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A META-ANALYSIS OF BIOCHAR APPLICATION TO MANAGE PLANT DISEASES CAUSED BY BACTERIAL PATHOGENS

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Abstract

The current agricultural scenario faces diverse challenges, among which phytosanitary issues are crucial. Plant diseases are mostly treated with chemicals, which cause environmental pollution and pathogen resistance. In light of the UN Sustainable Development Goals (SDGs), the biochar alternative use to chemical inputs fits into at least six of the proposed goals (2, 3, 7, 13, 15, and 17), highlighting the 12th, which explains responsible consumption and production. Biochar is valuable for inducing systemic resistance in plants because it is a practical and frequently used resource for improving physical, chemical, and biological soil attributes. This review assessed the beneficial and potential effects of applying biochar to agricultural soils on bacterial pathogen management. Such application is a recent strategy; therefore, this research evaluated 20 studies that used biochar to manage plant diseases caused by pathogens inhabiting the soil in different systems. The effectiveness of biochar application in controlling plant diseases has been attributed to its alkaline pH, which contributes to the growth of beneficial microorganisms and increases nutrient availability, and its porous structure, which provides habitat and protection for soil microbiome development. Therefore, the combined effect of improvements on soil attributes through biochar application aids pathogen control. Biochar application helps manage plant diseases through different mechanisms, inducing plant resistance, increasing activities and abundance of beneficial microorganisms, and changing soil quality for nutrient availability and abiotic conditions.

Keywords: Disease control. Economic viability. Phytopathogens. Sustainability.

1. Introduction

Several diseases potentially caused by fungi, nematodes, or bacteria affect crops of high economic relevance. These diseases may considerably reduce production, even causing a complete crop loss and, consequently, financial damage to producers (Beillouin et al. 2019). The most used methods to manage bacterial diseases include resistant cultivars, crop rotation, solarization, and chemical control, such as fumigation (Wang et al. 2014). However, these measures are not always efficient and impact the environment significantly, contaminating the soil, water, and even air and increasing production costs (Ji-Hui et al. 2021).

Using tools that minimize the impacts on environmental and human health has been encouraged. The nations that make up the UN have adopted guidelines to meet the Sustainable Development Goals (SDGs) - activities established in the so-called Post-2015 Agenda. The Ten-year Plan of Programs on Sustainable Production and Consumption stands out among these goals, and studies have reported biochar as a sustainable alternative for suppressing diseases, effectively preventing diseases transmitted by soil microorganisms without chemical inputs (Li et al. 2020; Medeiros et al. 2021a). However, available information on biochar use for suppressing bacterial diseases in plants is still incipient due to the scarcity of studies (Zhang et al. 2016).

Biochar is a carbon-rich material with over 50% carbon (Lima et al. 2021). It consists of fine and porous grains and has been used to increase crop yields and reduce greenhouse gas emissions (CO2, CH4, and N2O). It also improves soil quality, reducing nutrient leaching and irrigation and fertilizer requirements and enhancing soil microbial health (Li et al. 2017; Martins Filho et al. 2021; Medeiros et al. 2021b). Biochar is obtained through the pyrolysis process by burning different biomasses (vegetable or animal), such as coffee husk and grounds (Lima et al. 2018), sugarcane bagasse and straw (Haghighatjou and Shirvani 2020), rice and corn straws (Torres et al. 2020; Zhang et al. 2021), and poultry litter (Sikder and Joardar 2019). These products are inexpensive and easy to obtain.

Biochar can modify the physical and chemical properties of the soil by increasing its pH, which can significantly alter bacterial diversity (Whitman et al. 2016). Currently, the response of bacterial communities to biochar application is among the most relevant issues in agronomic, environmental, and agricultural science (Liao et al. 2019). Under given conditions, biochar can stimulate the development of cultivated plants, suppress phytopathogens, and modify microorganisms in the rhizosphere (Kolton et al. 2017; Zheng et al. 2017). These effects are due to the action of several direct and indirect mechanisms. For instance, the sorption of allelopathic and phytotoxic compounds that may harm the plant, and the induction of plant resistance with high activity and abundance of beneficial microorganisms and low phytopathogens due to a fungitoxic effect, such as changing soil quality with increased nutrient availability and improved root growth environment, among others (Bonanomi et al. 2015; Semida et al. 2019; Medeiros et al. 2021a).

