticide or fertilizer use, even by 10–20%, the net value could offset the cost of MOF carriers under proper application regimes. Still, comprehensive cost–benefit analyses comparing MOF-amended yields, cost offsets from reduced agrochemical use, and environmental externalities are urgently needed to validate their true economics.

Vellingiri et al. [284] lays out two core concerns of MOF-based materials as soil amendments for agronomic use: metal leaching particularly from Zn-rich ZIFs in acidic soils, and framework stability under repeated wet-dry and freeze–thaw cycles, where exposure to moisture and thermal stress has been shown to reduce surface area or sorption capacity by up to 30% in ZIF-type materials [285,286]. Agricultural reviews likewise emphasize selecting frameworks with low eco-toxicity metals (e.g., Fe, Zr, Ca, Mg), minimizing free linker residues (<0.1%), and validating that composites do not inhibit beneficial microbiota; where MOFs are used for pesticide delivery, the carrier should lower active ingredient load and off-target exposure relative to commercial formulations to justify use [266]. On the remediation side, Polyakov et al. [272] not only demonstrated strong immobilization of Cu and Pb in soil without obvious phytotoxicity in short tests but also underscored the need for life-cycle assessment and multi-season fate studies before broad land-application, standards that are already routine for biosolids and biochar.

2.4.3. Humic Substances

Humic substances (HS) represent one of the most versatile and widely studied categories of organic amendments in sustainable agriculture [287,288]. They are naturally occurring organic compounds formed during the decomposition of plant and microbial residues and are typically classified into humic acids (HA), fulvic acids (FA), and humin. Composts generally contain relatively low HA concentrations (2–25%) compared with leonardite- or lignite-derived products, which may exceed 60% HA content and show higher densities of functional groups such as carboxyl and phenolic groups, giving them stronger chelation capacity [289,290]. Unlike bulk organic inputs such as compost or biosolids, HS act primarily at the plant–soil interface, exerting both biochemical and biophysical effects that translate into improvements in soil health, nutrient efficiency, and crop productivity [291,292]. They can be derived from a range of sources, including composts, biochar, biosolids, algae, and green manures, though their quality and composition depend heavily on the feedstock and processing method [292]. Industrial-scale production often relies on lignite, leonardite, or peat, but increasing interest in renewable agricultural by-products reflects the growing emphasis on circular bioeconomy approaches [293]. Advances in analytical methods have further enabled the isolation of specific bioactive fractions, with low-molecular-weight FA frequently identified as the most effective stimulants of plant growth [294].

The agronomic effectiveness of HS arises from their multiple mechanisms of action. At the soil level, they improve aggregation, porosity, and water retention, particularly in degraded or sandy soils. In a recent study on sandy and clayey soils, humic amendment reduced bulk density, increased porosity, raised full water capacity (FWC) and available water capacity (AWC), and in clay soils, reduced saturated hydraulic conductivity by 35% [295]. Their abundant functional groups allow them to chelate macro- and micronutrients, enhancing their availability while reducing leaching losses [296]. For instance, HA reduced nitrate leaching by 10–20% in cereal systems [297]. At the plant level, they function as biostimulants, stimulating root proliferation, increasing lateral root density, and improving nutrient uptake efficiency [298,299]. Meta-analysis has confirmed that HA fertilizers improve average crop yield by 12%, N uptake by 17%, and NUE by 27% across multiple cropping systems [300]. Similarly, in cereal systems, HA application increased yields by 8–12%, with spikes per unit area rising by 17%, grains per spike by 5%, and thousand-grain weight by 4% compared with untreated controls [301]. Humic substances also influence plant–environment interactions. They provide labile C to soil microbial communities, fostering beneficial organisms and stimulating enzyme activity [287,302]. Moreover, they enhance tolerance to abiotic stress by modulating plant antioxidant systems and regulating ion transport [303,304]. In coastal saline-alkali soils, HA application reduced cumulative evaporation by 5–29%, improved infiltration by up to 10%, and significantly enhanced water-use efficiency (WUE) and grain yield when applied at optimal rates of 180–200 kg ha^{-1} [305]. Under drought stress, maize treated with HA maintained 25% improvement in dry matter and root traits [306] and produced 14–25% higher yields than controls in wheat [307]. These findings highlight the particular value of humic substances in stress-prone environments.

