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Review

Effects of Vermicompost on Soil and Plant Health and Promoting Sustainable Agriculture

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Abstract: This review highlights the potential of vermicompost and its derived products as sustainable and eco-friendly solutions for enhancing production and pest management in grain crops. It assesses their impact comprehensively on crops such as maize, wheat, barley, rice, and pearl millet. Vermicompost improves soil quality, increases nutrient availability, boosts crop productivity, and enhances pest and disease tolerance. It acts as an organic fertilizer, enriching the soil with essential nutrients, humic acids, growth-regulating hormones, and enzymes, improving plant nutrition, photosynthesis, and overall crop quality. Furthermore, vermicompost shows promise in mitigating soil degradation and sequestering organic carbon while demonstrating the potential for pest management, including effectiveness against pests like fall armyworm (*Spodoptera frugiperda*). This review emphasizes the importance of integrated nutrient management and proper application strategies to maximize the benefits of vermicompost in grain crops. Factors such as the form and timing of application, efficacy against specific pests, and economic viability for different farming scales are discussed. Understanding these factors is crucial for successfully implementing and adopting vermicompost-based pest management strategies in grain crops. This review also explores the potential of vermicomposting as an eco-friendly and cost-effective solution to remediate organic contaminants, emerging contaminants, personal-care and pharmaceutical products, and microplastics. The review further identifies knowledge gaps and highlights the need for future studies to effectively utilize vermicompost and its derived products in cereal production for sustainable agriculture, contributing to global food security.

Keywords: sustainable agriculture; organic fertilizers; integrated nutrient management; pest management; organic pesticides; enzymes; carbon sequestration; greenhouse gases

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1. Introduction

Grain crops play a pivotal role in global food production, serving millions of people as a primary source of nutrition and livelihood. However, the conventional use of chemical fertilizers and pesticides in production and pest management has raised significant concerns regarding human health risks and environmental sustainability. As a result, there is an increasing demand for sustainable and eco-friendly alternatives that can ensure optimal crop yield and quality. Among these alternatives, vermicompost (VC) and its derived products have emerged as a promising solution, offering numerous benefits for grain crop production and effective pest management.

Maize, wheat, barley, rice, and pearl millet are important cereal crops worldwide, contributing significantly to the 9.5 billion tons of global food production in 2021 and the 54% increase in food production since 2000 [1]. Between 2020 and 2021, global cereal production increased by 2.1%, driven by a 4.1% surge in maize production, with maize, wheat, and rice contributing to 90% of the total cereal output [2]. Additionally, pearl millet, the sixth major cereal crop, is vital in agriculture, covering approximately 30 million hectares in arid and semi-arid tropical regions of Asia and Africa, accounting for nearly half of global millet production [2]. Maize, the most produced grain globally, has high nutritional value with protein, carbohydrates, oil, fiber, and ash content [3]. Wheat, a similarly vital source of protein for billions of people, often suffers from nutrient deficiencies in soils, adversely affecting human nutrition. Zinc and iron deficiencies are prevalent in agricultural soils globally [4]. Wheat grain is rich in starch, protein, fat, cellulose, minerals, and vitamins, making it nutritionally valuable.

To meet the ever-growing demands for food, maximizing crop yield per unit area has become imperative. Organic fertilizers such as VC present a sustainable approach to achieving this goal. VC, produced through the symbiotic interactions between microorganisms and earthworms, represents a cost-effective and environmentally friendly process that enhances soil quality and improves microbial biodiversity [5–10]. Incorporating VC into agricultural systems has shown great potential for boosting grain crop productivity while minimizing environmental impacts.

A balanced supply of nutrients is crucial to ensure high productivity and nutritional value in grain crops. Combining chemical and organic fertilizers, including VC, has been recommended to address nutrient deficiencies and mitigate soil quality deterioration caused by intensive crop cultivation practices [3,11]. Farmers can improve soil fertility, enhance nutrient availability, and promote sustainable long-term productivity in grain crops by incorporating VC, crop residues, and cover crop biomass.

Micronutrient malnutrition poses a significant challenge to global public health, affecting a substantial portion of the population. Ensuring the enrichment of widely consumed cereals with essential nutrients has become imperative. VC offers a natural solution enriched with crucial nutrients, humic acids, plant growth-regulating hormones, and enzymes, which positively influence plant nutrition, photosynthesis, and the nutrient content of various plant parts [12,13]. Moreover, VC has been shown to enhance crop tolerance against pests and diseases, making it a favorable alternative to inorganic fertilizers in agricultural and horticultural practices.

Overreliance on mineral fertilizers in cereal production has led to severe soil degradation and environmental problems. Integrated nutrient management practices, including VC, mitigate these issues. VC is vital in improving soil quality, sequestering organic carbon, and reducing excessive CO_2 emissions associated with intensive agricultural practices [14–17]. Farmers can achieve sustainable agriculture practices by implementing VC -based strategies while reducing environmental impacts.

Several factors must be considered to assess the feasibility of large-scale implementation of VC and its derived products in grain crops. These include the appropriate form and timing of application, effectiveness against prevalent pests, such as armyworms, and economic viability for different farming operations. This comprehensive review aims to evaluate the impact of VC and its derived products on grain crop production and pest management. Specifically, the focus will be on major cereal crops such as maize, wheat, barley, rice, and pearl millet, which play a crucial role in global food security and have diverse applications. The search covered articles published between January 2001 and January 2023. Understanding the multifaceted aspects of VC-based strategies is essential for their successful implementation and for fostering sustainable agriculture practices that can ensure global food security.

2. Vermicompost Production

2.1. Vermicompost Raw Materials

Vermicomposting, a valuable method to convert diverse organic wastes into nutrient-rich VC, relies on carefully managing raw materials outlined in Table 1. Organic residues, generally safe for earthworms, can be directly used as feedstock in vermicomposting beds, resulting in high-quality VC. However, some feedstocks may contain volatile gases that can be toxic to earthworms and have excessive moisture, requiring thorough pre-treatment to ensure earthworm safety and quality. Pre-treatment methods in the vermicomposting process include drying organic materials to eliminate volatile gases harmful to earthworms, reducing excessive moisture, initiating microbial degradation, and softening waste [18].

Subsequently, pre-composting makes the feedstock more palatable for earthworms and aids in odor reduction.

Furthermore, ref. [19] emphasizes the critical role of pre-treatment in transforming brewers' spent grain (BSG) into a more biodegradable and extractable substrate. BSG, containing biopolymers like lignin and cellulose, necessitates pre-treatment to break down these complex compounds for easier assimilation by microorganisms. Various pre-treatment methods, including alkali, acid, hydrothermal, or enzymatic treatments, enhance nutrient availability by hydrolyzing BSG biopolymers. Additionally, using *Aspergillus oryzae* during pre-treatment exhibits the capacity to break down BSG biopolymers in a pre-fermentation phase.

However, the economic feasibility of pre-treatment methods that involve high or low temperatures and the use of microbial starters to enhance composting and vermicomposting performance is currently being questioned due to the associated high costs [19]. When composts and VC are produced from various types of waste, undesired substances can enter the extracts, resulting in inhibitory or even toxic effects on crops. Therefore, it is essential to use only clean components in producing all compost types used for extract production [20].

Table 1. Raw materials for vermicomposting.

Type of Organic Waste	Source (Plants/Animals)	References
Dry grass	Grasses	[4]
Straw	Cereal crops	[4]
Fresh plant residues	Plants	[4]
Cow manure	Cows	[4]
Wood ash	Wood	[4]
Sewage sludge	Sewage	[19]
Rice straw	Rice plants	[19]
Animal wastes	Animals	[19]
Brewer spent grains	Brewing industry waste	[19]
Tree prunings	Trees	[19]
Paper waste	Paper	[19,21]
Crop residues	Crops	[19]
Leaf litter	Leaves	[19]
Medicinal herbal residues	Medicinal herbs	[19]
Dairy farm waste	Dairy farms	[22]
Azolla pinnata	Aquatic fern	[23]
Weeds like congress grass and water hyacinth, bhang, allelopathic weeds like ipomoea (*Ipomoea carnea*), parthenium (*Parthenium hysterophorus*), lantana (*Lantana camara*), or weeds with high lignin content like salvinia (*Salvinia molesta*)	Weeds	[24]
Pressmud	Sugar industry waste	[25]
Distillation waste of Mentha arvensis	Mint distilleries	[26]
Biodigested slurry	Biodegradable waste	[27]
Coir pith	Coconut husks	[27]
Cow dung	Cows	[27]
Rice field weeds	Weeds	[27]

2.2. Formation of VC

Vermicomposting is a controlled bio-oxidative process that utilizes earthworms and microorganisms to convert organic wastes into quality organic manure (Figure 1), positively influencing physicochemical parameters and nutrient concentrations [21]. This process occurs at lower temperatures, neutral pH, and higher humidity to facilitate the growth of earthworms and the activity of mesophilic microorganisms essential for organic matter decomposition and soil fertility [28]. The process takes 3–6 months from when raw materials are subjected to earthworms to obtaining the final VC, but this time depends on the species and number of earthworms used and the conditions provided. VC, the end product of vermicomposting, is rich in humus, macronutrients, and micronutrients, and it has higher nutrient content and microbial activity than compost [19], making it highly valuable in the market.