However, biochar has a limiting effect on soil microbial communities. Its impact on these communities can be affected by product quality regarding feedstock, pyrolysis, aging, and site characteristics of soil properties (such as texture, mineralogy, pH, and cation exchange capacity) and management (Imparato et al. 2016; Woolet and Whitman 2020).

Although the potential use of biochar has been reported (Li et al. 2020; Medeiros et al. 2021a), there are still gaps concerning the direct and indirect effects of the bioproduct on the management of diseases caused by phytopathogenic bacteria, requiring an in-depth study to deliver an alternative and safe tool to producers, aiming to reuse low-cost agro-industrial waste for managing diseases that may damage crops.

Considering the potential use of this tool, the current search and incentive for alternative technologies, and the existing gaps, the present study discussed the establishment of these bio-inputs against soil phytopathogens that, even though in diffusion, have exposed relevant data to elucidate the problem. This investigation summarizes the latest reported data (dissemination is still limited to the last six years) of microbiota effects under biochar application.

We hypothesized that biochar would be good for managing plant diseases caused by bacterial pathogens, mainly due to changes in soil properties and their interactions. This premise was supported by a meta-analysis, a valuable statistical technique to establish efficient conclusions about the effects of biochar treatment based on the data available in the literature (Li et al. 2019). This meta-analysis provides an overview and critical view of the impacts of biochar use on physical, chemical, and biological soil attributes and their influence on plant health. It also verifies whether such changes affect the management of diseases caused by phytopathogenic bacteria.

2. Material and Methods

Data collection

An extensive literature search was conducted to assess the efficiency of biochar as a management tool against plant diseases caused by bacterial pathogens. The keywords "biochar," "control," and "phytopathogens" were combined and used to search Google Scholar, Science Direct, and Elsevier search engines and select relevant studies for the meta-analysis. The selection was based on the following criteria: (I) original articles (study design); (II) publications between 2016 and 2021 (date of publication); (III) studies including biochar and an agricultural crop, regardless of plant type and species (sampling criterion); (IV) articles establishing the relationship between biochar type and plant disease and controls (relationship criterion); (V) publications in English (language criterion).

Using biochar for managing plant diseases caused by bacteria is a recent strategy; thus, 20 peer-reviewed studies met our particular criteria for this meta-analysis, of which seven were selected. Table 1 presents the distribution of studies across time, showing an increasing interest in biochar research with several articles published from 2016 to 2021.

Table 1. List of studies selected for the meta-analysis that used biochar to manage plant diseases caused by bacterial pathogens.

Study Title	Year of publication	Reference
Biochar significantly alters rhizobacterial communities and reduces Cd concentration in rice grains grown on Cd-contaminated soils	2019	Wang et al., 2019
Application of biochar reduces *Ralstonia solanacearum* infection via effects on pathogen chemotaxis, swarming motility, and root exudate adsorption	2016	Gu et al., 2016
Diversity of bacterial strains in biochar-enhanced Amazon soil and their potential for growth promotion and biological disease control in tomato	2020	Caniato et al., 2020
Biochar amendment controlled bacterial wilt through changing soil chemical properties and microbial community	2020	Chen et al., 2020
Wheat straw biochar amendment suppresses tomato bacterial wilt caused by *Ralstonia solanacearum*: Potential effects of rhizosphere organic acids and amino acids	2021	Tian et al., 2021
Effects of biochar amendment on tomato bacterial wilt resistance and soil microbial amount and activity	2016	Lu et al., 2016
Tobacco bacterial wilt suppression with biochar soil addition associates to improved soil physiochemical properties and increased rhizosphere bacteria abundance	2016	Zhang et al., 2016

Data on phytopathogen control along with standard deviations or standard errors were collected from tables or figures in studies using DataThief software (Tummers 2006).

Data screening

Extreme values were excluded via data screening. Each evaluated scientific study observed the efficiency of different biochars in controlling various bacterial pathogens and recorded the frequency as a percentage.

