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REVIEW

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Biochar and minerals impact on plant defense mechanism

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ABSTRACT

Regarding plant defense management (PDM), synthetic chemicals for pathogens (SCP) promote incredible plant growth. Conversely, SCP affects the plant by accumulating toxic chemicals, posing serious health risks and malnutrition. SCP has negative side effects that start during production because they produce harmful byproducts contributing to environmental pollution, and their application induces negative effects on soil physiochemical and biological properties. Biochar and mineral nutrients (BMN) impart positive impacts on PDM. BMN contributes to PDM by enhancing plant's metabolic and enzymatic activities (MEA). PDM includes the management of the entire plant's defense, including root and foliar disease management. The availability of certain nutrients leads to PDM. BMN follows an integrated pathogen and pest management system (IPPM) by providing essential nutrients to plant's MEA. Using BMN-containing soil amendments provides a promising strategy that is consistently accompanied by the circular economy's emphasis on zero waste and works as a critical part of IPPM. Therefore, it is essential to conduct a toxicological risk assessment and research aiming to fully understand the impacts of biochar and the best methods for using it for PDM.

KEYWORDS

Plant defense management; Synthetic chemicals; Biochar; Mineral nutrients; Integrated pathogen and pest management; Soil management

ARTICLE HISTORY

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Introduction

The utilization of synthetic chemicals for pests and pathogens (SCPP) has been recognized as a vital technological innovation in agriculture [1]. SCPP was introduced to control disease rates and improve yield, but excessive use of it shows an adverse effect on plant immunity, advantageous organisms, and human health (Figure 1). Moreover, instead of controlling the pathogen's attack, SCPP leads to a reduction of plant immunity [2]. Living bodies directly or indirectly face the effects of chemicals, i.e., pathogens in the form of contaminated air, water, and food, applied for agricultural activities. Toxicological risk assessment (TRA), research reports, and epidemiologic findings prove harmful effects on living bodies due to agricultural pathogens application [3].

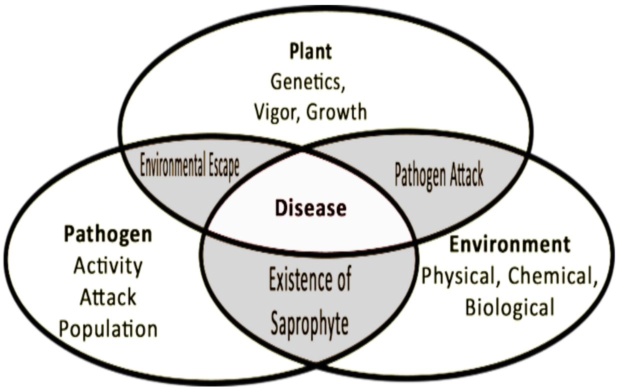

Figure 1. The interdependent elements controlled in the agricultural ecosystem influence the severity of diseases, crop productivity, and nutritional status [4].

Plant diseases are key influencing factors in yield reduction. There is a 20 to 30 percent yield loss recorded per annum, which is probably due to inadequate management, lack of knowledge, and the reduction of nature, i.e., biological resources [5]. But the cereal food demand is also increasing with the gradually increasing population shown in Figure 2 [6].

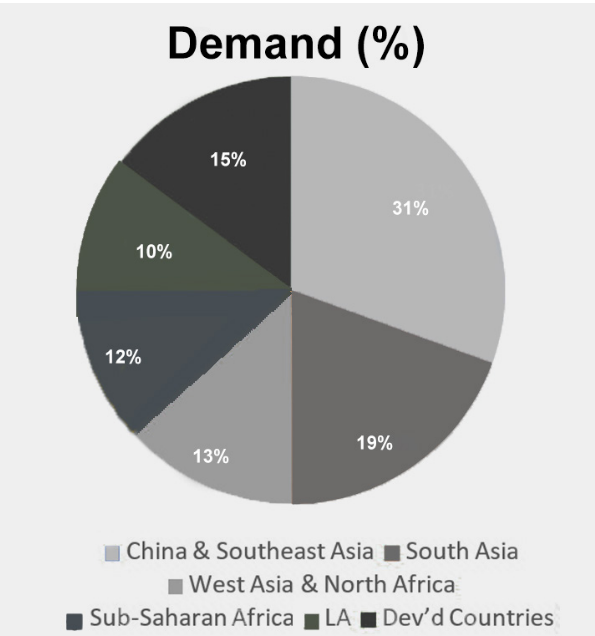

Figure 2. Increase in cereal product demand globally [8].