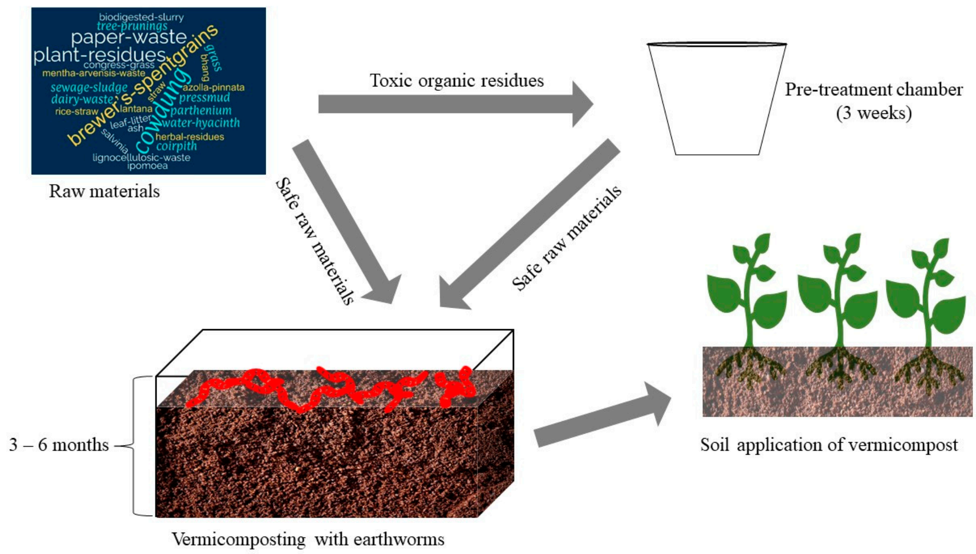

Figure 1. Schematic illustration of the vermicomposting process. The earthworms on top of the vermicomposting bed are shown in red color.

During vermicomposting, significant changes occur in microbial diversity and quantity due to the influence of microorganisms and digestive enzymes in the worms' intestines [29]. VC contains enzymes such as amylase, lipase, cellulase, chitinase, and plant growth hormones like gibberellic acid, cytokinins, and auxins. It also possesses antimicrobial substances and defense systems that protect worms from the infective effects of microorganisms [29]. Using VC in nutrient management offers cost savings and mitigates environmental issues associated with raw manure, providing a safer and more stable soil amendment [23].

To enhance the nutrient content of VC, the addition of nitrogen-rich *Azolla pinnata*, cattle dung, and inoculation with nitrogen-fixing bacteria has been suggested. This combination, known as VAM (VC, Azolla, manure), has demonstrated high-quality VC suitable for agricultural applications and has shown the highest biological yield [23]. Earthworms play a vital role in increasing nitrogen content through various mechanisms, including introducing nitrogen-rich mucus, decaying worm tissues, and promoting microbial-mediated nitrogen mineralization. Phosphorus mineralization during vermicomposting enhances the availability of phosphorus in VC, likely due to the action of earthworm phosphatases and phosphorus-solubilizing microorganisms in the worm's gut. Potassium availability in VC can vary, with increased levels due to enzymatic activities [21] and grinding. In contrast, reduced levels can be attained due to leaching caused by excessive water drained during composting [21].

In addition to vermicomposting, anaerobic composting is another method for composting animal dung. This process involves the breakdown of organic waste by bacteria in an oxygen-free environment, and the resulting effluent, known as biodigested slurry, serves as a nutrient-rich product of the biogas digester [27].

2.3. Vermicompost Rates Applied

VC application rates vary depending on the specific crop and soil conditions, as shown in Table 2. For example, in a study by [30] on barley, rates ranging from 0 to 250 t ha^{-1} were examined, with the highest yield and biomass observed at 250 t ha^{-1}. The study by [31] found that a combination of 10 t ha^{-1} VC with mineral fertilizer resulted in the best treatment for wetland rice, considering yield parameters, grain yield, nutrient uptake (except S uptake), and N use efficiency. However, ref. [32] found that 3 t ha^{-1} of VC worked well for rice. However, it is crucial to avoid excessive application, as higher concentrations of soluble salts in VC can negatively affect crop growth. For instance, ref. [13] observed that higher doses of VC had a negative impact on radicle growth in legumes. It is crucial to consider factors such as crop type, soil characteristics, and experimental conditions when determining the optimal VC rate.

Table 2. Vermicompost rates applied in grain crops.

Crop	Vermicompost Rate	Reference
Barley	25 t ha^{-1}, 50 t ha^{-1}, 125 t ha^{-1}, 250 t ha^{-1}, 5 mg ha^{-1}, 238 kg ha^{-1}	[14,30]
Rice	10 t ha^{-1}, 3 t ha^{-1}, 4 t ha^{-1}, 38.96 g/ 10 kg of soil, 3.3 t ha^{-1}, 8 t $acre^{-}$, 6250 kg ha^{-1}, 60 kg ha^{-1}	[24,31–37]
Wheat	0.9 km m^{-2}, 15 t/ha, 10 t ha^{-1}	[21,38,39]
Buckwheat	0.75 t ha^{-1}, 1.50 t ha^{-1}, 2.25 t ha^{-1}, 3.00 t ha^{-1}	[13]
Maize	5 t ha^{-1}, 3 t $acre^{-1}$, 1 t $acre^{-1}$	[40–42]

2.4. Microbial and Chemical Composition of Vermicompost

VC is a unique, organic amendment that offers numerous benefits for pest management in cereal crops. It is characterized by high microbial activity and a nutrient-rich composition, including essential elements like N, P, K, Ca, Mg, Fe, Mn, Zn, and Cu (Table 2). These nutrients are readily available and easily absorbed by plants, thanks to the biological effects of the compost, such as increased enzyme activity, beneficial microbial populations, and plant-growth-promoting substances like hormones [31].

Furthermore, VC exhibits biocontrol properties due to its ability to harbor antagonistic organisms that can effectively suppress plant pathogens [43]. This dual functionality as an organic amendment and a biocontrol agent makes VC a promising tool for pest management in grain crops.

Furthermore, the nutrient content of VC varies depending on the input materials used (Table 1). Ref. [27] found variations in NPK contents between different types of VC. Weed-based VC had higher nitrogen (N), phosphorus (P), and potassium (K) contents compared to coir pith-based VC. The N content in weed-based VC increased from 1.51% in the input material to 2.03%, while coir pith-based VC had an N content ranging from 1.24% to 1.52%. Moreover, digested slurry-based VC exhibited higher N content (1.52% to 2.03%) than cow dung-based VC (1.24% to 1.85%). These variations in nutrient content highlight the importance of considering the input materials when selecting VC for nutrient recycling and organic waste management [27].

2.5. Vermicomposting and Its Effects on Enzymes and Nutrient Content

Vermicomposting, which involves the collaboration between earthworms and microorganisms to biodegrade and stabilize organic materials, is a crucial process in organic waste management [44]. During vermicomposting, earthworms and mesophilic microorganisms work together to break down organic matter, resulting in the production of VC enriched with various enzymes such as cellulose and chitinase, as well as proteins, vitamins [45], growth hormones, and amylases. These enzymes play a vital role in decomposing organic matter and breaking down complex compounds [44]. Applying VC to soil enhances the production of polysaccharides by soil microorganisms, improving soil structure and composition (Table 3).

Table 3. VC's physicochemical, macro, and micronutrient concentrations are based on the composting raw material.

Compost Raw Material	pH	OM (%)	N (%)	P (ppm)	K (ppm)	Zn (ppm)	Others	Reference
Paper waste	8.01	2.1%	0.24	23.2	1425	1.02	EC = 6.12 msm^{-1} Fe = 1.84 ppm	[21]
Cow dung	8.00	2.1	0.3	11.56	346	1.06	EC = 5.95 msm^{-1} Fe = 3.09 ppm	[21]
Rice straw	7.98	2.01	0.07	6.34	127	0.97	EC = 2.98 msm^{-1} Fe = 4.21 ppm	[21]
Cow dung	7.4	40.00	1.4	18,000	22,000	110	EC = 1.12 (ds m^{-1}) Mg = 12,000 ppm Na = 8000 ppm Mn = 450 ppm Cu = 20 ppm Ca = 10,000 ppm	[12]
Brewer's spent grain	7.08	6.64	3.28				C:N = 11	[19]
Cow dung	7.82	48.92	2.26	9100	10,400		C:N = 15	[22]
Cow dung	7.43	49	2.53	15,400	13,700	369	C:N = 11.3 Cu = 164.8 ppm Fe = 416.6 ppm Mn = 248.7 ppm	[23]
Cow dung and rice straw	7.6	87.6	2.16	12,700	10,100	342	C:N = 17.14 Cu = 152 ppm Fe = 372.1 ppm Mn = 212 ppm	[23]
Cow dung		58.48	1.68	4100	13,000		S = 50,000 ppm C:N = 11.09	[31]
Cow dung			1.71	11,800	9800	100	Fe = 940 ppm Mn = 240 ppm Cu = 120 ppm	[46]
Cow dung	6.8	98.04	3.1	12,000	8900		Organic N = 2.0% C:N = 9.2	[13]
Rice straw and animal wastes	7.62	31.92	1.69	12,600	13,100		C:N = 11.46	[14]

A study by [45] examined the enzymatic activity of eight different enzymes in three types of aged VC derived from household biowaste, malt house sludge mixed with agricultural waste, and grape marc. The vermicomposting process was carried out in large-scale systems with continuously feeding earthworms. The study found that the vermicomposting process with household biowaste exhibited the highest enzyme activity, particularly β-D-glucosidase, acid phosphatase, arylsulphatase [45], and lipase in the youngest layers. Chitinase, cellobiohydrolase, alanine aminopeptidase, and leucine aminopeptidase also showed significantly higher activity in the vermicomposting heap with household biowaste. These results suggest that household biowaste is highly suitable for soil application, as it promotes the rapid decomposition of organic compounds due to its high enzymatic activity. However, further research is necessary to understand the practical correlation between enzyme activity and the number of earthworms [45].