The following variables were established for the studies evaluated in the meta-analysis: pH, hydrogen potential; P, total available phosphorus in mg kg^{-1}; K^+, total available potassium in mg kg^{-1}; N, total available nitrogen in mg kg−1 (Figure 1); Shannon, Shannon Index; Chao−1, Chao−1 Index (Figure 2); CFU, colony-forming units (Figure 3). The analysis of these variables showed the potential of biochar to inhibit pathogens.

Meta-analysis (MA)

An MA was performed to determine biochar efficacy for managing bacterial diseases in plants. The statistical analyses used the RStudio (R Studio Team 2021). First, the degree of heterogeneity and biochar influence on soil properties were calculated using the "meta" R package, version 4.18-1 (Schwarzer 2007; Veroniki et al. 2016; Balduzzi et al. 2019). The standardized mean difference (MD) was used to compare the significant differences between the control and treatments at a 5% significance level and 95% confidence interval.

The tau-squared (τ^2) method (Dersimonian and Laird 1986) determined the variation extent among random effects; the higher the τ^2, the more uniform the weights assigned to the compared studies. The I^2 statistic (Higgins and Thompson 2002) was calculated to measure the heterogeneity among studies, with a probability test equivalent to the p-value of Cochran’s Q test. When the statistic value is negative, I^2 is converted to zero, and heterogeneity levels are adapted based on the ranges indicated by Deeks et al. (2021): 0–30% - might not be relevant; 31–50% - may represent moderate heterogeneity; 51–75% - may represent substantial heterogeneity; 76–100% - considerable heterogeneity.

3. Results

Our meta-analysis revealed that biochar application improved soil chemical and microbiological attributes and decreased the population of phytopathogenic bacteria, such as *Ralstonia solanacearum*, under different conditions. A bibliographical survey showed that 100% of selected studies reported that biochar effectively controls phytopathogens. Among these investigations, 57% validated biochar as a tool to increase soil pH, which is a disease suppression mechanism; 43% demonstrated that biochar efficiency in disease management is due to the lower pathogen population (reported reduction of 55% of *R. solanacearum* population); and 29% showed that P, K, and N contents and the Shannon and Chao-1 indices increased when applying different biochars (Table 2).

Table 2. Matrix of the studies that provided data for the meta-analyses.

Author	Country	pH	CFU	P	K^+	N	Shannon	Chao-1
Wang et al., 2019	China	-	-	-	-	-	×	×
Gu et al., 2016	China	-	×	-	-	-	-	-
Caniato et al., 2020	Brazil	-	×	-	-	-	-	-
Chen et al., 2020	China	×	-	×	×	×	-	-
Tian et al., 2021	China	×	-	-	-	-	-	-
Lu et al., 2016	China	×	×	-	-	-	-	-
Zhang et al., 2016	China	×	-	×	×	×	×	×
Total of studies	7	4	3	2	2	2	2	2
Relative	100%	57%	43%	29%	29%	29%	29%	29%

* x indicates the presence of the variable in the study; - indicates the absence of the variable in the study.

Effects of biochar addition on soil chemical attributes

Biochar applied to soil is usually efficient as an alternative to control plant diseases caused by bacterial pathogens. According to the parameters defined for systematic research, the studies found that biochar increased pH values and available N, P, and K in the soil (Figure 1). Furthermore, the MA indicated a high degree of heterogeneity among studies in both cases ($I^2 > 94\%$). According to these investigations, biochar increased the mean soil pH from 5.7 to 6.4, approximately 12% higher (Figure 1A). Biochar notably increases soil pH, one of the suppression mechanisms for plant diseases, mainly those caused by soilborne pathogens. Our study assessed the impact of biochar on plant diseases caused by bacteria and confirmed its effectiveness.

Biochar application to the soil increased P and K concentrations in all studies. On average, P levels were 41.5 mg kg^{-1} and 63.4 mg kg^{-1} for soils treated without and with biochar, respectively, which is 52.9% higher (Figure 1B). Similarly, P contents were 258 mg kg^{-1} and 334 mg kg^{-1} (+29.5%, Figure 1C), and N contents were 103 mg kg^{-1} to 118 mg kg^{-1} (+14.5%, Figure 1C) without and with biochar treatment, respectively. After determining the lowest variability, the fixed-effect model was used to explain the contrasts between treatments with and without biochar. The MA indicated that biochar application increased by 1.09 units in pH values (Figure 1A). Along with the pH, the fixed-effect model showed that biochar increased P, K, and N contents by 20.96 mg kg^{-1} (Figure 1B), 58.65 mg kg^{-1} (Figure 1C), and 12.62 mg kg^{-1} (Figure 1D), respectively.