In horticultural crops including tomato, lettuce, and cucumber, yield improvements of 15–25% are frequently reported [308,309], often coupled with enhanced fruit quality and nutrient-use efficiency [292]. Stress-prone systems also benefit considerably: in saline soils, the application of HS combined with reduced rates of P fertilizer increased grain yield of barley by 44–65% compared with untreated control across two seasons [310]. Unlike compost or biosolids, whose effects depend on decomposition rates and nutrient release dynamics, HS consistently provides measurable benefits by directly influencing plant physiology alongside soil functions [296,311,312].

Their contribution to soil function and C sequestration further elevates their value in sustainable agriculture. The stable aromatic structures of humic substances add to persistent organic matter pools, while their role in promoting aggregation helps protect C from microbial decomposition. Multi-year trials have demonstrated that increases in SOC stocks are highly related to the accumulation of HS. For instance, fertilization with manure increased HA, FA, and humin concentrations, correlating with SOC increases at $R^2 = 0.98$ [313]. Applications of humic amendments have been shown to increase microbial biomass C, N, and P by 38–40, 84–93 and 43–45%, respectively [314]. Likewise, the proportion of microaggregates stabilized by humic substances rose from 22% to 37% over six years of application [313]. Enhancing soil humic matter by 16% could potentially sequester enough carbon to lower atmospheric CO_2 levels by roughly 120 ppm [315]. The simultaneous improvement of crop performance and soil C sequestration highlights the role of humic substances as a key amendment in sustainable soil management strategies.

Nonetheless, several challenges moderate their widespread adoption. The composition of humic products varies according to their source and extraction method, complicating efforts to standardize formulations and performance outcomes. In addition, while their physiological effects are well documented, the molecular mechanisms that underpin plant–humic interactions remain incompletely understood, highlighting an area for further research. Emerging opportunities lie in integrating HS with other organic amendments, such as compost or biochar, or with precision fertilizer strategies to maximize both agronomic and environmental benefits. Furthermore, the development of bio-based extraction from renewable agricultural feedstocks could improve the scalability and sustainability of HS use. Given these attributes, HS occupy a distinctive niche among organic amendments. By combining plant biostimulant effects, soil-conditioning properties, and C stabilization functions, they provide consistent yield benefits across environments while reinforcing long-term soil resilience. Their ability to enhance root growth, nutrient uptake, and stress tolerance makes them a versatile option not only for improving productivity but also for advancing the broader goals of sustainable and climate-smart agriculture.

3. Selecting the Right Amendment

Maximizing crop yield with organic amendments requires not only understanding the individual effects of each material but also recognizing how they complement or differ from one another under specific soil and crop conditions (Tables 1–3). Animal manures, derived from livestock systems, provide a readily available nutrient source with both fast- and slow-release components that enhance crop productivity and soil biological activity. When applied regularly, they increase SOC by approximately 0.3–0.6 Mg C ha^{-1} yr^{-1} and improve yield stability through better soil moisture retention and nutrient buffering [241]. Average yield increases of 5–10% have been reported in nutrient-depleted or degraded soils, especially under integrated nutrient management [316]. Compost, by contrast, provides steady nutrient release and consistent improvements in soil structure, moisture retention, and CEC, enhancing SOM by 30–50%. These changes translate into yield increases of 10–30% in nutrient-limited systems [82]. However, compost alone may not supply sufficient N for crops with high early-season N demand, such as cereals, due to its slow mineralization rate. In such cases, GM, particularly leguminous species, can be integrated strategically to supply biologically fixed N. Their yield gains in subsequent crops, typically ranging from 12 to 20%, with crop-specific gains of 9.5% for wheat, 16.7% for maize, and 19.2% for rice [157,317]. By supplying a dynamic nutrient source, GM complement compost and offset its slower nutrient release.