In another study by [47], conducted in a semi-arid Mediterranean agroecosystem, the effects of VC derived from different sources on soil properties and rice growth were investigated. Adding VC to the soil increased soil microbial biomass C, especially at higher organic matter doses, while stimulating soil dehydrogenase and urease activities. Cow dung VC exhibited more significant activity compared to green forage VC. Furthermore, the activity of β-glucosidase increased over time in all VC-amended soils, and soils amended with VC containing higher fulvic acid content displayed higher levels of water-soluble carbohydrates [47]. These findings emphasize the positive impact of VC additions on soil biological properties, with higher fulvic acid content associated with increased soil microbial biomass C and soil respiration. The labile fraction of organic matter in VC with higher fulvic acid content likely served as a readily available energy source for microorganisms, contributing to the observed effects. The study also suggests that forming humus-enzyme complexes, particularly in humic acids, may explain the higher enzymatic activity observed in VC with higher fulvic acid content [47]. Therefore, vermicomposting of various organic wastes offers a maintenance-free, cost-effective, and environmentally friendly method for achieving cleaner production and managing organic waste effectively [44].

2.6. Advantages and Limitations of Vermicompost

VC offers several advantages over non-composted organic wastes and mineral fertilizers, resulting in improved crop growth, biomass, and yield. The gradual release of nutrients in VC, facilitated by humic and fulvic acids, enhances the availability of soil nutrients to plants and promotes root growth, leading to better water and nutrient uptake [4]. Furthermore, VC supplies plants with readily available micro and macronutrients, converting unavailable nutrients into accessible forms. It has also been found to have higher sulfur content than mineral fertilizers [30]. While the organic carbon content in VC is relatively lower than that in other organic manures, the continuous application of VC contributes to soil carbon buildup. It ensures an adequate nitrogen supply, improving soil properties and carbon accumulation [43].

VC is environmentally friendly and non-toxic to plants, offering essential nutrients (Table 1) and active growth-promoting substances like cytokinins, auxins, and gibberellins. These compounds support plant growth and provide desirable characteristics such as permeability, aeration, drainage, water-holding capacity, and microbial activity [40].

However, while VC and organic manures have numerous benefits, their large-scale application for grain crops faces limitations. Challenges such as high transport costs, elevated application rates, and environmental concerns associated with their use pose difficulties, particularly in developing countries with limited livestock availability and reliance on agricultural waste as fuel [31]. Overcoming these challenges requires exploring potential solutions to ensure VC's overall production and utilization.

3. Techniques for Enhancing Vermicompost Efficiency in Cereal Production

VC has gained significant attention in agricultural practices. Its application in cereal crops has shown promising results in improving growth and yield. Figure 2 shows the different cereals in which VC studies were conducted, and the number of articles that conducted the studies per crop is indicated in parentheses. Fewer studies have been published on applying VC in barley, millet, and sorghum cultivation. This knowledge gap may need to be filled, as organic farming is highly valued. However, Figure 3 shows the various techniques recommended for enhancing VC use for cereal production.

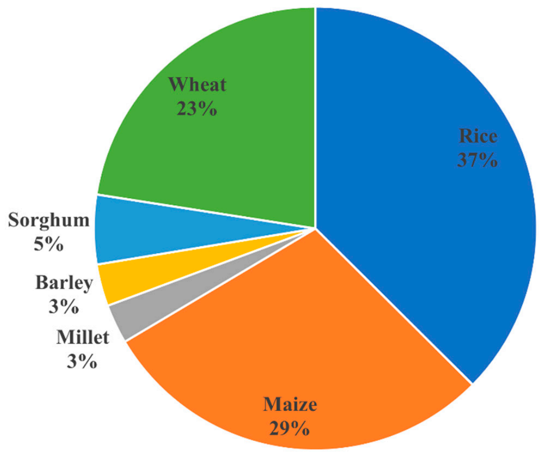

Figure 2. Research studies with VC application in cereal crops for the last 23 years.

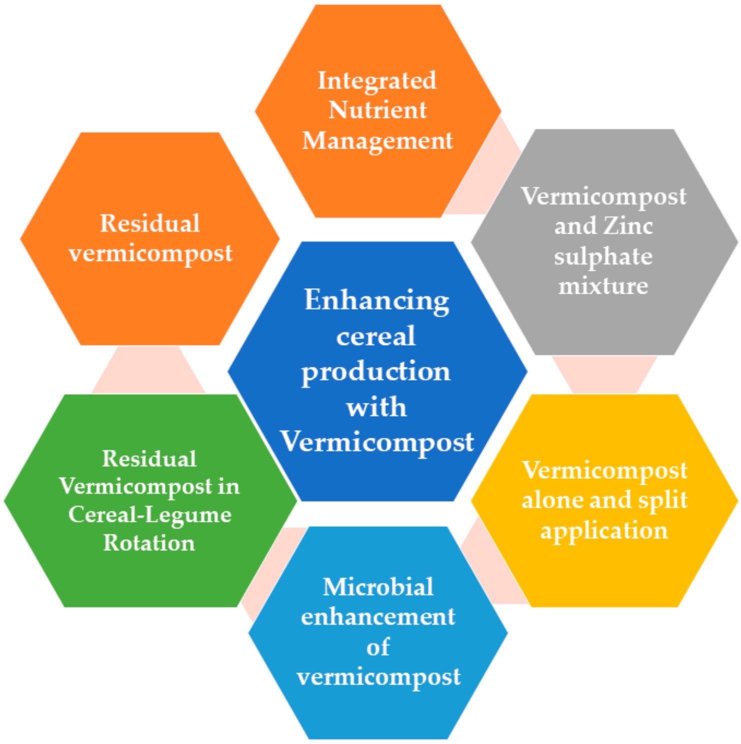

Figure 3. Summary of the various techniques used to enhance the efficiency of vermicompost for cereal production.

3.1. Split Application of Vermicompost and Its Application Alone

The application of VC alone in grain crops has been extensively researched, highlighting its feasibility and effectiveness [3]. Studies have revealed its positive impact on various crops, including maize, barley, and buckwheat, increasing plant height, grain yield, and grain nutrient content [13,14]. Furthermore, VC has been found to contain a nutrient-rich composition, significantly benefiting plant physiology, growth, chlorophyll content, and overall yield.

In addition to applying VC alone, the split application of VC has gained attention in improving soil properties, microbial activity, and crop growth [22]. Combining VC with other organic amendments like farmyard manure (FYM) and biofertilizers has shown promising results in rice cultivation, significantly enhancing grain yield and yield components [48]. Notably, split applications of VC have increased panicle count and filled grains per panicle and improved nutrient use efficiency [49].

The application of VC, alone or through split applications, demonstrates its potential to enhance soil fertility, nutrient availability, and overall crop productivity [3,22]. These findings emphasize the importance of incorporating VC in sustainable agricultural practices to promote sustainable crop production and achieve agrarian sustainability. Further research and exploration of VC application techniques are necessary to optimize its benefits across diverse agricultural systems.

3.2. Vermicompost and Microbial Enhancements for Improved Crop Production and Seed Quality

Recent research has shed light on the potential of VC and effective microorganisms (EM) in augmenting grain crop production, as summarized in Table 4. The study by [4] highlighted a significant increase in wheat yield by combining EM with VC, surpassing the performance of conventional compost fertilizers. The positive effects of EM were also evident in maize crops. Incorporating EM compost with VC was particularly effective, attributed to gradual nutrient release, growth-regulating substances, and enzymes in VC.

In rice cultivation, organic fertilization incorporating farmyard manure, VC, Azolla, and cyanobacteria increased total phosphorus content compared to chemical fertilization and integrated nutrient management (INM) [50]. Additionally, VC application in large-scale grain crop production increased rice yield, improved soil carbon content, and enhanced nutrient availability and micronutrient concentrations [46].

The combination of VC with microbial inoculants, such as Azotobacter, Azospirillum, phosphate-solubilizing bacteria, and arbuscular mycorrhizae, demonstrated positive effects on soil carbon content, nitrogen availability, and crop yield [51]. However, when comparing VC treatments alone with the combination of VC with microalgae or microalgae with chemical fertilizer, the latter achieved higher rice yields, attributed to rapid nutrient release and phytohormone production by microalgae [33].

Studies have also explored the interaction of VC, mycorrhiza, and fertilizers, revealing their significant influence on grain yield and kernel weight in grain crops [52]. These findings underscore the potential of VC, EMs, mycorrhiza, and microbial inoculants in improving nutrient availability, soil health, and grain crop productivity, offering sustainable alternatives to chemical fertilizers.

Moreover, ref [53] investigated the effects of applying a commercial mycorrhizal arbuscular fungi mixture (Tec Myc 60®) and cow manure VC on maize grains' chemical composition, energetic parameters, and amino acid profile. The study included treatments of VC plus mycorrhizal fungi (V + M), VC alone (V), and chemical fertilization (CF). While the V + M treatment led to maize grains with 1.9% higher starch content than that achieved with CF, other components did not show significant differences. Amino acid content variations were noted between the treatments, emphasizing the importance of pre-planting VC application in influencing seed quality [53].

Table 4. Vermicompost application for cereal production systems.