Effects of biochar addition on soil microbial diversity and species richness

Other studies have reported a significant increase in the diversity and richness of microorganisms in the soil after biochar application (Figure 2). Shannon index values were 8.85 and 9.10 for soils without and with biochar, respectively (Figure 2A). Chao-1 index values were 2.995 and 3.393 for soils with and without biochar, respectively (Figure 2B). The presence of biochar in soil considerably increased the abundance of bacteria for both diversity indices of microbial species, and the degree of heterogeneity was significant ($I^2 > 71\%$) for the Chao-1 index. Specifically, biochar applied to the soil increased the Shannon and Chao-1 indices, representing higher diversity and species richness of soil microbial communities, respectively.

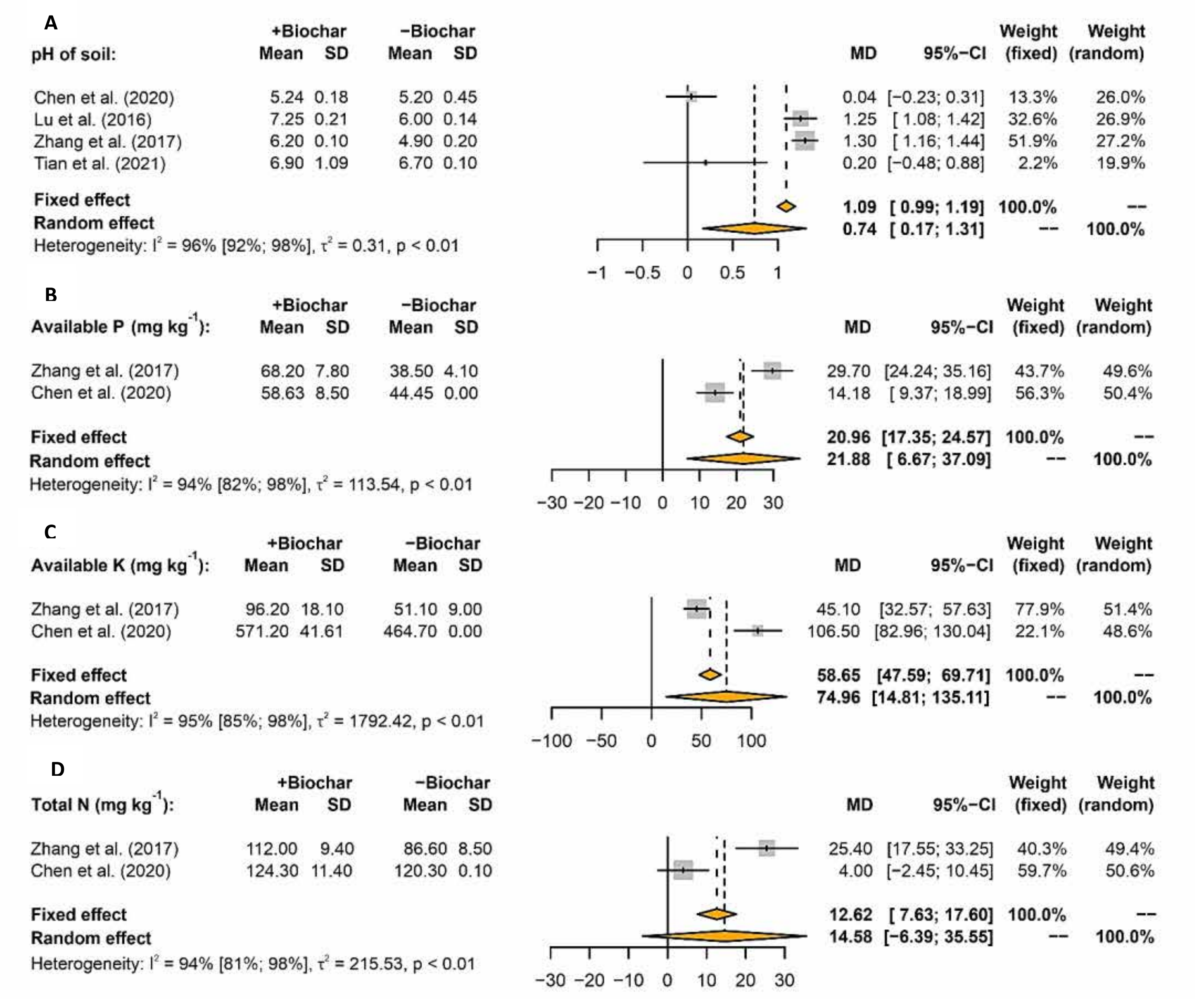

Figure 1. Meta-analysis of chemical attributes of soil treated with biochar to manage plant diseases caused by bacterial pathogens. According to the terms of the systematic search, a few viable ones demonstrated that biochar significantly increased the values of A – pH, B – phosphorus, C – potassium, and D – nitrogen in the soils.

