E-ISSN: 2618-0618
P-ISSN: 2618-060X
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www.agronomyjournals.com
2024; 7(8): 680-683
Received: 05-06-2024
Accepted: 12-07-2024

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Advancements in soil health and disease management through organic amendments

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DOI: https://doi.org/10.33545/2618060X.2024.v7.i8i.1400

Abstract
The pursuit of sustainable agriculture has heightened interest in using organic amendments to improve soil health and manage plant diseases. This review examines recent developments in organic amendments such as compost, biochar, and green manure. Advances in composting methods, including aerated and vermicomposting, have enhanced nutrient release and pathogen suppression, leading to healthier soil microbial communities and reduced disease incidence. Biochar, produced *via* optimized pyrolysis, improves soil structure and nutrient retention while supporting beneficial microorganisms and toxin adsorption. Green manure crops, with improved breeding and management, boost soil nitrogen and structure, outcompete pathogens, and enhance soil conditions. Practical applications are becoming more sophisticated, with better soil testing and amendment formulation allowing for tailored solutions. Future research will likely focus on optimizing these amendments, understanding their long-term impacts, and integrating them with other sustainable practices. This review underscores the potential of organic amendments to enhance soil health, crop resilience, and overall agricultural sustainability.

Keywords: Advancements, overall agricultural sustainability, enhance soil health, crop resilience

Introduction

Soil health is fundamental to sustainable agriculture, impacting crop productivity, environmental quality, and resilience against plant diseases. Traditional agricultural practices, heavily reliant on synthetic fertilizers and pesticides, have led to soil degradation, reduced biodiversity, and increased resistance of pathogens to chemical treatments (Lal, 2021) [14]. Consequently, there is a growing emphasis on organic amendments as a means to restore soil health and manage plant diseases more sustainably. Organic amendments, derived from natural sources such as compost, manure, biochar, and green manure, play a crucial role in enhancing soil properties and promoting beneficial microbial activity. Composting technology has seen significant advancements, including the development of aerated and vermicomposting methods that produce compost with improved nutrient profiles and pathogen suppression capabilities. These advancements contribute to enhanced soil microbial diversity and nutrient availability, which are critical for maintaining soil fertility and health (Pankhurst *et al.*, 2023) [18]. The Biochar, another innovative organic amendment, is produced through pyrolysis of organic materials. Recent advancements in pyrolysis technology have optimized biochar properties for different soil types, enhancing its effectiveness in improving soil structure, water retention, and nutrient availability. Biochar has also been shown to suppress soil-borne pathogens by adsorbing toxins and enhancing beneficial microbial activity.

The Green manure, consisting of crops grown specifically to be incorporated into the soil, has also evolved with advancements in crop breeding and management. These developments have led to green manures with enhanced nutrient content and disease-suppressive properties. Incorporating green manures into soil improves organic matter content, soil structure, and microbial health, while also reducing pathogen loads and enhancing crop resilience (Sullivan *et al.*, 2023) [23]. Recent research highlights the potential of these organic amendments to address the limitations of conventional methods and promote sustainable agricultural practices.

By improving soil health and managing plant diseases through organic means, farmers can achieve more resilient agricultural systems that support environmental sustainability and crop productivity (Smith *et al.,* 2023) [21].

Advancements in composting technologies

Aerated composting involves the active introduction of air into the compost pile to accelerate decomposition and enhance aerobic microbial activity. Recent innovations in aerated composting systems, such as in-vessel and turned windrow systems, have improved the efficiency of compost production by optimizing airflow and temperature control. These advancements result in compost with higher nutrient content and reduced pathogen levels (Abbasi *et al.,* 2002; Brockett *et al.,* 2023) [1, 7]. Vermicomposting utilizes earthworms to decompose organic matter, resulting in a high-quality compost known as vermicompost. Advances in vermicomposting technologies, including improved worm species and management practices, have enhanced the nutrient profile and disease-suppressive properties of vermicompost. Vermicompost has been shown to contain higher levels of beneficial microorganisms and organic matter compared to traditional compost (Sinha *et al*., 2023) [20]. Recent research has focused on improving the consistency and quality of compost products through standardized composting processes and quality control measures. High-quality composts are characterized by stable organic matter, balanced nutrient levels, and low concentrations of contaminants. Studies have demonstrated that high-quality compost contributes to better soil health and more effective disease management (Kumar *et al.,* 2024) [12].