Cereal	Vermicompost Application Strategies	References
Maize	VC alone	[3]
	VC, EM, and biofertilizers	[4]
	VC and zinc sulphate	[12]
	INM	[17,54,55]
Rice	VC alone	[33,56]
	INM	[31,36]
	VC EM and biofertilizers	[23,46,50]
	Residual VC in cereal–legume rotation	[37]
	VC and manure	[57]
	Split application of VC	[48,49]
Wheat	VC alone	[13,58]
	INM	[4,21,59]
	VC, EM, and biofertilizers	[4,50]
	Residual VC in cereal–legume rotation	[4]
	VC and manure	[60]
	Split application of VC	[22]
Barley	VC alone	[14]
	VC and manure	[60]
	VC and nano zinc foliar spray	[14]
Pearl millet	INM	[61,62]
	VC and manure	[16]

3.3. Residual Vermicompost in Cereal–Legume Rotation

Crop rotation involving legumes and the application of residual VC has shown promising results in improving wheat yield compared to continuous wheat cropping systems. A study by [4] demonstrated that a faba bean–wheat rotation led to enhanced wheat yield compared to constant wheat cropping, even when both systems received the same nitrogen level. Moreover, the combination of EM, VC, and mineral fertilizer further increased grain yield in the faba bean–wheat rotation, indicating the potential benefits of incorporating legumes, organic materials, and biofertilizers in crop rotation systems [4,63].

In a study by [37], the residual effects of organic materials and biofertilizers on rice and wheat yields, nutrient status, and the economics of succeeding mung bean were evaluated in an organic cropping system. The results revealed that incorporating short-duration mung bean after wheat and its residue in the following rice cultivation significantly improved the rice–wheat cropping system's productivity, profitability, and soil recovery compared to traditional practices. The application of organic manures, biofertilizers, and VC carried over subsequent crops, as a portion of the applied nitrogen became available to the immediate crop and benefited subsequent crops. Combinations of farmyard manure with crop residues and biofertilizers and VC with crop residues and biofertilizers resulted in improved grain quality and nutrient uptake [37,64].

These studies highlight the advantages of incorporating legume rotations and organic materials, such as VC, in cereal crop systems. The integration of crop rotation with legumes enhances wheat yield and promotes soil health, nutrient availability, and crop quality when applying organic materials and biofertilizers. These findings suggest that incorporating VC and its derived products and appropriate agricultural practices can be a viable approach to enhance grain crop production and promote sustainability. However, further research is needed to explore specific forms and applications of VC, evaluate its effectiveness in pest control (e.g., armyworm), and assess its suitability for different farming scales. Such investigations will contribute to expanding our knowledge and optimizing the utilization of VC in diverse agricultural systems.

3.4. Residual Effect of Vermicompost

The residual effects of VC have been investigated in various studies, highlighting its long-lasting benefits on crop productivity. A study by [58] found that applying VC at 10 t ha^{-1} in wheat significantly increased rice yield during the subsequent two years, ranging from 16.3% to 39%, depending on the NPK application rate. This indicates a substantial residual effect of VC on rice productivity. Furthermore, applying 10 t ha^{-1} of VC, combined with 100% recommended inorganic fertilizers, resulted in higher organic carbon content and increased levels of N, P, and K in the soil [42,58,65,66].

Similarly, ref. [67] conducted a field experiment evaluating the residual effects of NP fertilizers, VC, and sulfur on cluster beans and the subsequent wheat. They found that applying NP fertilizers at 100% of the recommended dose, along with 2.0 t ha^{-1} of VC and 60 kg ha^{-1} of S, significantly increased the grain yield of the subsequent wheat crop from 12.04% to 21.54% compared to the control. These treatments had residual effects on the growth and yield attributes of the wheat crop [67], as well as nutrient availability.

Furthermore, ref. [68] observed the direct and residual effects of VC, biofertilizer, and phosphorus on chickpeas and maize fodder. VC application increased the protein content in chickpea grains, while seed inoculation with Rhizobium and phosphorus application also positively affected protein content. Additionally, VC, along with Rhizobium and phosphorus, had a residual impact on the yield of maize fodder, increasing it by 6.3% to 26.12%. These treatments enhanced the N and P uptake by the cropping system and improved the soil's N and available P status after both crop cycles [68].

A study by [68] assessed the residual effect of VC and mulching on popcorn growth, productivity, profitability, and energetics in a toria-popcorn cropping system. VC application to the preceding toria crop influenced popcorn's dry matter accumulation and leaf area index (LAI). The highest dry matter accumulation was achieved with rice straw mulch at 5 t ha^{-1}, while VC at 1.5 t ha^{-1} showed significantly higher LAI values at different stages. VC application also affected yield attributes, with the highest values observed for cob length, girth, cob grain count, and 1000-grain weight with 1.5 t ha^{-1} of VC. The application of VC positively influenced the energetics of popcorn, resulting in higher gross energy output, net energy output, energy use efficiency, and energy productivity compared to the control [69]. These findings suggest that VC, in combination with appropriate mulching, can enhance popcorn productivity, profitability, and energy productivity.

3.5. Enhancing Crop Productivity and Soil Health through Vermicompost and Zinc Treatment Strategies

In a study by [39], the combined application of arsenic (As), zinc sulfate, and VC ($As_{30}Zn_{20}V_{15}$) significantly decreased As concentrations in grains, straw, and roots compared to other treatments. This treatment also increased total soluble protein content compared to the As_{30} treatment. Zinc sulfate alone ($As_{30}Zn_{20}$) or combined with VC ($As_{30}Zn_{20}V_{15}$) led to a significant increase in grain yield compared to the As_{30} treatment. VC application alone or combined with zinc sulfate did not significantly enhance grain yield. The reduction in As concentrations in plants treated with zinc sulfate and VC may be attributed to decreased As release in the soil solution and enhanced As adsorption by forming insoluble complexes. VC application may also limit As movement in the soil by chelation, thereby reducing its accumulation in grains. The study suggests that applying zinc sulfate and VC is an effective and readily available solution for farmers to mitigate As-induced oxidative stress [39].

Similarly, in a study by [12] investigating the benefits of integrated nutrient management (INM) on popcorn maize, the effects of foliar spraying with iron (Fe) and zinc (Zn), Thiobacillus thiooxidans inoculation, and VC application were examined. VC, sourced from cow manure, was applied at 2 t ha^{-1} in strip form below the seeds before cultivation. The biofortification studies demonstrated that Fe application did not significantly affect plant macronutrient content but increased Fe content by 12.9%. Zn application significantly increased N by 6.7%, Zn by 12.6%, and protein content by 7.2%. Although Fe and Zn foliar applications had minimal effects on plant yield and farmer income, their importance lies in their impact on biofortification features and product quality. The study suggests that despite potential costs, treating plants with micronutrients is recommended to improve human health [12] and combat micronutrient malnutrition, which affects a significant portion of the global population.

Furthermore, ref. [70] studied integrated nutrient treatments in grain crops and found that combining VC at 2.5 t ha^{-1} with 25 kg ha^{-1} of $ZnSO_4$ or seed treatment with biofertilizers increased grain yield compared to the control group. These integrated nutrient treatments were able to partially substitute chemical fertilizers without compromising yield. However, using the complete recommended dose of chemical fertilizers resulted in higher yields due to the low fertility of the experimental soil. Nonetheless, the integration of VC, $ZnSO_4$, and biofertilizers showed promising results in improving nutrient availability and yield [70]. Therefore, the application of VC and $ZnSO_4$, individually or in combination, has demonstrated positive effects on pest management, reduction of As toxicity, nutrient content, and grain yield in cereal crops. These findings highlight the potential of integrating organic amendments and micronutrient treatments for sustainable crop production and addressing nutritional challenges.

In the context of VC mixed with nano zinc foliar spray [14], the impact of water stress on barley yield and soil properties can be mitigated. Adding VC with 2 g nano-Zn improved barley growth and yield when water was deficient at 85% of irrigation requirements. The treatment combining VC with 1 g nano-Zn and 100% irrigation supplementation produced the highest kernel weight in the second season of the barley crop [14]. However, the interactions between irrigation supplements, organic amendments, and nano-Zn foliar spraying did not significantly affect soil properties.

VC and nano-zinc foliar spray have demonstrated their efficacy in enhancing barley yield and mitigating the harmful effects of water stress. This approach presents a potential strategy for sustainable agriculture, offering a means to improve crop productivity and soil health in water-limited environments.

3.6. Enhancing Crop Yield and Soil Fertility: Integrated Approaches with Organic and Chemical Fertilizers

Integrated nutrient management (INM) combines organic and chemical fertilizers to improve soil fertility, enhance crop yield, and promote environmental sustainability

(Table 5). Relying solely on chemical fertilizers can lead to soil degradation and reduced organic matter content [31]. In this context, VC, known for slow nutrient release through microbial mineralization, addresses these limitations, ensuring nutrient availability during critical growth stages and subsequent crops [43].

Table 5. Effect of vermicompost on grain yield in cereal crop production.