Effects of biochar against *Ralstonia solanacearum*

Overall, the surveyed studies indicated a significant reduction in the *R. solanacearum* population in soils after applying different biochars (Figure 3). The same population was 46.6×10^6 CFU in soils without biochar, decreasing to 20.8×10^6 CFU after biochar application, a reduction of approximately 55%. Furthermore, the MA indicated a high degree of heterogeneity in this particular case in the study ($I^2 > 100\%$).

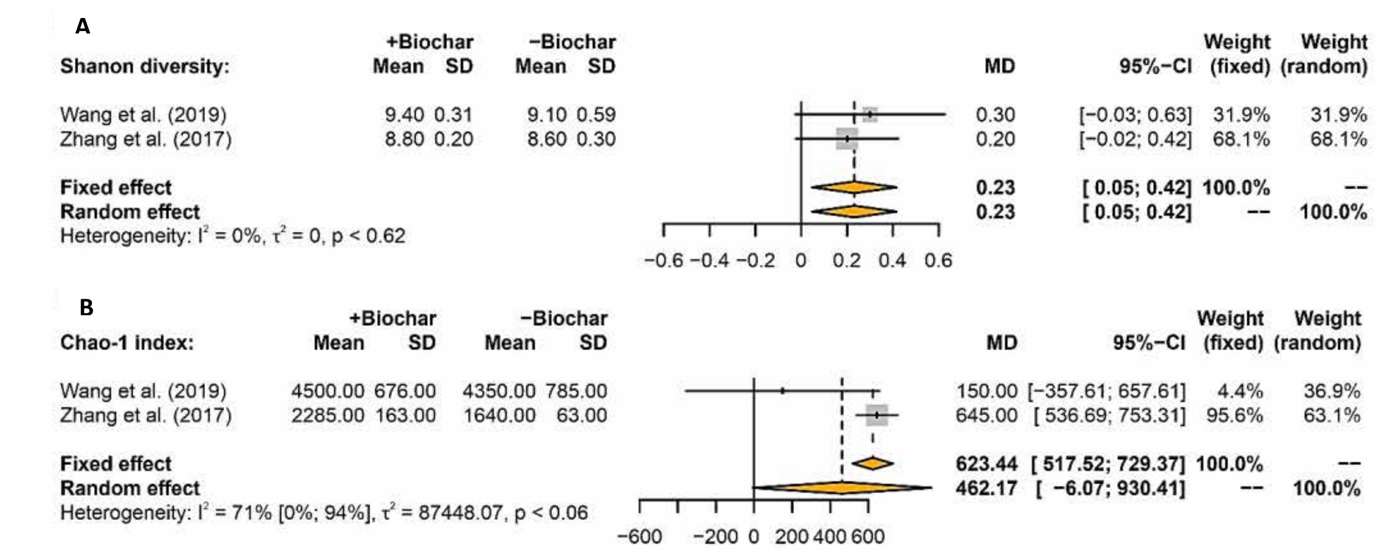

Figure 2. Meta-analysis of alpha-diversity indices (Shannon and Chao-1) in soils treated with biochar to manage plant diseases caused by bacterial pathogens. A – the Shannon index represents species diversity considering an equal weight between rare and abundant species; B – the Chao-1 index estimates the absolute number of species in a community by weighing the number of rare species within a sample. The higher the Shannon and Chao-1 indices, the higher the species diversity and richness, respectively.