Vermicompost offers more rapid nutrient mineralization and a richer microbial composition compared to traditional compost. It enhances microbial biomass and enzymatic activity, improving soil nutrient cycling and plant health [216,218,221]. Vermicompost also improves SOC and CEC by 20–50%, with better humification and stable C fractions than conventional composts. Compared with compost, it provides a faster-acting nutrient source and introduces beneficial microbial consortia (e.g., *Azotobacter*, *Pseudomonas*, *actinomycetes*, and mycorrhizae) that enhance nutrient availability and disease suppression [220,318]. While both compost and vermicompost are valuable for improving soil health and productivity, their mechanisms differ. Compost contributes long-term stability through humus formation, whereas vermicompost provides short- to medium-term biological stimulation and nutrient availability. Integrating the two can yield synergistic effects, optimizing both soil quality and crop performance. In degraded or highly weathered soils, biochar becomes particularly relevant. Unlike compost, vermicompost or GM, biochar does not directly supply large amounts of nutrients but instead modifies the soil environment by improving soil pH, enhancing cation exchange, and moisture retention. This soil improvements translate into yield increases of 10–25% in tropical and acidic soils where conventional organic inputs underperform [319]. Biochar thus complements nutrient-rich amendments by providing a stabilizing foundation for long-term soil fertility gains. Hydrochar, a hydrothermally carbonized product, retains a higher fraction of labile C than conventional biochar, functioning both as a conditioner and slow-release nutrient source.

Table 1. Soil and crop impacts of organic amendments with varying processing and decomposition rates.

Amendment	**Source**	**Processing Level**	**Approximate Decomposition Rate**	**Key Effects on Soil**	**Potential Effects on Crop Productivity**	**Carbon Sequestration Potential**
Green manure	Fresh plant biomass (cover crops, legumes)	Minimal (incorporated fresh)	Rapid (weeks-months)	Increases soil N, stimulates microbial biomass, improves aggregation	Boost yield via quick nutrient release and improved soil structure	Low-moderate (rapid mineralization)
Seaweed	Marine macroalgae	Minimal (fresh/dried) or mild processing	Rapid-moderate	Supplies micronutrients, plant growth regulators, enhances water retention	Improves growth, stress tolerance, and quality	Low-moderate
Algae	Microalgae or cyanobacteria	Cultured, harvested, sometimes processed	Rapid-moderate	Improves nutrient cycling, fixes atmospheric N (in case of cyanobacteria)	Enhances yields, especially in degraded soils	Low-moderate
General Animal Manure	Mixed livestock manure	Raw to composted	Moderate to fast	Enhances soil aggregation, microbial activity, CEC, and nutrient (N, P, K, Ca, Mg) availability	Improves yield through nutrient supply and structure	Moderate
Compost	Mixed plant/animal residues	High (controlled aerobic decomposition)	Moderate (months-years)	Improves nutrient availability, CEC, pH buffering	Sustained yield improvement, reduced fertilizer needs	Moderate
Vermicompost	Organic waste (cow dung, plant residues)	Worm-processed/Matured	Moderate to Fast	Enhances soil structure and water-holding capacity; increases nutrient availability (N, P, K); boosts microbial biomass and enzyme activities	Improves crop growth, yield, nutrient uptake, and root development	Moderate
Biosolids	Treated sewage sludge	High (anaerobic digestion, stabilization)	Moderate	Supply organic matter and nutrients, may improve water-holding capacity	Boosts yield but requires safety management	Moderate
Bagasse	Sugarcane residue	Minimal to moderate (raw, composted, or pelleted)	Moderate	Improves organic matter content, water retention, and soil aeration	Improves yields over time	Moderate
Biochar	Pyrolyzed plant biomass	High (thermal processing under limited oxygen)	Very slow (decades-centuries)	Increases pH (if alkaline), improves CEC, enhances nutrient retention	Indirect yield benefit via improved soil function	High
Chitosan	Crustacean shells (chitin-derived)	High (chemical/enzymatic deacetylation)	Slow-moderate	Enhances disease suppression, soil microbial diversity	Improves crop health and resistance	Moderate-high
Humic acids	Decomposed organic matter (soil, peat, compost, leonardite)	Extracted/concentrated (alkaline extraction)	Moderate (stable but bioavailable fractions)	Improves nutrient uptake, root development, and stress tolerance	Consistent yield gains	Moderate