Cereal	Fertilizers Applied	Vermicompost Applied Rate	Grain Yield/Increase	References
Maize	VC	1.5 t ha^{-1}	35.7%	[69]
	VC	1.0 t ha^{-1}	18.2%	[69]
	50% RDF NPK + 25% FYM + 25% VC	25%	5400 kg ha^{-1}	[3]
	VC	2 t ha^{-1}	20.9%	[12]
	VC + Empower at 12.5 kg ha^{-1}	5 t ha^{-1}	2549 kg ha^{-1}	[54]
	100% RDF NPK + VC	3 t ha^{-1}	3.26 quintals	[55]
Rice	Microalgae at 50% N + VC	50% N	76.1 g/plant	[33]
	VC	8 t ha^{-1}	3509–3700 kg ha^{-1}	[35]
	VC (2.5 t ha^{-1}) + 75% RDF NPK	2.5 t ha^{-1}	6.27 t ha^{-1}	[43]
	RDF NPK + VC + phosphate solubilizing bacteria at 7.5 kg ha^{-1} + *Azotobacter* at 7.5 kg ha^{-1}	2.5 t ha^{-1}	5.80 –5.86 t ha^{-1}	[46]
	Green manuring + VC	2.5 t ha^{-1}	3209 kg ha^{-1}	[71]
	VC + BF	100% N	5.7%	[48]
	VC	10 t hm^{-2}	4667 kg ha^{-1}	[23]
	VC + mineral fertilizer	10 t ha^{-1}	26%	[31]
	VC	10 t hm^{-2}	5081 kg ha^{-1}	[23]
	VC + mineral fertilizer	20 t ha^{-1}	12%	[31]
	VC + biofertilizer	100%	3.5 t ha^{-1}	[48]
	50% FYM + VC + biofertilizer	50%	3.7 t ha^{-1}	[48]
Wheat	VC + 100% NPK	5 t ha^{-1}	7–14%	[58]
	VC + 100% NPK	10 t ha^{-1}	20–28%	[58]
	VC	21,007 kg ha^{-1}	4975 kg ha^{-1}	[4]
	Different NPK doses + VC		3.22–5.37%	[21]
	VC 75% P fertilizer	20 t ha^{-1}	5462 kg ha^{-1}	[60]
	VC at sowing + VC at tillering	50% at sowing + 50% at tillering	5132.56 kg ha^{-1}	[22]
Barley	VC	5 Mg ha^{-1}	13.2–14.9%	[14]
Pearl millet	VC	6 t ha^{-1}	51.4%	[61,62]
	VC	4 t ha^{-1}	20.1%	[61,62]
	VC	2 t ha^{-1}	7.3%	[61,62]

Note: VC = Vermicompost, BF = Biofertilizer, RDF = Recommended Dose of Fertilizer, FYM = Farmyard Manure.

Numerous studies have showcased the benefits of integrating VC with chemical fertilizers in various grain crops (Table 2). Rice and wheat cultivation, in particular, demonstrated significant improvements in plant height, tiller count, grain yield, and soil fertility status when VC was combined with specific nutrient ratios [15,21]. The integration of VC with inorganic fertilizers also exhibited promising results across various crops, enhancing plant growth, yield attributes, and nutrient availability [34,59].

However, composts undergo slow decomposition processes and have limited nutrient availability, requiring large quantities for practical fertilizer application [4,63]. To meet the nutrient demands of high-yielding cultivars, adopting integrated plant nutrient systems (IPNS) combining organic and inorganic sources is necessary [25,72]. Pressmud-based VC has mainly stood out, significantly increasing grain yield due to enhanced nutrient uptake and improved soil organic carbon storage [25,59,72]. Consequently, INM integrating VC with chemical fertilizers offers a synergistic approach to sustainable crop production, enhancing soil fertility and nutrient availability and promoting environmentally friendly agriculture. The positive impact of VC integration has been observed in various grain crops, including wheat, rice, maize, and pearl millet [36,61,62,73–75].

Furthermore, the combination of VC and manure has been extensively studied, demonstrating its efficacy in enhancing crop growth, yield, and soil fertility [16,57,60,71]. These studies highlight the positive impact of combining organic and conventional fertilizers in improving plant growth, nutrient availability, and soil fertility, ultimately contributing to increased productivity in grain crops [35].

4. Vermicompost Application under Different Conditions

4.1. Vermicompost in Drought and Irrigated Soils

Applying organic amendments, such as compost and VC, has improved soil properties and crop drought tolerance. Ref. [14] found that compost application increased soil porosity, water storage capacity, and nutrient content, improving water holding capacity, nutrient uptake, and plant growth. In their study, VC treatment demonstrated maximum barley yield traits and positively influenced soil fertility, structure, and microbial activity [14].

The interaction between irrigation supplements and organic amendment treatments significantly impacted the biological yield traits of barley. When VC was added under 100% supplement irrigation, it achieved the highest grain yield and enhanced plant growth response. Additionally, VC increased irrigation water productivity for grain and straw by reducing water application while improving barley yield. Furthermore, combining VC with nano-Zn foliar spraying under deficit irrigation further enhanced irrigation water productivity [14].

Applying organic amendments, particularly VC, improved the soil's physical and chemical properties. Combining VC with irrigation supplements showed the most significant improvements in soil quality. However, reducing irrigation supplements increased soil salinity, exchangeable sodium percentage, and bulk density while decreasing soil organic carbon, available nitrogen, and field capacity [14].

Another study by [32] demonstrated that applying VC in conjunction with deficit irrigation in rice resulted in a higher grain yield of 3 t ha^{-1}. This finding suggests that VC can be an effective strategy for improving crop productivity under water-limited conditions.

4.2. Release of Nutrients from Vermicompost under Anaerobic Conditions

A study by [31] investigated the release of nutrients from VC under waterlogged conditions in floodplain and terrace soils. The results indicated that mineral phosphorus (P) release was highest at 15 days after VC amendment in floodplain soil, while the lowest release occurred at 15 days in control floodplain soil. P mineralization was higher in terrace soil than floodplain soil under control conditions but adding VC increased P mineralization in both soil types. Sulfur (S) release was highest 30 days after incubation in VC-amended floodplain soil and lowest at 15 days in control terrace soil. The treatment combining VC (10 t ha^{-1}) and mineral fertilizer resulted in rice crops' highest grain yield, straw yield, and nutrient uptake. However, applying VC at a higher rate (20 t ha^{-1}) did not significantly increase the yield. The study also found that VC-amended soils exhibited higher NH_4^+-N content than unamended soils. The findings emphasize the importance of combining mineral fertilizer and VC at an optimal rate for achieving higher yields and nutrient supply, considering the influence of soil characteristics on nutrient release from VC [31].

5. Vermicompost Derivatives

5.1. Effect of Humic Substances on Plant Growth and Development

VC and its derived products have shown promising potential for pest management in cereal crops by improving soil nutrient availability and enhancing plant morphological traits [30]. VC increases soil nutrient availability by reducing soil pH and contains humic acid, which enhances plant height, leaf expansion, and leaf area index [3]. Humic substances present in VC, such as fulvic acid and humic acid carbon, improve soil buffering capacity and water retention and serve as a source of micronutrients for plant uptake [59]. Furthermore, VC contains plant growth regulators and phytohormones like humic acid, auxin, gibberellin, and cytokinin [12].

Studies have demonstrated the positive effects of humic acids derived from VC on plant growth and development. For example, humic acid extracted from pig manure VC improved tomato plant height, leaf area, shoot dry weight, and root dry weight [76]. Humic acids isolated from earthworm compost also promoted root elongation and lateral root emergence in maize [77].

In grain crops, VC has shown positive effects on plant growth, marketable yield, and ear quality of sweet corn hybrids [12]. Additionally, the application of humic substances derived from VC in combination with arbuscular mycorrhizal fungi (AMF) positively influenced corn growth and nutrient uptake, resulting in increased shoot and root dry mass, stimulated plant height, and enhanced nutrient content in plants [78].

Humic substances, particularly those derived from VC and organic sources, have been shown to stimulate spore formation and mycorrhizal colonization and enhance the abundance and intensity of arbuscular mycorrhizal fungi (AMF), thus positively impacting soil and plant health [78]. In arid regions, vermicomposting and applying humic substance extracts have enhanced soil fertility and wheat productivity by improving soil nutrient cycling, organic matter decomposition, and nutrient availability [44].

Humic substances derived from VC, such as alkaline VC extract (AVE) and humic acid (HA), benefit maize plants. AVE treatment modulates membrane proteins, activates defense mechanisms, and improves photosynthesis rate, nutrient uptake efficiency, and phytoextraction potential [79]. It also enhances iron (Fe) concentration, mitigates the toxicity of arsenic (As), and alters nutrient absorption. Similarly, HA derived from cattle manure VC promotes maize root growth through enhanced proton pump activity and nitric oxide accumulation [80]. Lignin components are preserved during the humification process, suggesting the replacement of cattle manure with cotton residues. Different VC types also exhibit varying lignin concentrations [81].

5.2. The Efficacy of Vermicompost Tea

Vermicompost tea (VCT), also referred to as worm tea, vermiwash, compost tea, vermi-extract, or liquid VC, is a liquid extract produced through various methods, such as solid VC fermentation with water and specialized reactors [29,82]. This organic liquid extract can serve as a liquid fertilizer and an organic pesticide, offering efficacy comparable to synthetic pesticides [83]. VCT is enriched with amino acids, enzymes, vitamins, nutrients, growth hormones, and beneficial microorganisms, all contributing to enhanced crop resistance against diseases and promoting growth [8,82].

The VCT extract contains beneficial bacteria such as Bacillus, Ochrobactrum, Spingomonas, dissolved plant nutrients, and phytohormones (Figure 4) that foster plant development and improve yield. Several studies have shown the positive effects of VC applications on corn crops, leading to increased grain yield, protein content, plant height, and other growth parameters [29,41,83].