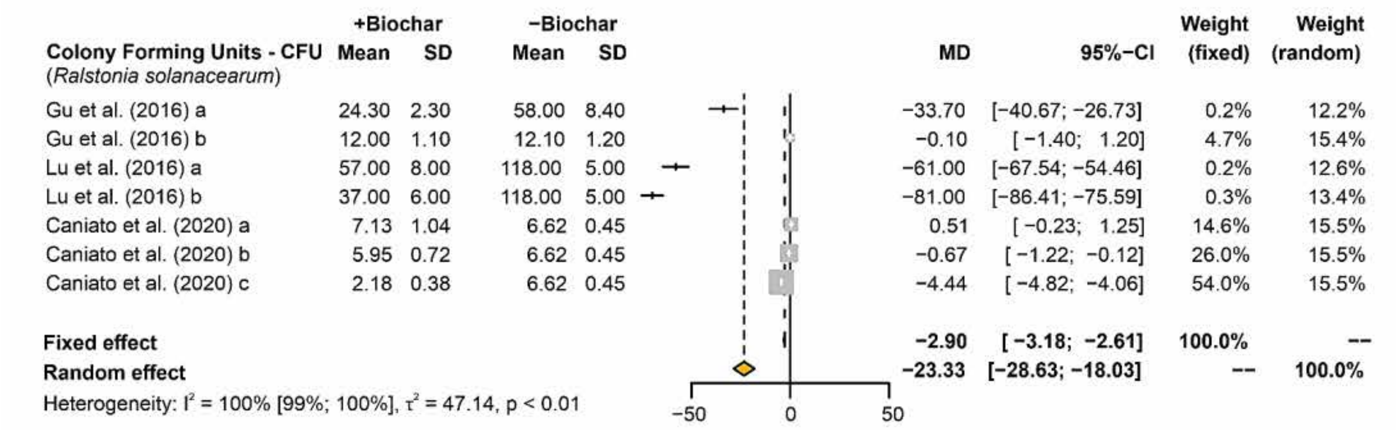

Figure 3. Meta-analysis for abundance of the phytopathogenic fungus *Ralstonia solanacearum* in soils treated with biochar. Values are expressed in colony-forming units (CFUs).

4. Discussion

Our MA shows that biochar applied to the soil for controlling plant diseases caused by bacterial pathogens changes soil chemical attributes, one of the main mechanisms of disease suppression. However, different crops have varying interactions with pathogens and environmental conditions, potentially affecting response variables and outcomes. For instance, environmental factors, such as temperature, humidity, and soil type and properties (e.g., pH and rainfall), are crucial for determining the occurrence and development of plant diseases. These environmental conditions may influence the impact of biochar on disease management, potentially affecting pathogen survival and proliferation by using biochar from different sources against tomato bacterial wilt disease caused by *Ralstonia solanacearum* (De Medeiros et al. 2022). Overall, applying different biochars improves soil quality, mainly by increasing its pH (Medeiros et al. 2021b) due to the dissolution of alkaline minerals and the deprotonation of acidic functional groups (Bandara et al. 2017; Lima et al. 2018). The biochar surface is rich in functional groups, such as carboxyl (COOH) and hydroxyl (OH) ones, which interact with cations in the soil, thus increasing the pH buffering capacity (Han et al. 2020). Moreover, alkaline ash is also present in biochar composition and incorporated into the soil as oxides, hydroxides, and carbonates, which explains the pH increase.

The biochar effects on soil pH may be influenced by changes in the biochar because of aging, as the time it remains in the edaphic environment can modify interactions in chemically reactive sites, such as increased oxygenation of functional groups in the soil from increased cation exchange capacity (Chen et al. 2020). Additionally, biochar ash content, pyrolysis temperature, resistance time in production, and the manufacturing material also significantly interfere with the dynamics of pH in the soil (Suman and Gautam 2017). Usually, the amount of fertilizer in biochar varies considerably, but most biochars have an alkaline pH from 7 to 11, helping to increase soil pH (Pandit et al. 2018). Adekiya et al. (2019) studied hardwood biochar, showing an elevation in soil pH, nutrients such as N, P, K, Ca, and Mg, and organic matter (Figure 4).