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Biotic or abiotic interruption disturbs normal plant development because of the vibrant activity of plant diseases [7]. Integrated pest and pathogen management system (IPPM) was introduced in the past to control the increasing pathogen attacks, but the chemical method was adopted, which is now more costly than yield rate and economic return; moreover, it is imparting negative effects on the entire ecosystem. [5].

Plant disease management (PDM) focuses on managing host plants to attain optimized yield rate, quality output, efficiency, and environmental and food safety. IPPM is a vital comprehensive method that focuses on a systematic perspective and depends upon a wide range of long-lasting sustainability solutions for pathogen and pest attacks. IPPM includes a wide range of plant protection approaches that provide measurements against pathogen attacks. Moreover, without negatively impacting the agroecosystem, the IPPM boosts healthy plant growth by promoting natural disease control tactics. IPPM follows measurements for biodiversity boost, natural resources conservation, and effective agricultural pollutant control [9].

Biochar contributes its vital role in the defense of foliar and root diseases in various plants [10]. Pyrolysis of carbon enriched compounds (CECs) under intensive temperature and oxygen-less conditions transforms CECs into solids, vapors, and liquids, from which the solid portion owns the fixed carbon (C) and various minerals, relatively known as biochar [11-13]. Forestry and agricultural residues, poultry and animal manure, and decomposed unicellular and multicellular organisms, i.e., flour and fauna are sources of biomass [14]. Biochar shows positive effects in response to fungal, bacterial, nematodes, oomycetes, and arthropod weeds and pest attacks on the plant so biochar not only improves soil physiochemical and biological properties but also shows useful antipathogen effects [10].

In reducing agricultural production, plant diseases play a major role and the use of toxic chemicals to control plant diseases is common in farmers without knowing that a balanced nutrition application can restrict disease to an effective range. Optimum application to plants not only regulates plant growth but also imparts a positive role in disease management. Nutrients can enhance plant disease resistance by synthesizing natural defense compounds and forming mechanical barriers that protect against pathogens [15]. By direct penetration or through natural spaces or physical injuries pathogens enter plant tissues. Plants need balanced hormone segregation to effectively control plant diseases. [16]. Additionally, balanced nutrient availability is necessary for plant metabolism and hormone segregation [17].

The objective of this study is to evaluate the long-term viability of applying BMN as a way to improve plant growth, their interaction with the PDM and how this affects sustainable farming. The research also aims to identify the most advantageous mineral nutrient-focused plant defense techniques that can successfully address the challenges encountered in achieving sustainable agriculture. By focusing on these goals, the study hopes to advance knowledge in the area and encourage the creation of more environmentally friendly agricultural methods. As nutrient-based plant diseases appear lethal for commercial-scale cultivation, an IPPM is essential to sustain the availability of nutrients *via* fertilizers or by changing the soil environment, which substantially impacts nutrient availability [18].