Alkaline VC extract has been found to modulate membrane proteins, activate defense mechanisms, and alleviate stresses in plants [79]. Properly composed vermi-extracts positively impact crop growth and help mitigate potential adverse effects of unclean waste materials [20]. Furthermore, foliar applications (Figure 4) of vermi-extracts have been shown to enhance chlorophyll and biomass production in cultivated crops, leading to increased yields [20,41]. However, further research is needed to fully understand the influence of VCT on disease inhibition, soil microflora, and overall crop health and quality in cereal crops. The study by [20] investigated the effects of vermi-extract application on maize yield and nutrient content, demonstrating variable impacts depending on the timing of application and maize cultivar used. Although studies have explored the effectiveness of VC against pests and diseases in fruits and horticultural crops [8,83], there is a knowledge gap regarding the use of VCT in cereal crops. Additionally, limited research has been conducted on using VCT as an organic fertilizer in cereals, with most studies focusing primarily on maize. Therefore, further research is warranted to explore the potential benefits of VCT in cereal crops and address these research gaps.

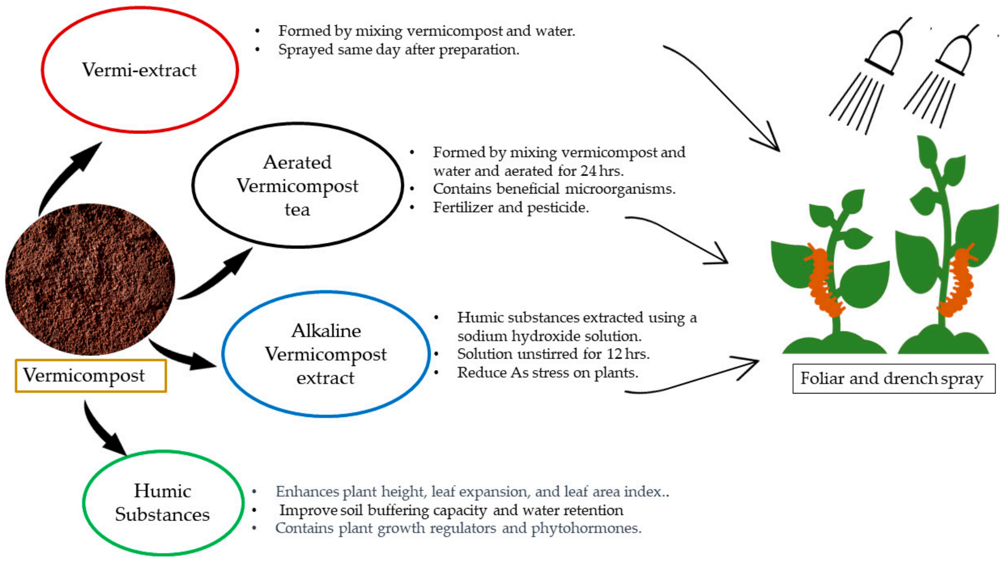

Figure 4. Vermicompost derivative applications.

VCT contributes to soil health by improving nutrient uptake and microbial diversity. It has gained significance in water-scarce regions due to its water efficiency, requiring less irrigation water than conventional fertilizers [82]. Additionally, combining different microorganisms in VCT enhances plant growth through microbial diversity. Organic fertilizers, including VCT, optimize soil nutrient availability, especially under optimal moisture conditions [82]. However, caution must be exercised when using VCT, as it can inhibit seed germination [84].

5.3. Vermicompost and Vermicompost Tea for Pest and Disease Control

VC has been extensively studied for its potential in pest control and soil improvement (Figure 4). Research conducted by [85] evaluated the effects of different fertilizers and the application of *Carica papaya* aqueous extract on *Spodoptera frugiperda* (fall armyworm) larvae mortality and maize plant damage. The study demonstrated that VC-treated plants experienced reduced damage from *S. frugiperda* larvae compared to chemical fertilizers [85]. The VC and VCT application on corn enhanced plant growth, nutrient accumulation, and improved resistance to fall armyworm infestation [41].

Additionally, the study by [85] found that the aqueous extract of *C. papaya* seeds effectively inhibited larval damage, particularly when combined with ammonium sulfate, further highlighting the potential of VC in reducing pest damage and minimizing water demand in maize crops.

Another study by [86] focused on compost tea technology and its impact on plant diseases and growth promotion. The researchers found that aerated compost tea, containing beneficial aerobic microbes and nutrients, showed promising results in suppressing plant diseases and promoting plant growth. Applying compost tea derived from organic compost sources such as rice straw, VC, and Hinoki cypress bark compost enhanced shoot and root growth and increased crop yield. These findings suggest that compost tea can be a valuable tool for promoting plant growth in organic farming practices [86].

Moreover, adding VC to soil offers several benefits, including increased soil organic matter content, improved water-holding capacity, and enhanced pore space within the soil. These improvements in soil quality positively impact seed germination, plant growth, and overall crop yield. Furthermore, VC possesses pest-repelling properties, further contributing to plant protection and health [8,24,42].

6. Vermicompost Application in the Remediation of Soils

6.1. Removal of Heavy Metals

VC has been recognized as an effective organic fertilizer for reducing the accumulation of cadmium (Cd) and arsenic (As) in crops and soil. The study by [87] found that adding VC significantly reduced the $CaCl_2$-extractable Cd in the soil through Cd adsorption onto VC (Figure 5) and increased soil pH. The effectiveness of organic amendments, including VC, in reducing Cd accumulation depends on factors such as plant species, type and dosage of organic materials, and modifications in the physicochemical and biological characteristics of the rhizosphere. Organic amendments, including VC, have also shown promise in reducing As bioavailability in soils through the chelation of organo-As compounds, thus lowering As accumulation in plants [32]. The complexation of As with humic acid and binding mechanisms involving cation bridges contribute to As immobilization. Machine learning algorithms, particularly random forest (RF), have been used to predict As concentrations in rice grains, considering soil parameters such as soil As, pH, organic carbon (OC), and soil phosphorus (P) concentration [32].

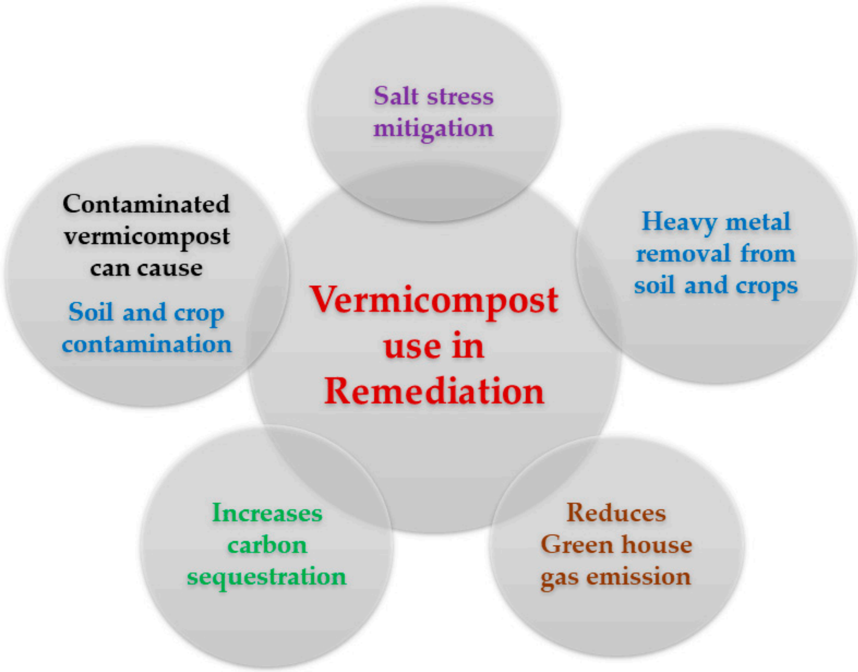

Figure 5. Summary of the use of VC in remediation.

Various studies have explored the effectiveness of VC, biochar, and humic substances in mitigating Cd accumulation in plants [88]. These natural materials have demonstrated the potential to retain Cd in soils, with VC -derived humic substances exhibiting the highest retention capacity for Cd^{2+}. The interaction between these materials and roots, along with acid exudation and rhizosphere acidification, may influence the release of weakly or superficially retained Cd^{2+}. The assimilation of Cd^{2+} in plants grown on different substrate materials has varying toxicity levels and impacts plant growth. VC and VC-derived humic substances show less inhibition of root and shoot growth than biochar and humin.

Furthermore, the co-application of VC and selenium (Se) has further reduced Cd concentrations in rice tissues compared to treatments with single organic amendments [56]. This suggests the potential of combined approaches to enhance the remediation of Cd contamination in crops.

6.2. Heavy Metal Accumulation in Earthworms during Vermicomposting

Using chemical fertilizers and pesticides in agriculture has resulted in soil degradation and environmental contamination with heavy metals such as Cd, Pb, and As [89]. These heavy metals can originate from natural sources and human activities, including industrial processes and waste disposal, which has led to heavy metal accumulation in the tissues of earthworms such as *Eisenia fetida*. However, VC, produced through vermicomposting, has been shown to reduce toxic metal levels and enhance soil fertility.

A study conducted on *Eisenia fetida* examined the concentration of Co, Cr, and Pb in different combinations of animal dung used in the initial feed mixture and the resulting VC. The results revealed that Co levels decreased the most when the soil was combined with cow dung VC inoculated with *Eisenia fetida*. The concentration of Cr was significantly increased in the earthworm body when the soil was combined with horse dung VC. On the other hand, Pb levels showed the maximum decrease when the soil was mixed with cow dung VC inoculated with *Eisenia fetida*. This indicates that *Eisenia fetida* contributes to the accumulation of heavy metals from various combinations of soil and VC during vermicomposting [89].