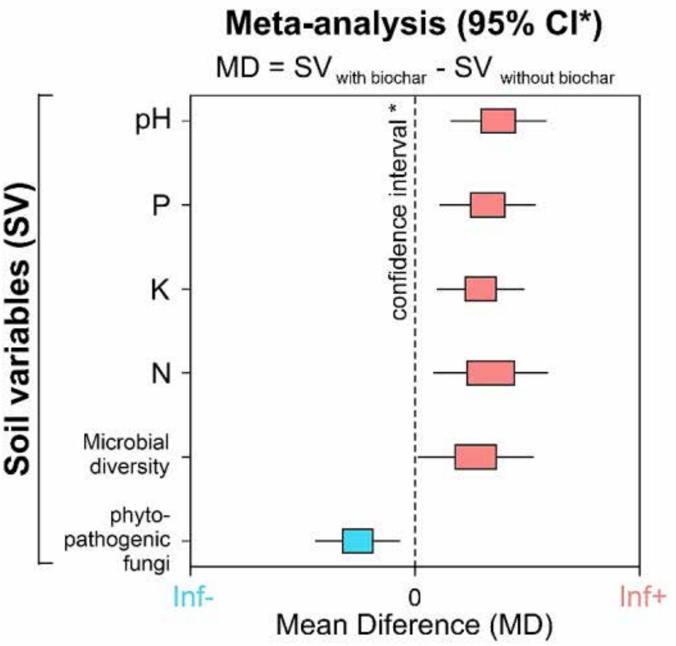

Figure 4. Summary of the meta-analysis of valid datasets according to the mean difference of variables before and after biochar use. Overall, biochar significantly increased soil pH, P, K, and N contents, and the alpha diversity of beneficial microbial communities, controlling the growth of soil pathogens such as *Ralstonia solanacearum*.

The pH is relevant for the soil because it determines the availability of toxic elements and beneficial crop nutrients (Blume et al. 2016). Moreover, soil acidification is one of the limiting factors for agricultural production, so biochar is significant for increasing productivity (Buss et al. 2018). Changes in soil pH due to biochar incorporation significantly affect microbial diversity and activity in the soil and other biochemical processes (Yu et al. 2019). The porous biochar surface provides microhabitats that stimulate microorganism development because of the higher pH and nutrient content, thus affecting microbial activity.

The elevation of soil pH is among the main factors that alter the structure of the microbial community. It is also the main soil chemical attribute involved in plant disease control due to its effect on microorganism population density and nutrient availability (Zhu et al. 2019; Silva et al. 2020). These nutrient availability changes are correlated to an increased microorganism activity that suppresses plant diseases, such as phosphorus (P)-solubilizing bacteria or those involved in the nitrification process (Herrmann et al. 2019). Thus, biochar and its components work cohesively and directly to alter microbial activity, including that of enzymes that control plant diseases caused by soil pathogens (Medeiros et al. 2021a).

Biochar may contain essential nutrients, such as N, P, and K, but it depends on its chemical composition from the raw material and the pyrolysis process. Therefore, adding biochar to the soil changes its nutrient content. Similar to the present study, Velli et al. (2021) reported an increased N and P availability after adding biochar. Cao et al. (2021) also observed a higher content and absorption of available P. Conversely, other studies reported no increases in available P and N in plots treated with biochar (Phares et al. 2021). Investigations have demonstrated an increase in K availability after biochar addition. In this sense, Wang et al. (2018) highlight that higher nutrient availability and uptake by plants depend on soil properties and biochar type.

The effects of biochar application on soil properties have drawn the attention of specialists worldwide, especially its impact on the bacterial community essential to maintain ecosystem balance, soil quality, and nutrient content (Lehmann et al. 2011; Campos et al. 2020). The changes in these soil properties caused by biochar application significantly affect edaphic microbial communities (Xu et al. 2016). Additionally, bacterial abundance is usually related to changes in soil pH and plant development soon after biochar application (Campos et al. 2020). The porous biochar surface provides microhabitats for the soil biota, potentially preventing plant diseases caused by phytopathogens by altering nutrient availability, physicochemical soil properties, and abundance of soil microorganisms and changing pathogen development, survival, and virulence (Hernandez-Soriano et al. 2016; Jaiswal et al. 2019).