Role of Biochar in Reducing Disease Potential

Biochar application improves soil nutrients like nitrogen, phosphorus, and potassium [19]. Moreover, biochar plays a vital role in enzyme activities to promote the nitrogen and phosphorus cycle [20]. Biochar has a porous structure that provides suitable conditions for enhanced microbial activity, and microbes have beneficial effects on the enhanced nitrogen cycle [21,22]. Biochar shows effective bacterial, fungal, and other pathogenic control in various plants like tobacco, tomato, rice, and much more [23,24]. There is a description and various vital instances of biochar's role in plant defense control: bacterial pathogen *Ralstonia solanacearum* attacks on tomato and tobacco, biochar of peanut shell, wheat straw, pinewood, and rice straw are effective respectively by the mechanism of action of rhizosphere colonization, pathogen swarming motility reduction, actinomycetes, and improvement of various of soil physiochemical properties [24-26]. *Leveillula taurica* and *Botrytis cinerea* are fungus attacks on pepper and tomato treated by biochar of citrus wood by systemic-induced resistance [27]. *Rhizoctonia solani* fungi attacks on beans can be controlled by decomposed eucalyptus wood [27]. On tomatoes, a fungus pathogen Botrytis cinerea is controlled by decomposed eucalyptus wood chips by enhancing the metabolic process in the rhizosphere microbiome [28].

Pythium ultimum is an oomycete that attacks lettuce, sweet pepper, coriander, geranium, and basil by enhancing root colonization and is controlled by the biochar of pine parent material [29]. *Meloidogyne graminicola* is a nematode attack on rice but pyrolysis of oak wood can act as defender against this pathogen attack by ethylene genes transcriptional enhancement and water accumulation [30]. Even the insect *Sogatella furcifera* attack on rice is controlled *via* the decomposition of deciduous trees (70%), dolomite (20%), and molasses (10%) by foliar accumulation of jasmonic acid (priming method) [31].

Role of Mineral Nutrients in Reducing Disease Potential

With crop stress and nutrient shortages and imbalances, the probability of problems of leaf and stem disease rise [32]. As the mineral nutrients show forthright involvement in plant defense so the first preference of plants against disease attack is always balanced nutrition. Naturally, nutrients are involved in plant protection *via* various activities. Nutrients affect plant immunity by positive involvement in its various physiochemical reactions, i.e., metabolism, enzyme activity, pH level fluctuations, uptake and utilization of other nutrients, or deposition of lignin [33]. Regarding the quality and quantity of yield, the dependency of the plant is always on abiotic and biotic factors. These environmental factors impart positive or negative impacts on the agronomical and chemical processes of plants [34].

Nitrogen

Nitrogen form, i.e., NH^{4+} and NO_3 impart positive impacts on plant defense [35]. In various metabolic and physiological processes of plants, the vital role of nitrogen has been studied [36]. Rice blast, powdery mildew, stem rot, downy mildew, and leaf rust diseases are a few instances of disease attacks controlled by nitrogen in plants [37]. On the other hand, agriculture has become more intensive to improve

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production, primarily with monocultures that depend greatly on higher chemical inputs, like synthetic fertilizers and pesticides [38].

Azospirillum is a bacterium that uses and fixes the nitrogen from the atmosphere and makes it available for plants [39]. Moreover, these plant growth-regulating bacteria (PGRB) play an essential role in plant growth and various mechanisms. *Azospirillum* helps in the synthesis of hormones like cytokinin, ethylene, gibberellin, salicylic acid, and abscisic acid. Majorly, it provides resistance against various abiotic and biotic stresses (ABS), like induced systemic acquired resistance (SAR), and systemic resistance (ISR) induced systemic tolerance (IST) [40]. Oxidative damages (ODs) are the results of ABS. ODs are the starting step/period for the pathogen attack [40,41]. These PGRB provides primary resistance against such kind of conditions and pathogen attacks [40,42].

Nitrogen limitation on *Pseudomonas syringae* (pv. Syringae) B728a revealed (after comprehensive analysis) the importance of pathogenicity-associated traits like polyketide metabolism, swarming motility, gamma-aminobutyric acid metabolism, and type 3 secretion system [42]. Nitrogen stimulates the pathogen effector genes like avirulence, in *Magnaporthe oryzae* the hydrophobin MPG1 genes and the hypersensitive response and pathogenicity [43]. Also, the nitrogen involvement in plant defense-related enzymes studied, these enzymes help in resisting the plant against pathogen attack [44].