Eisenia fetida, through its feeding and microbial activity during vermicomposting, has shown effectiveness in reducing cobalt levels in different waste materials. Vermicomposting can be a suitable metal remediation technology, particularly in urban sludges. Buffalo dung is a good feed material for earthworms, with a higher accumulation of Co in the gizzard compared to the posterior region of the intestine. However, concerns arise when VC derived from municipal solid waste (MSW) containing heavy metals is applied to soil, as the earthworms can absorb these metals and potentially affect crop yield, long-term soil quality, and human health. Despite these concerns, inoculating *Eisenia fetida* in crop fields can help decompose various wastes and improve soil conditions. Therefore, vermibiotechnology offers a valuable approach to managing heavy metals in soil and waste materials, safeguarding human health and the environment [89].

6.3. Heavy Metal Contamination from Vermicompost Application

The application of VC can introduce heavy metal contamination into soil and crops (Figure 5), mainly when sourced from feedstock materials such as municipal solid waste, sewage sludge, and manures [90]. This contamination poses risks to soil organisms, plants, and potentially human or animal health, depending on the concentrations of heavy metals involved.

A recent study by [30] investigated the effects of VC contaminated with heavy metals (Cd, Cr, Cu, and Zn) on mudflat soil and barley crops. The study revealed increased concentrations of these heavy metals in the soil and crops following VC application. However, it is essential to note that the concentrations remained within permissible limits set by the National Environmental Quality Standard for Soils China, indicating no immediate risk to the environment or human health. Nevertheless, using domestic sludge as the VC source limited the earthworms' capacity to fully remediate heavy metals, resulting in their persistence within the VC. It is crucial to consider that different VC sources can yield varying levels of heavy metal contamination. In this case, the high concentrations introduced outweighed the potential benefits of VC application in mudflat soils.

While most VC research has focused on soil micro- and macronutrients, micronutrient responses and their transfer to crops have received less attention. A study by [90] investigating the accumulation of micronutrients in soil and their uptake by rice plants after long-term VC application revealed an enhanced uptake of trace elements. However, the increase in uptake did not consistently occur with extended application periods, possibly due to variations in soil properties such as acidity and organic carbon. Long-term fertilization practices can modify soil characteristics, including pH, organic matter, and nutrient levels, subsequently influencing the behavior of micronutrients in soil and crops [90].

Despite the potential heavy metal contamination risks, VC produced through the digestion of sewage sludge by earthworms has been found to have beneficial effects on soil fertility and nutrient availability in mudflat salt-affected soils [30]. Applying VC improved the soil's physical and chemical properties, including increased bulk density, pH, organic matter, and organic carbon, while decreasing electrical conductivity (EC) [30]. Higher rates of VC application also increased nutrient content, such as total nitrogen, alkaline nitrogen, total phosphorus, and available phosphorus in the soil [30]. Therefore, applying VC contaminated with heavy metals can affect soil and crop health. To minimize heavy metal contamination, carefully selecting high-quality VC sources becomes crucial, considering the variations in contamination levels among different sources. Continuous research and monitoring are necessary to develop effective risk mitigation strategies and ensure agricultural practices' sustainability in the face of potential heavy metal contamination from VC applications.

6.4. Mitigating Salt Stress with Vermicompost

In addition to improving soil properties, VC application promoted the growth of barley plants in mudflat environments, resulting in increased plant height, total biomass yield, and grain yield [30]. This positive effect can be attributed to VC's rich organic matter and organic colloid content, which form a good soil structure with increased porosity and decreased bulk density. These soil conditions reduce capillary tension and limit the upward movement of water and salt, thereby inhibiting soil resalinization. Furthermore, the acidity of VC and the production of small-molecule organic acids during decomposition contribute to the decrease in electrical conductivity observed after its application [30]

Research conducted by [91] demonstrated that VC and water treatment residuals (WTR) positively affect saline-sodic soils and wheat yield. Adding VC and WTR improved soil structure, water retention, and nutrient uptake, ultimately enhancing crop productivity. Similarly, ref. [92] found that VC, combined with WTR, effectively reduced soil salinity (Figure 5) and sodicity while enhancing soil physical properties and nutrient availability. Although not directly addressing pest management, reducing soil salinity and improving soil conditions through VC and WTR applications indirectly benefit pest control in cereal crops. Another study by [93] assessed the effectiveness of VC and sorghum water extract [94] in mitigating salt stress in maize seedlings. The combined application of VC and SWE alleviated the adverse effects of salt stress, improving plant growth, photosynthetic efficiency, and nutrient uptake in salt-affected soils.

6.5. Impact of Vermicompost on Greenhouse Gas Emissions and Carbon Sequestration

Adopting suitable crop patterns can help reduce greenhouse gas (GHG) emissions from fields [95]. In rice cultivation, VC has shown promising results in reducing GHG emissions (Figure 5) and increasing grain yield. The study by [11] found that the VC-IPNSF (integrated plant nutrient system fertilization) treatment in a triple rice cropping system reduced CH_4 emissions by approximately 14% compared to the cow dung-IPNSF treatment. The VC-IPNSF treatment also led to a 5–13% increase in grain yield and significant reductions in CH_4, CO_2, and N_2O emission factors. GHG intensity was reduced by approximately 16–24%, and the global warming potential decreased by 13–17% with VC-IPNSF compared to cow dung treatment. These findings suggest that VC is a better carbon source than cow dung and can potentially reduce GHG emissions while improving rice yield [11].

In a comparison between VC and synthetic fertilizers in rice cultivation, ref. [24] observed that VC-fertilized plots emitted more methane during the early and active vegetative stages but less methane during the panicle initiation and maturity stages than plots fertilized with synthetic fertilizers. Although the overall difference in methane flux was not statistically significant, the study highlighted that VC-fertilized rice cultivation might result in lower net GHG emissions due to the higher nitrous oxide emissions associated with synthetic fertilizers. This emphasizes the potential of VC to reduce GHG emissions in rice cultivation [24].

Organic amendments like biochar have also shown positive effects on reducing GHG emissions. The study by [59] compared the impacts of biochar and VC on various factors, including GHG emissions. Both amendments suppressed methane, nitrous oxide, and carbon dioxide emissions. VC application positively affected the soil organic carbon pool, crop yield, and nitrogen loss reduction. However, the effectiveness of biochar varies depending on feed materials, production processes, and soil types [59].

It is important to note that specific greenhouse gas emissions from rice cultivation patterns amended with VC are not widely available. Further research is needed to explore alternative organic substances and fine-tune the VC application rate to minimize GHG emissions while enhancing rice yield and soil health [11].

Regarding carbon sequestration, ref. [43] evaluated different treatments to assess their impact on organic carbon stock, total carbon stock, and organic carbon sequestration in grain crops. The treatment involving the application of poultry manure (PM) at a rate of 5 t ha^{-1} with a 50% recommended dose (RD) of chemical fertilizer yielded the highest values in these parameters. This treatment resulted in an organic carbon stock of 18.70 t ha^{-1}, 20.81 t ha^{-1}, and organic carbon sequestration of 1.75 t ha^{-1}. The second-highest values were observed in the VC treatment, at a rate of 5 t ha^{-1} with 50% RD of chemical fertilizer. These findings highlight the significant enhancement of organic carbon accumulation in the soil of cereal crops when PM or VC is incorporated at the specified rates. These practices have promising implications for mitigating carbon emissions and promoting sustainable agricultural systems. However, the effectiveness of these treatments may vary depending on factors such as soil type, crop species, and local conditions. Further research is needed to determine the optimal application strategies for different scenarios to maximize the benefits.

6.6. Mitigation Effects of Organic and Emerging Contaminants

The environmental consequences of contaminants such as personal-care and pharmaceutical products (PPCPs), microplastics (MPs), and emerging contaminants (ECs) have necessitated innovative strategies for their remediation and mitigation. Vermicomposting, harnessing the capabilities of earthworms, has emerged as a promising approach for achieving these objectives. A study by [96] investigated the bioremediation of organic contaminants, with a focus on polycyclic aromatic hydrocarbons (PAHs) and heavy-phase hydrocarbons found in automotive residual oil. Their study revealed that introducing earthworms significantly enhanced the removal of PAHs from contaminated soils. Similarly, ref. [97] employed vermiremediation by harnessing the power of earthworms to address PAH-contaminated soil, demonstrating the earthworms' ability to accelerate the transformation of PAHs into less toxic metabolites. The resulting nutrient-rich worm castings were suitable for use as a soil amendment. However, the response of earthworms to PAH toxicity varied depending on factors such as PAH type, concentration, exposure duration, and earthworm species involved.

The effectiveness of vermicompost application in mitigating hydrocarbon-contaminated soil is underscored by studies conducted by [98] and [99]. A study by [98] integrated vermicompost into contaminated soil, leading to a remarkable 34.4% degradation of hydrocarbons. This enhanced degradation was attributed to mechanisms such as adsorption and sequestration, wherein the vermicompost bound PAHs, limiting their availability for uptake by microorganisms or plants. In addition, ref. [99] targeted the remediation of soils contaminated with polychlorinated biphenyls (PCBs) using biological sewage sludge and *Eisenia fetida* earthworms, effectively reducing highly chlorinated PCB contamination in soils.

Another study by [100] demonstrated a substantial reduction in PPCPs during vermicomposting of sewage sludge, attributed to the transformative influence of earthworms on the humification process. This transformation led to the generation of humic-like and fulvic-like substances known for their proficiency in binding organic and inorganic pollutants, further contributing to contaminant mitigation. Furthermore, ref. [101] compared the efficiency of vermifiltration, which employs earthworms, to conventional activated sludge methods in removing PPCPs from hospital effluent. The study highlighted the significant role played by earthworms in biodegrading organic compounds, heavy metals, and solids in sewage. Vermifiltration proved nearly as efficient as activated sludge in removing PPCPs. Also, ref. [102] explored the interaction between earthworms and PPCPs and found that their physicochemical properties and soil characteristics influenced the uptake of these compounds.