Impact on Soil Health

Soil Structure and Water Retention, Compost enhances soil structure by increasing aggregate formation and improving soil porosity. This leads to better water infiltration, reduced erosion, and enhanced water-holding capacity. Recent studies highlight the significant improvements in soil physical properties and moisture retention resulting from compost application (Abbasi *et al*., 2007; Pankhurst *et al.,* 2023) [18].

The compost enriches soil with essential nutrients, including nitrogen, phosphorus, and potassium. The slow-release nature of composted nutrients ensures long-term availability to plants. Research has shown that compost application can reduce the need for synthetic fertilizers and improve nutrient uptake efficiency (Luna *et al*., 2023) [16]. Compost boosts soil microbial diversity and activity, fostering a healthy soil microbiome. This enhanced microbial community supports nutrient cycling, organic matter decomposition, and disease suppression. Recent studies have demonstrated that compost applications increase the abundance of beneficial microbes and improve soil biological health (Zhang *et al*., 2024) [26].

Physicochemical Soil Properties

Several physicochemical parameters of the soil, including soil pH, nitrogen content, carbon and organic carbon content, as well as various cations and trace elements, have frequently been associated with disease suppression. Numerous studies have aimed to elucidate the role of these physicochemical soil properties in specific experimental contexts. For instance, Tenuta and Lazarovits (2002) [24] demonstrated that the accumulation of ammonia and nitrous acid, released from nitrogenous amendments like meat and bone meal, effectively suppresses the soil-borne pathogen *Verticillium dahliae*. Similarly, Heyman *et al.* (2013) [11] found that the concentration of calcium in the soil was negatively correlated with the incidence of *Aphanomyces* root rot in peas. Their greenhouse bioassays revealed that disease severity was directly related to the levels of water-soluble calcium in the soil, while soil sterilization did not consistently influence this relationship. Furthermore, Bonanomi *et al.* (2010) [5] observed that, in general, the pH of amendments was not statistically correlated with disease suppression, except in the case of *Fusarium* species. Supporting this, Borrero *et al.* (2004) [6] reported the beneficial effects of high soil pH in reducing *Fusarium* wilt in tomatoes. However, even in this study, the sterilization of the amendments led to an increase in disease incidence, suggesting that the biological activity within the soil plays a critical role in disease suppression.

Despite these findings, there is no universal rule that links physicochemical parameters with disease suppression. Both positive and negative correlations with disease incidence have been observed, along with many instances where no correlation was found. Overall, physicochemical variables have been statistically shown to be less reliable predictors of the suppressive potential of organic amendments compared to enzymatic and microbiological factors. The most plausible hypothesis is that disease suppression generally has a biological basis, with physicochemical parameters potentially influencing the growth and activity of soil microbiota, including pathogens, thereby modulating the effectiveness of disease suppression (Abiven *et al.,* 2009; Acharya *et al.,* 2012) [3, 4].

Mechanisms of disease management

Pathogen Suppression Through Biological Control

Compost enhances soil health by promoting beneficial microorganisms that compete with, prey on, or inhibit plant pathogens. The introduction of diverse microbial communities through compost can outcompete pathogens for resources and space, thus reducing pathogen populations. Key groups involved include bacteria, fungi, and protozoa that are known to suppress diseases such as Fusarium wilt and *Rhizoctonia* root rot (Chen *et al*., 2023; Zhang *et al.,* 2024) [15, 26]. Recent research has demonstrated that high-quality composts contain elevated levels of beneficial microorganisms and microbial enzymes that actively suppress pathogen growth. For instance, composts enriched with *Trichoderma* species have been shown to enhance disease suppression by producing antifungal compounds and promoting plant growth (Sarma *et al.,* 2023) [19].

Improvement of Soil Conditions

Compost improves soil conditions that are less favorable to pathogen development. By enhancing soil structure, water retention, and aeration, compost creates an environment that is less conducive to pathogen proliferation. Improved soil conditions also support healthier plant roots, which are more resistant to pathogen attacks. Recent studies have shown that compost applications can alter soil pH and moisture levels, reducing conditions favourable to pathogens like *Phytophthora* spp. and *Pythium* spp. (Luna *et al.,* 2023) [16]. A study by Liu *et al.* (2023) [27] demonstrated that compost applications led to a significant reduction in soil-borne pathogens in tomato and pepper fields by improving soil drainage and aeration, which are critical factors in controlling root diseases.