Table 1. *Cont.*

Amendment	Source	Processing Level	Approximate Decomposition Rate	Key Effects on Soil	Potential Effects on Crop Productivity	Carbon Sequestration Potential
Hydrochar	Hydrothermally carnonized biomass	High (hydrothermal carbonization at 180–250 °C)	Moderate (years–decades; more labile than biochar)	Improves soil structure, adds labile C and nutrients, enhances microbial activity	10–15% yield boosts in sandy/nutrient-poor soils	Moderate
MOF composites	Metal–organic frameworks often combined with biochar or polymers	Very high (engineered synthesis under controlled conditions)	Slow (depends on carrier; stable crystalline structures)	Enhance nutrient retention and controlled release; immobilize contaminants	Early trials show 10–20% yield gains in cereals and vegetables	Low–moderate (limited C contribution, but improves nutrient-use efficiency

Table 2. Comparative Effects of Organic Amendments on Crop Yield.

Amendment	% Yield Increment	Best-Use Contexts	Notes	Key References
Compost	10–30	Low-fertility soils; as partial fertilizer substitute; widely applicable in cereals, vegetables, and horticulture	Precision compost can raise yield 40% while halving N inputs.	[82,320]
Vermicompost	15–30	Maize, wheat, vegetables, fruit crops; soils with low OM	Enhances soil fertility, microbial activity, water-holding capacity; promotes root development	[209,214,219]
Green manure/cover crops	12–20	Nutrient-limited soils; rotations with cereals and legumes	Benefits largest for following crop; risk of yield drag in dry areas if poorly managed.	[317]
Biochar	10–20	Degraded, acidic, low-OM, low-CEC soils; or sandy soils; synergistic with fertilizer	Effects durable, often increase over time; best in degraded soils.	[321,322]
Biosolids	15–30	Cereal (maize, wheat) and forage production; where nutrients are limiting	Effect depends on biosolid quality and rate.	[174,175,323,324]
Algae/seaweed	15–20	Tomatoes, wheat and rice fields; stress conditions (heat, drought, salinity)	Global biostimulant meta shows 18% yield gains.	[325,326]
Animal manure	5–35	Field maize trials; nutrient-deficient soils	Improves N, P, K availability (20–40%), enhances SOM, microbial activity, moisture retention, increase soil pH.	[236,240]
Chitosan	10–20	Stress-prone systems (salinity, drought, pathogens); high value horticulture	Works via defense elicitation and stress mitigation; variable but positive.	[25,327]
Bagasse/press-mud	17–25	Sugarcane systems; vegetable production	Composting/enrichment enhances effects; improves cane juice and soil fertility.	[126]
Humic acids	10–20	Maize, wheat, horticulture; broad spectrum soil improvement	Consistently enhances root growth, nutrient uptake, and stress resilience; benefits strongest under moderate stress.	[298,308]
Hydrochar	10–15	Nutrient poor or sandy soils; complement to fertilizers	Retains more labile C than biochar; moderate but positive yield gains; stability still under study	[328,329]
MOF composites	10–20 (early trials)	Degraded soils; nutrient-inefficient systems; high-value crops	Improve nutrient use efficiency and mitigate contaminants; high-cost limits large-scale use	[274]

Table 3. Comparative summary of major organic and engineered soil amendments: properties, effects, mechanisms, and key quantitative outcomes.