Moreover, ref. [103] investigated the mineralization of ciprofloxacin in soils and demonstrated that adding earthworms could enhance mineralization up to eightfold when introduced into the soil. In another context, ref. [104] employed vermicompost to create an environment conducive to the proliferation of fungi capable of degrading 3,4-dichloroaniline (DCA) in winery wastes. These fungi, such as *Aspergillus niger* and two *Fusarium sp.* strains, indirectly facilitated the growth of earthworms and offered an alternative for bioremediation techniques focused on DCA degradation and environmental impact reduction. Furthermore, ref. [105] introduced vermifiltration as a method where earthworms break down organic matter and remove ECs from wastewater. Earthworms played a crucial role in enhancing aeration and water flow within the system, effectively mitigating ECs through physical and biological processes, including adsorption, biodegradation, and bioaccumulation. Therefore, VC application offers valuable solutions to address the environmental challenges posed by these contaminants, ultimately contributing to cleaner and healthier ecosystems.

7. Economic Assessment of Vermicompost in Grain Crop Production

Various studies have examined the economic viability of VC application in grain crop production (Table 6), providing valuable insights. The study by [33] found that while the cost of VC-based treatments was higher than that of chemical fertilizers, combining microalgae and chemical fertilizer resulted in the most cost-effective option with the lowest price per kilogram of rice grain and the highest yield. Similarly, ref. [34] reported that VC fertilization led to higher gross return, net return, and yield than control, emphasizing the economic benefits and lower costs associated with VC application.

Table 6. Economic assessment of vermicompost applications.

Treatment	Profitability (Currency)	Reference
Highest cost of fertilizer input for vermicompost. Lowest yield in vermicompost-only treatments.	USD 0.003896 per plant	[33]
Cheapest option: is vermicompost-microalgae-chemical fertilizer.	USD 0.00534 per kg rice grain	[33]
25% N + 75% N through vermicompost + 100% P + 100% K through inorganic manures.	INR 63,544 (net return)	[34]
75% N + 25% N through vermicompost + $ZnSO_4$ (25 Kg/ha) + 100% PK through inorganic fertilizer + microbial consortium. Highest benefit–cost ratio	3.18	[34]
Highest net returns with RDF + vermicompost at 5.0 t/ha	INR 31,056	[40]
Lower net returns associated with 80% fly ash + 20% vermicompost + 20% RDF.	INR 1406	[40]
Highest benefit–cost ratio in 100% vermicompost + 100% RDF.	1.36	[40]
The benefit–cost ratio is higher in inorganically fertilized plots. Vermicompost showed lower values compared to biochar for both crops.	Higher B: C for inorganic fertilizer	[59]
Combined application of NPK at half RDF and VC sustained higher wheat yield than organic or chemical fertilization. The cost of cultivation included various inputs. Better net return in the long run.	Higher wheat yield	[50]

Table 6. *Cont.*

Treatment	Profitability (Currency)	Reference
Maximum B:C (benefit–cost) ratio for 100% RDN through FYM+ BF	2.46	[48]
B:C ratio of 50% RDN through FYM + 50% RDN through VC + BF	2.41	[48]
100% N through FYM + GM + BF + VC + Zn.	Highest gross and net returns	[65]
Higher B:C ratio with 75% RDN + 25% VC	1.46	[65]
B:C ratio of 100% RDN	1.41	
Net returns influenced by vermicompost doses in pearl millet cultivation. Higher doses increased cost with minimal return. The highest net return was observed with 100% RDF.	INR 13,794 per ha	[61]
The highest net return was obtained when vermicompost was applied at 2 tonnes/ha.	INR 9407/ha	[61]
NPK (75% of full dose) + vermicompost at 2.5 t ha^{-1} + PSB at 7.5 kg ha^{-1} + Azotobacter at 7.5 kg ha^{-1}	Highest B:C ratio	[46]

Regarding net returns, ref. [40] observed that the combined application of VC and recommended dose fertilizer (RDF) resulted in higher net returns than other treatments. The study by [58] showed that VC showed higher economic benefits than biochar in a wheat and green gram crop rotation. Additionally, ref. [50] demonstrated that the combined application of NPK and VC sustained higher wheat yields, albeit with higher cultivation costs. However, the improved crop quality and potential premium prices led to higher net returns in the long run.

Several other studies have also highlighted the economic potential of VC in grain crop production. Refs. [48,66] found that applying VC, along with organic and inorganic sources of nutrition, resulted in higher gross and net returns in rice cultivation. Refs. [46,62,70,106] reported similar findings for various grain crops, highlighting the positive impact of VC on net returns and benefit–cost ratios.

It is important to note that the cost of cultivation may vary depending on the type and quantity of VC used. While applying VC increased total income, ref. [26] found that it did not significantly improve net income compared to using only inorganic fertilizers in mint-rice-wheat production. These studies demonstrate the economic viability of VC application in grain crop production, considering the increased yield and overall financial returns associated with its use.

8. Conclusions and Future Directions

8.1. Conclusions

Based on the comprehensive literature review, applying VC and its derived products in large-scale grain crop production offers several potential benefits. It is feasible and economically viable, particularly when combined with other organic sources and biofertilizers. VC has shown effectiveness in pest management, with promising results in controlling pests such as armyworms and aphids in cereal crops. The timing and form of VC application have also been identified as essential factors. Split applications of VC, with 75% applied before planting cereal crops and 25% applied during the growing season, have been suggested as a potential strategy. Additionally, using VC two to three weeks before planting allows for slow nutrient release, ensuring the availability of nutrients in the soil at the time of crop establishment. Furthermore, VC is an eco-friendly and cost-effective strategy not only for remediating but also for mitigating a broad spectrum of environmental contaminants, encompassing organic contaminants, PPCPs, MPs, and ECs.

However, further research is needed to explore the long-term effects of VC applications derived from different raw materials and their efficacy without inorganic fertilizers. Mechanistic investigations regarding the biocontrol potential of VC against aphids in wheat and other crops are also warranted. To enhance future research, the application of machine learning techniques can be considered to predict and determine the relationships between soil characteristics and VC application. Furthermore, conducting a cost–benefit analysis would provide valuable insights into VC utilization's economic feasibility and potential profitability in grain crop production. In conclusion, the findings of this literature review highlight the potential of VC and its derived products in pest management, nutrient enhancement, and sustainable grain crop production. Stakeholders can make informed decisions regarding adopting and optimizing VC application practices in agricultural systems by further exploring and addressing the identified research gaps.

8.2. Future Directions

Future studies and recommendations in the field of VC and its application in grain crop production are as follows:

1. Split Application of VC: Instead of applying VC at once at the beginning of the season, it may be beneficial to consider split applications. This approach involves dividing the VC application into two or more doses, such as applying 75% of the recommended dose initially and the remaining 25% at a later stage. This strategy can help optimize nutrient availability throughout the growing season and improve crop performance.
2. Timing of VC Application: Research should investigate the optimal timing of the VC application. Applying VC two to three weeks before planting allows for the slow release of nutrients, ensuring their availability in the soil when the crop is planted. Understanding the timing and rate of nutrient release from VC will contribute to effective nutrient management practices.
3. Exploration of VC Without Inorganic Fertilizers: While many studies have evaluated the combined use of VC and inorganic fertilizers, there is a need to assess the efficacy of VC as a standalone fertilizer. Investigating VC's nutrient content and release dynamics alone can provide insights into its potential as a sole nutrient source and reduce reliance on synthetic fertilizers.
4. Mechanistic Investigations of VC as Biocontrol: Further research should explore the mechanical aspects of VC in pest management. Specifically, investigating the use of VC as a biocontrol agent against aphids and other pests in wheat and other crops can provide valuable insights into its potential as a sustainable pest management strategy.
5. Cost–Benefit Analysis: Conducting a comprehensive cost–benefit analysis is essential to assess the economic viability of large-scale VC applications in grain crop production. Evaluating the costs associated with VC production, application, and the resulting benefits in crop yields, pest management, and soil health will help farmers make informed decisions about adopting this practice.
6. Long-Term Effects of VC: While VC has shown promise in sustaining rice production, it is essential to investigate the long-term effects of applying VC derived from different plant and animal residues. Long-term studies can provide insights into the impact of VC on soil fertility, crop productivity, and environmental sustainability.
7. Integration of Machine Learning: Future research can explore the application of machine learning techniques to predict and determine the relationships between soil properties and the effectiveness of VC. Machine learning algorithms can analyze large datasets and provide valuable insights into the interactions between soil characteristics, crop growth, and pest management.
8. Contaminant-Specific Strategies: Future studies can delve deeper into the optimization of vermicomposting processes for specific contaminants, such as emerging pharmaceuticals or novel pollutants. Tailoring the techniques to address the unique challenges posed by these contaminants can improve efficiency and effectiveness.
9. Field Studies and Real-World Applications: Many studies are conducted in controlled laboratory settings. Future research should focus on implementing vermicomposting in real-world, field-scale applications to evaluate its performance and scalability. This could involve pilot projects in contaminated sites to assess practicality and challenges.

By addressing these recommendations, future research can enhance our understanding of VC application in grain crop production and contribute to developing sustainable and economically viable agricultural practices.

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