Enhanced Plant Resistance

Compost can enhance plant resistance to diseases by promoting overall plant health and vigor. Plants grown in compost-amended soils tend to have stronger root systems, better nutrient uptake, and improved physiological resilience, all of which contribute to increased resistance to disease. Research has shown that compost application can induce systemic resistance in plants, enhancing their ability to resist various pathogens (Smith *et al.*, 2023) [21]. For example, a recent study by Zhang *et al.* (2024) [26] found that compost-treated plants exhibited increased expression of defense-related genes and higher levels of resistance to bacterial wilt and blight.

A field study conducted by Kumar *et al*. (2024) [12] investigated the effectiveness of compost in managing Fusarium wilt in tomato crops. The study found that compost applications reduced disease incidence by up to 50% compared to untreated controls. The reduction in disease was attributed to the suppression of pathogen populations and improved soil health resulting from compost application. Research by Chen *et al*. (2023) [15] focused on the effects of compost on *Rhizoctonia* root rot in bean crops. The study demonstrated that compost applications led to significant reductions in disease severity and improved plant growth. The authors attributed these results to the increased microbial diversity and production of antimicrobial compounds in compost. A recent study by Williams *et al.* (2024) [25] explored the role of compost in managing *Phytophthora* blight in pepper crops. The study found that compost amendments reduced disease incidence and improved plant health. The authors noted that compost's ability to improve soil drainage and its antimicrobial properties were key factors in disease suppression.

Recent studies have expanded our understanding of compost's role in soil health and disease management. For example, a study by Kumar *et al.* (2024) [12] demonstrated that compost application improved soil fertility and reduced disease incidence in tomato crops, highlighting the practical benefits of compost in commercial agriculture. Another study by Zhang *et al.* (2024) [26] explored the impact of compost on soil-borne diseases in vegetable crops, showing significant reductions in disease severity and increased crop yields.

Hydrolytic activities, particularly chitinase production, are crucial in soil suppressiveness and the biocontrol of soil-borne pathogens. Chitin, a key component of fungal cell walls, is targeted by chitinolytic microorganisms, making them effective in controlling fungal diseases. Recent studies, including those by Chae *et al*. (2006) [8] and more recent work by Zhang *et al.* (2023) [27], highlight the effectiveness of chitinolytic amendments. For instance, a chitin-compost composed of 30% crab shell was shown to reduce late blight symptoms caused by *Phytophthora capsici* in peppers. This compost increased the presence of chitinase-producing bacteria and boosted chitinase and β-1,3-glucanase activities in the rhizosphere compared to a control compost. Additionally, Zhang *et al.* (2023) [27] found that similar chitin-based amendments enhanced the suppression of root pathogens in tomato crops, further demonstrating the role of chitinolytic composts in disease management. Instead of focusing on isolating single biocontrol strains, this approach emphasizes designing effective amendments like chitinolytic composts for improved disease suppression.

Future Aspect

The future of soil health and disease management through organic amendments is promising, with advancements in precision agriculture enabling tailored applications that optimize benefits and reduce waste. Research is likely to focus on developing microbial consortia within amendments to target specific pathogens and enhance disease control. Biotechnology may lead to next-generation amendments with improved pathogen resistance and climate resilience. Sustainability efforts will drive the use of waste products in producing high-quality amendments, contributing to soil health and climate change mitigation. The integration with agroecological practices and supportive policies will further promote sustainable farming, leading to more effective strategies for managing soil health and plant diseases.

Conclusion

In conclusion, the advancements in soil health and disease management through organic amendments represent a vital shift towards more sustainable and resilient agricultural practices. By harnessing the potential of precision agriculture, biotechnology, and microbial consortia, we can develop highly effective solutions that not only enhance soil fertility but also suppress harmful pathogens. The integration of these innovations with agroecological practices and the promotion of circular economy principles will ensure that farming systems are better equipped to face future challenges, including climate change. As policies and incentives increasingly support these approaches, the widespread adoption of organic amendments will play a crucial role in securing global food production while preserving environmental health for future generations.

Acknowledgments

We are grateful to S. S. Kansasa, NMCA, Navsari Agricultural University, Navsari, Gujarat-396450, for their invaluable suggestion to compose a review paper on this subject.

Data Availability

There is not hidden data, all data are presented in this manuscript.

Ethical Statement

This study did not involve human or animal subjects; therefore, informed consent is not applicable.

Conflict of Interest

The authors declare that they have no knows competing financial interests or personal relationship that could have approved to influence the work reported in this paper.

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