In tomatoes, early blight and gray mold are caused by *Alternaria solani* and *Botrytis cinerea*, respectively and are treated by nitrogen by its effect of reducing high severity [45,46]. High resistance against early blight caused by *Alternaria solani* was observed under the nitrogen effect in potatoes [46]. Balanced nitrogen supply reduces disease severity in rice the blast disease caused by *Magnaporthe grisea* [47]. In wheat, stripe rust caused by *Puccinia striiformis f. sp* is controlled as the nitrogen supply reduces the infection severity [48].

Phosphorus

Phosphorus is ranked as 2nd most vital mineral nutrient in plant growth [49]. Moreover, it is essential for pathogen defense in various plants [50]. Soil phosphorus enhances the symbiosis between plants and microbes like fungi, bacteria and oomycetes, nematodes, and insects. This mutualism imparts positive impacts on phosphate starvation responses regulators (PHR1, PHF1, NLA, mir399, MIR872), pi transporters (PHT4 and PHO1), and hormones (cytokinins and strigolactones) [51] and that is essential for plant immunity [49].

Phosphorus is an essential part of a regulated and consistent fertility system that can improve plant health and minimize the extent and frequency of certain crop diseases [32]. *Bacillus amyloliquefaciens* (GB03) is a bacterium that assists in the development of Arabidopsis when phosphorus levels are sufficient. On the other hand, when phosphorus levels are low, plants become sensitive to rising anthocyanin accumulation, lower photosynthesis, and higher cell death. [52]. Arabidopsis affected by *P. syringae* DC3000 is controllable by SA and SAG induction due to phosphorus [53]. According to a study, on the miR399f (rice) a pathogen *M. oryzae* could be affected by phosphorus [50].

Potassium

Potassium is an essential macronutrient that regulates various metabolic processes, enzyme activation in plants, nutrients, and essential element movement in plant tissues. In detail, potassium imparts a key role in the synthesis of starch, protein, and adenosine triphosphate, and the opening and closing of stomata [54]. As potassium is important in photosynthesis so its deficiency causes chlorosis because of redox oxygen species accumulation and also leads to a highly decreased level of photosynthesis [55]. Potassium utilization has not only beneficial effects on plant growth besides, but it also has sufficient effect against biotic and abiotic stresses [56].

The role of potassium in relation to drought-stressed plants is enhancing photosynthetic carbon dioxide fixation, transporting photosynthates, and inhibiting the exchange of photosynthetic electrons to oxygen with decreased capacity to produce reactive oxygen species (ROS). ROS synthesis is essential for growth depression and cellular function's defacement in stress circumstances [57]. Approximately 70% of diseases are caused by the fungus, 69% by bacterium, 41% by viral, and 33% of diseases caused by nematodes are resisted by the balanced availability of potassium in the plant (Figure 3) [58].