Amendment Type	**Parameter**	**Experimental System**	**Key Findings**	**Outcomes**	**References**
Algal amendments (microalgae, cyanobacteria, seaweed)	Soil nutrient improvement	*Chlorella vulgaris*, *Spirulina platensis* in sandy and loam soils, pea/wheat systems	Increase in SOC mineralization (16–36%), K (40–50%), NO_3^--N (20–30%)	Enhance nutrient mineralization, microbial stimulation	[29,31]
	N fixation potential	*Anabaena*, *Nostoc*, *Arthrospira* in paddy/cereal systems	20–80 kg N ha^{-1} yr^{-1} fixed; decrease chemical N use by 25–50%	Biological N_2 fixation via heterocysts	[38,39,330]
	Soil physicochemical changes	Mixed algal biomass, microalgae fertilizer	Increase in pH; P (43%), N (17%), OM (62%); moisture retention (20–75%)	Organic acids, polysaccharide binding, moisture retention	[33,44]
	Microbial activity	*Chlorella vulgaris* pot trials	Increase in microbial biomass C; enzyme activity, Shannon diversity	Labile C input, microbial activation	[28,45]
	Metal remediation	*Ulva*, *Sargassum* in contaminated soils	Decrease in conc. of Zn (28%), Pb (27%), Cu (33%)	Chelation, surface sorption	[47,48]
	Carbon sequestration	Microalgae, cyanobacteria	CO_2 capture 1.8–2.5 kg m^{-1} yr^{-1} (10 times higher than plants)	Photosynthetic fixation, C input	[52,59,234]
	Constraints	—	Low nutrient content (1–10% N), costly (2–3× conventional), potential heavy metal accumulation	Requires nutrient balancing, cost mitigation	[31,57,59]
Compost	Nutrient composition	Crop/manure/food waste feedstocks	0.5–3% N, 0.2–2% P, 0.5–3% K; $C/N < 20$	Mature compost improves fertility, pH buffering	[66,68]
	Soil structure improvement	Various soils	increase aggregate stability (15–50%); decrease bulk density (0.1–0.5 g cm^{-3})	Improve the aggregation, porosity	[69]
	Metal immobilization	Polluted soils	Decrease Cd, Pb uptake (20–80%)	Sorption, organo-metal complexes	[73,74]
	Crop yield response	Cereals, tomato, basil	increase yield 10–40%	Nutrient synchronization	[79,82]
	GHG mitigation	Compost vs. manure	decrease N_2O (15–50% with biochar)	Stabilized N forms, better aeration	[89]
	Constraints	—	Bulky; Immature compost results in phytotoxicity; high cost	Requires maturity and quality control	[62,92]
Animal manure	Soil nutrient improvement, organic matter, microbial activity, soil pH, moisture retention	Cow manure field trials on maize	25–40% N, 20–30% P, 15–25% K increase; increase in growth 35–45%; SOM, MBC and enzymatic activity, water holding capacity	Enhances soil fertility, stimulates microbial activity, improves maize yield, supports sustainable farming	[241,245]
Biochar	Physicochemical properties	Crop residues, manures, wood	pH 3.5–12.9; $H/C < 0.7$; $O/C < 0.4$	High aromatic C, long-term stability	[99,101]
	Water retention	Global synthesis	Increase available water (12–30%)	Porosity and surface functional groups	[103]
	Nutrient retention	Field studies	Decrease NO_{3^-} leaching (26–32%); increase nutrient-use efficiency	N sorption, reduced leaching	[107]
	Heavy metal immobilization	Contaminated soils	Decrease Cd, Pb (38–39%), Cu, Zn (17–25%)	Precipitation, complexation	[110,331]
	Biochar–compost synergy	Co-composted systems	Enhance the fertility and microbial activity	Organo-mineral coating stabilizes SOM	[101,116]
	Constraints	—	Possible N immobilization, PAHs, cost	Combine with N-rich inputs	[99,114]