Thus, biochar efficiency in managing bacterial diseases refers to its ability to change the soil biota and increase the number of beneficial microorganisms that directly protect plants against the invasion of soil pathogens, such as fungi of the *Trichoderma* genus (De Medeiros et al. 2020), via the production of antibiotics or competition with potentially harmful microorganisms (Elad et al. 2010; Akanmu et al. 2020).

In this sense, the soil changes observed and discussed in the present study, whether abiotic or biotic, after applying biochars, envision their potential use as a biofertilizer in the form of an inoculant (De Medeiros et al. 2020; França et al. 2022). For instance, the management with biochar + *Trichoderma* species, highlighted by Medeiros et al. (2021b), favors the formation of organo-mineral complexes, stimulating edaphic microbial activity (including the increase in microbial communities) and acknowledging this eco-sustainable input as a promising inoculation vehicle, even though the discussion about its viability is still at early stages.

The microbial community increase caused by biochar application to the soil is due to its high organic carbon content, which works as a substrate for microorganisms (Chen et al. 2020). However, potentially high biochar doses can be risky because, depending on the concentration, it can weaken the plant's defenses, leaving the root system susceptible to pathogen infestation (Frenkel et al. 2017). Therefore, determining the ideal concentration for diverse systems is required (Medeiros et al. 2021a). Studies have shown the efficiency of several biochars in increasing bacterial abundance and diversity in inventoried edaphic environments. Qiao et al. (2020) studied the effect of wheat straw biochar on bacterial community diversity in Molysol, reporting an increase in the Chao-1 index (3,980) compared to the control (3,597), corroborating the present study. The authors also reported a slightly higher Shannon index (6.81) than the control (6.34). Although their value is lower than the mean found in this MA, using biochar can increase the bacterial community.

Wei et al. (2020) used biochar in grape production, verifying a decrease in bacterial diversity and abundance in the soil. However, the bacterial structure of the surface slightly increased with more biochar. The authors reported a mean Shannon index of 6,535 with biochar application, not significantly differing from the control (6,496), but the Chao-1 index decreased under biochar treatment (1844.4) compared to the control (1899.3). Other studies demonstrated biochar efficiency in reducing the formation of *R. solanacearum* CFUs, with a 13–19% reduction in bacterial growth depending on the source of the studied biochar (Medeiros et al. 2021a), agreeing with our results. The reduction in CFUs and consequent suppression of the *R. solanacearum* population after adding biochars may be related to biomass increase, which promotes nutrient availability and microbial activity, potentially improving plant vigor and disease resistance (Tian et al. 2021).

Biochar efficiently manages plant diseases caused by bacterial pathogens, working through different mechanisms: increasing the density and activities of beneficial microorganisms, such as plant growth-promoting rhizobacteria, N2-fixing bacteria (Semida et al. 2019), *Trichoderma* spp. (De Medeiros et al. 2020), and mycorrhizal fungi. Biochar application changes the physical, chemical, and biological soil attributes that help suppress plant diseases (Medeiros et al. 2021a). It also aids plant disease management directly by inducing plant resistance, exhibiting fungitoxic effects, and allelopathic phytotoxin sorption (Bonanomi et al. 2015).

5. Conclusions

This study conducted a systematic literature review of several databases to assess the efficacy of biochar against plant diseases caused by bacterial phytopathogens. Different biochars effectively manage plant diseases caused by bacterial phytopathogens via distinct mechanisms: Antibacterial properties, such as polyphenols and volatile organic compounds, which can inhibit the growth and activity of bacterial pathogens; Induced systemic resistance; Soil microbiota modulation; and Nutrient and soil improvements that work directly and indirectly to suppress plant pathogens. Thus, changes caused by biochar are reflected in the significant reduction of damage severity from phytopathogens in crops. Overall, biochar may increase soil pH, P, K, and N contents, and the abundance of beneficial bacteria and reduce the population of disease-causing pathogens in plants. Our MA findings improve the understanding of potential biochars as sustainable tools for controlling bacterial diseases that affect plants worldwide.

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Ethics Approval: Not applicable.

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