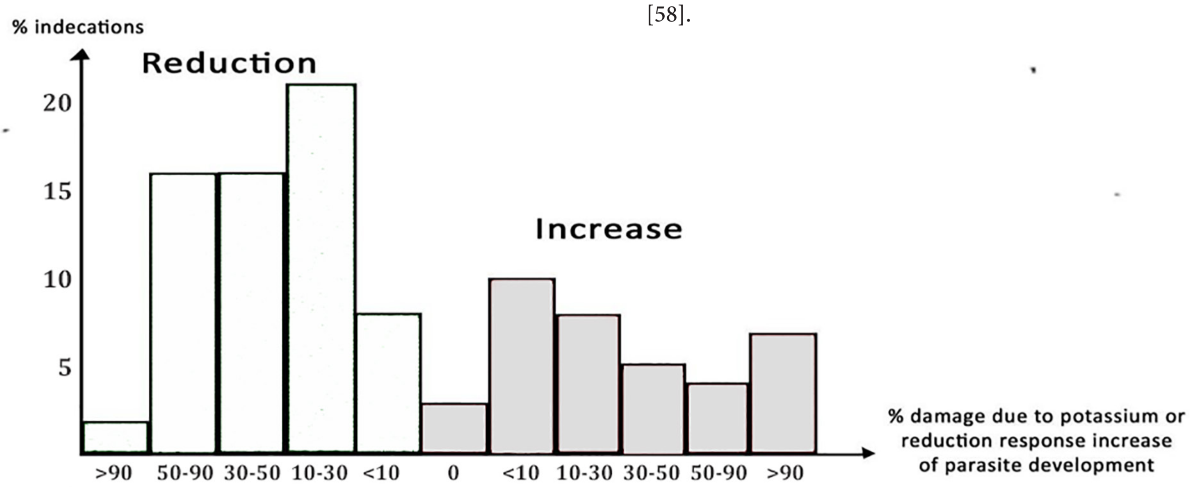

Figure 3. Reducing magnitude of pathogen attack due to potassium application [58].

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Calcium

Calcium acts as a physical barrier against plant diseases because it plays a key role in cell wall and cell membrane formation and support [59]. Its significance can be esteemed if it becomes deficient, can result in plant infectious diseases, and has a decreased element exogenous supply that can increase the chances of pathogen attack [60]. According to genetic studies, calcium has both positive and negative impacts on plant pathogen control [61]. A deficiency of calcium can lead to a fungal attack on plant tissue, xylem tissue invading, damaging cell walls, and its effects could be plant wilting [60]. Calcium concentration changes have biochemical and appropriate molecular responses [61].

Magnesium

Various comprehensive analytical studies concluded the magnesium effects in pathogen defense *via* magnesium comparison in diseased and healthy plant species, disease attack ratio in compressive and conductive soils, and pathogen growth rate in various varying concentrations of magnesium [62]. Magnesium helps to stimulate pectolytic enzymes *via* increased tissue resistance for degradation of a bacterial pathogen, soft rotting. Magnesium also creates balance with other mineral nutrients to overcome disease severity and its control [4]. On wheat, wet smut (fungus attack) is revokable via magnesium [63]. *Fusarium oxysporum* attack on tomatoes causes wilt to be decreased by magnesium [64]. Leaf spot on rice is due to pathogen attack of *Helminthosporium spp.* also revokable *via* magnesium application [65].

Sulphur

The positive effects of sulfur are against various harmful pathogen attacks and diseases like powdery mildews [66]. It also imparts a role in protein's disulfide bond-making and simultaneously in redox control and also in various enzyme activations [67]. *Via* glutathione and its derivatives of it, sulfur has positive management on oxidative damage [4]. Indicator biomolecules from sulfur contain amino acids (CAAs) cysteine have sufficient resistance against pathogens. *Phaeomoniella chlamydospora* and *Phaeoacremonium minimum* are pathogens that attack grapevines and are revokable by CAAs cysteine by a process of inhibition of mycelial growth and spore formation [68].

Micronutrients

Micronutrient deficiency is usually common in cropping systems, which affects plant growth and disease control [69]. In various processes like electron transfer, reaction regulations and metabolic activities, the involvement of micronutrients plays an essential role. However, micronutrients boost overall plant health [70]. Nutrients like zinc, iron, boron, manganese and copper are utilized by plants in less quantity but impart a vital role in plant growth as well as in plant defense systems [18]. In photosynthesis, antioxidative enzymes activation, and respiration, manganese is enrolled [71].

It has been demonstrated that particular micronutrients have a role in a plant's defense. For instance, a lack of zinc seems to be associated with a decreased phenolic compound formation that is crucial for plant defense against parasites and diseases [72]. Several physiological and biochemical procedures that support plant defense and health involve zinc. It is essential for triggering enzymatic processes, especially those connected to plant defense mechanisms. The production of defense-related substances, such as phytoalexins and antimicrobial peptides, which are necessary to fend off pathogen attacks, is enhanced by zinc [73]. Additionally, salicylic acid and jasmonic acid, two important mediators of the activation of defense responses in plants, are regulated by zinc [74]. According to studies, a zinc deficiency impairs a plant's ability to mount a successful defense against pathogens, increasing its susceptibility to illness. Therefore, maintaining proper zinc nutrition in plants and ensuring an adequate zinc supply in the soil is essential for strengthening the plant defense system [72].