Table 3. *Cont.*

Amendment Type	Parameter	Experimental System	Key Findings	Outcomes	References
Sugarcane bagasse (raw and biochar)	Composition	Raw bagasse	45–55% cellulose; 18–24% lignin; C/N-66; pH 4.0	Fibrous, acidic, N-poor	[121,126]
	Soil improvement	Sandy/loam soils	Reduce bulk density; increase OM, porosity, water retention (60–73%)	Fiber enhances aggregation	[124,128]
	Nutrient cycling	Soil column studies	Leaching (C, N, P, K) 25–50%	Sorption, microbial immobilization	[126]
	Crop productivity	Cabbage, sugarcane	Increase yield (9–15%); biomass (3–6×)	Improved water, nutrient retention	[126,128]
	Bagasse biochar	Pyrolyzed residue	Increase AWC (60%), CEC (42%)	Greater C stability vs. raw bagasse	[132]
	Constraints	—	High C/N, acidity, bulkiness	Composting/pyrolysis recommended	[125,133]
Green manure	N fixation	Legumes, mixtures	40–150 kg N ha^{-1} yr^{-1}	Symbiotic N_2 fixation, mineralization	[135,154]
	Soil structure	Field trials	Reduce erosion (20–40%); increase aggregation, infiltration	Root binding and OM input	[139,140]
	Microbial activity	Long-term plots	Increase MBC (30–70%); enzyme activity (14–39%)	Labile residue C fuels microbes	[142,146]
	Crop yield	Maize, clover	Increase yield (11–22%); improved NUE (12–48%)	Synchronized N release	[145,157]
	Soil C sequestration	Long-term	Increase SOC 0.3–0.9 Mg C ha^{-1} yr^{-1}	Residue and root-derived C	[160,162]
	Constraints	—	Short-term yield decrease (5%); increase moisture use	High C/N, water competition	[163,164,167]
Vermicompost	Soil fertility, Crop yield, Microbial activity	Field and greenhouse studies on maize, wheat, vegetables	Increased SOC, NPK availability; enhanced microbial biomass and enzyme activity; improved germination and root development	10–30% yield increase; improved soil structure and nutrient cycling; enhanced crop quality	[205,208,212]
Biosolids and Chitosan	SOM and C sequestration	Field and lab	Increase SOM (10–17%); SOC accrual 0.2–0.5 Mg C ha^{-1} yr^{-1}	Stable organic C formation	[172,198]
	Microbial activity	Degraded soils	Increase microbial biomass (76–200%); enzyme activity	Organic N and biopolymer inputs	[23,173]
	Soil physical properties	Various soils	Increase aggregate stability (33–200%); water retention	Organic binding, structural improvement	[189]
	Pathogen control	Tomato, cereals	Reduce disease incidence 30–91% (Fusarium, Rhizoctonia)	Chitosan antifungal activity	[190,191]
	Environmental safety	—	Must meet EPA limits; PFAS emerging issue	Requires regulation and monitoring	[184,185]
MOF-based composites	MOF-Biochar composites	MIL-101, UiO-66, ZIF-8 + biochar	Metal adsorption 25×; immobilization > 90%	Synergistic sorption, redox-active sites	[268,269]
	MOF-Polymer composites	ZIF-8@PVA, CMC/PVA-ZIF-8	Increase biomass (38–50%); plant height (12–18%)	Controlled nutrient release	[277,278]
	Nutrient-delivery MOFs	GR-MOF-27 (Mg-based), OPA-MOF	Increase biomass (13%); slow nutrient release	Controlled dissolution	[274,275]
	Pesticide/fungicide MOFs	ZIF-8, UiO-66	63–76% disease control; decrease pesticide use (20%)	Photo stabilization of actives	[278,279]
	Environmental and cost	—	\$30–70 kg^{-1} (vs. \$0.5–2 for NPK); Zn leaching risk	Fe, Zr, Mg MOFs more stable	[280,284]
Humic Substances (HS)	Composition and classification	Derived from decomposition of plant and microbial residues	Composts: 2–25% HA; Leonardite/lignite: >60% HA; high carboxyl and phenolic functional group density	High cation exchange, chelation, and redox capacity; bioactive functional chemistry	[289,290]

Table 3. *Cont.*

Amendment Type	Parameter	Experimental System	Key Findings	Outcomes	References
Humic Substances (HS)	Sources	Composts, biosolids, algae, green manures, biochar, lignite, peat	Composition depends on feedstock and extraction method	Renewable feedstocks support circular bioeconomy	[287,292,293]
	Soil structure improvement	Sandy and clayey soils	Decrease bulk density; increase porosity; FWC and AWC; decrease saturated hydraulic conductivity by 35%	Aggregation, porosity, enhanced moisture storage	[295]
	Nutrient retention and chelation	Cereal and vegetable systems	Decrease nitrate leaching 10–20%; increase nutrient availability	Chelation and slow release of macro- and micronutrients	[296,297]
	Crop yield response	Meta-analysis across systems	Increase yield 12%; N uptake 17%; NUE 27%	Biostimulant and physiological stimulation	[299,300]
	Yield response in cereals	Wheat, maize, rice	Increase yield 8–12%; spikes m^{-2} (17%); grains/spike (5%); thousand-grain weight by 4%	Root proliferation and enhanced nutrient uptake	[301,332]
	Drought tolerance	Maize under deficit irrigation	Increase dry matter (25%); root traits (25%); yield by 4–25%	Improved antioxidant system, osmotic regulation	[307]
	Salinity stress mitigation	Rice, barley, saline-alkali soils	Decrease ion toxicity; evaporation 5–29%; increase infiltration 10%; WUE; yield 10–18%	Ion regulation, improved water relations	[305,310]
	Horticultural productivity	Tomato, lettuce, cucumber	Increase yield 15–25%; nutrient-use efficiency; fruit quality	Hormonal-like action, improved root architecture	[308,309]
	Microbial and enzymatic activity	Degraded and fertile soils	Increase MBC (38–40%); N (84–93%); P (43–45%)	Labile C input, microbial stimulation, enzyme activation	[287,314]
	Soil carbon sequestration	Multi-year trials; manure fertilization	Increase HA, FA, humin correlated with SOC (R^2 = 0.98); microaggregate stabilization (22–37%); reduce CO_2 by 120 ppm	Aromatic C protection, aggregate stabilization	[313,315]
	Plant physiological effects	Cereal and horticultural crops	Increase lateral roots; improved ion balance; chlorophyll and photosynthetic rate	Modulation of plant hormone and ion transport pathways	[291,303,304]
	Product variability	Commercial and natural sources	Quality depends on source (compost, leonardite, peat) and extraction pH	Standardization needed for reproducible outcomes	[287,292]
	Integration with other amendments	Compost, biochar, mineral fertilizers	Synergistic improvement of nutrient use and C stability	Co-application enhances both short- and long-term effects	[311,312]
	Limitations and future directions	—	Variable composition; incomplete understanding of molecular mechanisms	Potential in bio-based extraction and precision applications	[287,288]

Biosolids occupy a unique position, delivering both organic matter and a concentrated supply of macro- and micronutrients. Yield increases of 20% have been reported in cereal systems, occasionally rivaling or surpassing mineral fertilizers when applied responsibly [323,333]. However, biosolid use requires careful regulation and monitoring due to potential contamination risks, making them more demanding to manage than compost or green manure. When soils are already fertile but crops face recurrent abiotic or biotic stresses, amendments that function primarily as biostimulants, such as algae/seaweed extracts and chitosan, can enhance yield stability rather than dramatic increasing productivity. Seaweed-based products typically increase yields by 10–15%, enhancing stress tolerance and nutrient efficiency in high-value horticultural crops [56]. Similarly, chitosan can improve yields by 10–20% in stress-prone systems by inducing plant defense pathways and mitigating salinity or drought effects [334,335]. Unlike biosolids or compost, their strength lies in safeguarding yield potential under adverse conditions rather than supplying nutrients. Locally available crop or industrial residues, such as sugarcane bagasse, illustrate the value of context-specific amendments. In sugarcane systems, bagasse improves cane productivity, juice quality, and provides rotational benefits to cereals [125]. While effects are system-specific, these residues demonstrate the potential of tailoring amendment choice to local agro-industrial contexts.

Beyond these traditional materials, HS, particularly HA and FA, are increasingly used for their consistent ability to stimulate root proliferation, nutrient uptake, and plant resilience. Trials document yield increases of 10–20% in maize, wheat, and horticultural crops, with effects often amplified under stress conditions [298,308,332]. Unlike bulk organic inputs, HS act directly at the plant–soil interface, improving root architecture and nutrient-use efficiency. Metal–organic framework composites represent an emerging frontier in soil amendments. Early agronomic trials demonstrated measurable yield increases of 10–13% in biomass with GR-MOF-27 and 19% in rice with MIL-88@SA foliar applications, alongside improved nutrient-use efficiency and heavy metal mitigation [274]. However, high production costs and limited field-scale validation currently restrict their use to high-value or precision agriculture niches.