The synthesis and metabolism of compounds related to defense, such as phenolic compounds, lignin, and flavonoids, depend on iron, a critical component of many enzymes [75]. These substances help strengthen the plant cell walls, increasing their resistance to being pierced by pathogens. ROS are involved in signaling pathways that initiate defense responses against pathogens, and iron is a critical component in their production [76]. Additionally, iron controls the levels of plant hormones such as salicylic acid and ethylene, which are crucial in triggering defense mechanisms. Lack of iron can make it more difficult for plants to activate their defense mechanisms and make them more susceptible to disease [77].

Many physiological and biochemical processes that support plant health and defense involve boron. The synthesis and stability of cell walls are influenced by boron, improving their structural integrity and function as a physical barrier to encroaching pathogens [78]. It encourages the activation of defense-related genes, which produce proteins involved in pathogenesis and antimicrobial compounds. Additionally, boron is necessary for the efficient operation of enzymes involved in the synthesis of lignin and the metabolism of phenolic compounds, both of which strengthen the plant's resistance to disease [79]. Calcium levels are controlled by boron, and calcium is essential for signal transduction during defensive reactions. Lack of boron impairs the plant's ability to launch its defenses and makes it more vulnerable to pathogens [80].

Manganese contributes an integral part in the synthesis and activation of enzymes that produce defense-related substances like phytoalexins and lignin, which fortify plant cell walls and stop pathogen growth [81]. Additionally, it aids in the activation of antioxidant enzymes like peroxidase and superoxide dismutase that aid in scavenging ROS created during pathogen attacks. It is necessary for photosystem II in chloroplasts to function properly, which contributes to energy production and the production of ROS that are involved in signaling pathways for the defense response. A lack of manganese makes a plant less able to activate its defense mechanisms, which increases its disease susceptibility [82].

For the enzymes involved in the synthesis of lignin, copper functions as a cofactor, strengthening cell walls and creating a physical barrier to prevent pathogen invasion. Additionally, it is essential for the activation of enzymes that produce compounds related to defense, such as phenolic compounds and phytoalexins with antimicrobial properties [83]. By taking part in the detoxification of ROS produced during pathogen attack, copper plays a role in the regulation of oxidative stress responses. Additionally, copper is necessary for the proper operation of several enzymes involved in signaling pathways,

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including those responsible for the metabolism of plant hormones and the induction of immune responses. [84,85].

Conclusions

This article concludes that both BMN are important for PDM. The results of the study show that BMN promotes plant growth and also increases resistance against biotic and abiotic stresses. BMN, including micronutrients and macronutrients, have significant beneficial effects on PDM. In particular, nitrogen, phosphorus, and potassium levels in the soil are raised by the application of biochar. This also increases microbial activity, which in turn encourages the nitrogen and phosphorus cycles. As a result, plant health and pathogen defense are enhanced. As a result of their positive effects on several physiological and biochemical processes, including metabolism, enzyme activity, pH level regulation, nutrient uptake, and lignin deposition, mineral nutrients also play a significant role in PDM.

A well-balanced application is essential for plant protection, and micronutrient deficiencies can have a negative effect on plant growth and disease prevention. The functions of micronutrients like zinc, iron, boron, manganese, and copper include electron transfer, reaction regulation, metabolic activities, photosynthesis, activation of antioxidative enzymes, and respiration. Overall, these results highlight the significance of managing BMN in sustainable agriculture by assuring IPPM to promote healthy plant growth and strengthen the PDM system.

In the future, recognizing the importance of BMN in agriculture will offer innovative pathways. Leveraging BMN will enhance crop yields, reduce disease reliance on chemicals, and promote organic farming for sustainability. BMN application can optimize soil health and provide precision agriculture options. This approach aligns with sustainability goals, enhancing food security, environmental resilience, and shaping the future of agriculture.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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