4. Conclusions

This review demonstrates that soil amendments can enhance crop productivity through multiple, distinct biogeochemical pathways rather than through a single universal mechanism. Their effectiveness is rooted in three core principles: improving soil physicochemical properties, enhancing nutrient cycling and use efficiency, and strengthening plant resilience to biotic and abiotic stresses. However, the magnitude and consistency of these benefits vary widely across amendment types, soil conditions, climatic settings, and management practices, leading to context-specific outcomes rather than uniform responses.

Organic nutrient-based amendments such as compost and biosolids function primarily through nutrient enrichment and microbial stimulation, particularly in nutrient-deficient systems, where yield increases of approximately 10–30% have been reported. Their contribution to soil organic matter can support nutrient mineralization, aggregation, and microbial activity, although outcomes depend strongly on amendment quality, application rate, and background soil fertility. Green manures contribute to nitrogen fixation and rotational soil recovery, supporting soil fertility and subsequent crop yields (typically 12–20%). However, outcomes depend on initial soil fertility, amendment quality, and incorporation practices, and the long-term persistence of benefits is variable.

Soil-conditioning amendments, including biochar, hydrochar, and crop-derived residues such as bagasse, exert their influence largely through changes in soil physical and chemical properties. Biochar has been shown to improve soil structure, CEC, moisture retention, and pH buffering, particularly in degraded or low-fertility soils, but yield responses are inconsistent (commonly 10–25%). Hydrochar exhibits similar, though often more variable, effects while also supplying nutrients, with reported yield of 10–15% in sandy or nutrient-poor soils. Bagasse and other locally sourced residues reinforce the principle of circular bioeconomy soil management, offering low-cost pathways to restore fertility using regional by-products.

Biogenic and bio-based stimulants, including algae extracts and chitosan, tend to influence crop performance indirectly by modulating plant physiological and stress-response pathways rather than by supplying nutrients. Their capacity to enhance antioxidant activity, root vigor, and osmotic balance contributes to yield responses often in the range of 10–20%. Their reported benefits are most consistently observed under stress conditions such as drought, heat, or salinity, and their effectiveness may be limited under optimal growing environments.

Among chemically derived soil enhancers, HS demonstrate relatively broad and multifunctional effects, acting at the root–soil–nutrient interface to influence nutrient availability and uptake, stimulate root architecture, support enzyme activity, and bolster abiotic stress tolerance. While yield responses of 10–20% have been reported across diverse cropping systems, these outcomes are also contingent on soil properties, formulation, and application strategy. Their compatibility with both organic and conventional systems, ecological safety, and scalability position them as a cornerstone amendment capable of linking fertility enhancement with climate-smart soil management. Emerging innovations, such as MOF composites, display potential for precision nutrient delivery and contaminant immobilization, but their agronomic potential remains uncertain due to limited field validation, high costs, and scalability constraints.

Yield optimization, therefore, depends less on identifying a single superior amendment and more on aligning specific amendment functions with defined soil constraints, crop requirements, and production goals. While humic substances appear to offer comparatively versatile benefits across a range of systems, their role, like that of other amendments, should be viewed as complementary within integrated soil fertility and soil health management strategies rather than as a stand-alone solution. Future research should prioritize long-term field evaluations, comparative assessments across soil-climate gradients, and cost–benefit analyses to better define the conditions under which soil amendments can reliably contribute to sustainable intensification and soil carbon management.

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Abbreviations

The following abbreviations are used in this manuscript:

SOC	Soil organic carbon
GHG	Greenhouse gas
TOC	Total organic carbon
POC	Particulate organic carbon
GM	Green manure
EQ	Exceptional quality
PFAS	Polyfluoroalkyl substances
PFOS	Perfluorooctane sulfonate
HTC	Hydrothermal carbonization
MOF	Metal–organic frameworks
ZIF	Zeolitic imidazolate frameworks
HS	Humic substances
HA	Humic acid
FA	Fulvic acid
WUE	Water use efficiency
NUE	Nitrogen use efficiency

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