Revitalizing fertility of global soils: Meta-analysis on benefits of poultry litter biochar on soil health

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Review

Revitalizing fertility of global soils: Meta-analysis on benefits of poultry litter biochar on soil health[1]

Revitalizando fertilidade dos solos globais: Meta-análise sobre benefícios do biochar de cama de frango na saúde do solo

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HIGHLIGHTS:

Biochar from poultry litter enhances soil by modifying pH, nutrient content, and capacity to retain cations.
Poultry litter biochar decreased Al^{3+} in soil by 71% while increasing pH, N, C, and CEC by 16, 20, 36, and 82%, respectively.
The meta-analysis revealed that poultry litter biochar is globally used to enhance soil quality.

ABSTRACT: This study aimed to conduct a meta-analysis (MA) of systematic review data on poultry litter biochar (PLB) to answer the following questions: (i) What are the major studies regarding this worldwide? (ii) Which soil chemical attributes are the most affected? and (iii) Does PLB improve soil quality and crop productivity? MA revealed that the application of PLB significantly changed several key soil attributes, including pH, cation exchange capacity (CEC), and nitrogen, carbon, potassium, calcium, magnesium, and aluminum content. Specifically, MA showed that PLB decreased Al^{3+} in the soil by 71% while increasing pH, N, C, and CEC by 16, 20, 36, and 82%, respectively. This significant increase in CEC was associated with the addition of Ca^{2+}, Mg^{2+}, and K^+ cations by 43, 202, and 636%, respectively. It was verified that PLB serves a dual function: it corrects soil acidity and pH while also enhancing the content of key nutrients, such as C and N. This study broadens the understanding of the potential of reusing poultry litter in biochar production, offering valuable data for developing strategies to improve both soil health and fertility.

Key words: waste reuse, pyrolysis, soil health, nutrient availability, plant production

RESUMO: Este estudo teve como objetivo realizar uma meta-análise (MA) de dados de revisão sistemática sobre biochar de cama de aves (BCA) para responder: (i) Quais são os principais estudos no mundo? (ii) Quais atributos químicas do solo são mais afetadas? (iii) O PLB melhora a qualidade do solo e a produtividade das culturas? A MA revelou que o BCA mudou significativamente várias propriedades-chave do solo, incluindo pH, capacidade de troca catiônica (CTC), nitrogênio, carbono, potássio, cálcio, magnésio e teor de alumínio. Especificamente, a MA mostrou que o BCA diminuiu Al^{3+} no solo em 71%, enquanto aumentou o pH, N, C e CTC em 16, 20, 36 e 82%, respectivamente. Este aumento significativo na CTC foi associado à adição de cátions Ca^{2+}, Mg^{2+} e K^+ em 43, 202 e 636%, respectivamente. Foi verificado que o BCA tem uma função dupla: corrige a acidez e o pH do solo, enquanto também aumenta o teor de nutrientes-chave como C e N. A pesquisa expande o entendimento do potencial de reutilização da cama de aves na produção de biochar, oferecendo dados valiosos para o desenvolvimento de estratégias para melhorar a saúde e a fertilidade do solo.

Palavras-chave: reutilização de resíduos, pirólise, saúde do solo, disponibilidade de nutrientes, produção vegetal

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Introduction

Biochar is a product of the pyrolysis of carbonized biomass (Pandey et al., 2020). When applied to soil, it has several benefits, such as carbon sequestration (Han et al., 2021); improved management of plant diseases (Medeiros et al., 2021); and improved soil structure, fertility, and microbial attributes (Oldfield et al., 2018; Lima et al., 2021; Silva et al., 2021a,b; Nepal et al., 2023).

Different raw materials result in biochars with different physicochemical properties (Medeiros et al., 2020), which vary in industrial solid waste (Wang et al., 2020; Lima et al., 2021), food (Xue et al., 2019), and sewage sludge (Figueiredo et al., 2019; Penido et al., 2019). Animal byproducts such as swine manure (Awasthi et al., 2020) and poultry litter can also be used (Steiner et al., 2018; Masud et al., 2020). Poultry litter is used as a biofertilizer because of its high N, P, and K concentrations (Adekiya et al., 2019). However, the direct application of poultry litter to the soil can cause environmental damage through eutrophication (Pilon et al., 2019).

Previous studies have reported the benefits of biochar on soil quality and plant production (Silva et al., 2022). However, data interpretation of other environmental conditions is hampered by the heterogeneity between studies, mainly owing to the types of raw materials, production, soil, management, and environmental conditions (Nepal et al., 2023). In this sense, the meta-analysis (MA) simplifies information and provides an objective view of data from systematic reviews, particularly in models assessing soil properties under different conditions (Oldfield et al., 2018).

This study aimed to conduct an MA of systematic review data on poultry litter biochar (PLB) to answer the following questions: (i) What are the major studies regarding this worldwide? (ii) Which soil chemical properties are the most affected? (iii) Does PLB improve soil quality and crop productivity?

Materials and Methods

An extensive systematic literature review of scientific articles on the worldwide use of PLB, published between 2010 and 2020, was conducted using the Web of Science, Scopus, and Google Scholar databases to discover the most critical edaphic parameters. Relevant to conducting this review, the publications necessarily contained the keywords "poultry litter and biochar" in the title. After the searches, the quantitative variable data observed in the soil and information from the articles such as title, abstract, first author, publication year, country of origin, and study location were tabulated. Nevertheless, to avoid publication bias, predefined criteria were applied in the screening: (i) written in English, (ii) presence of geographic coordinates of the study site, (iii) availability of the text in its entirety, and (iv) availability of clear quantitative data on soil chemical attributes.

A total of 1,800-paired comparisons of peer-reviewed studies on PLB were found on these platforms. After screening, 25 numerical datasets, each stemming from unique articles that satisfied the pre-established criteria and presented valid and high-quality data, were used for the statistical analysis stage and graphical representation in the meta-analysis (MA), based on the methodology presented by Deeks et al. (2023). This contrasted the effects of soils with and without PLB on the major chemical variables of the soil, with the origin of the data being properly georeferenced. All measurement units of these variables were standardized, allowing for the comparison of values before (control) and after (treatment) the application of PLB to the soil, as examined by MA. Locations of the 25 highlighted studies were plotted on a World Map using "maps" package version 3.3.0 of R software version 3.6.3 (https://www.r-project.org/).

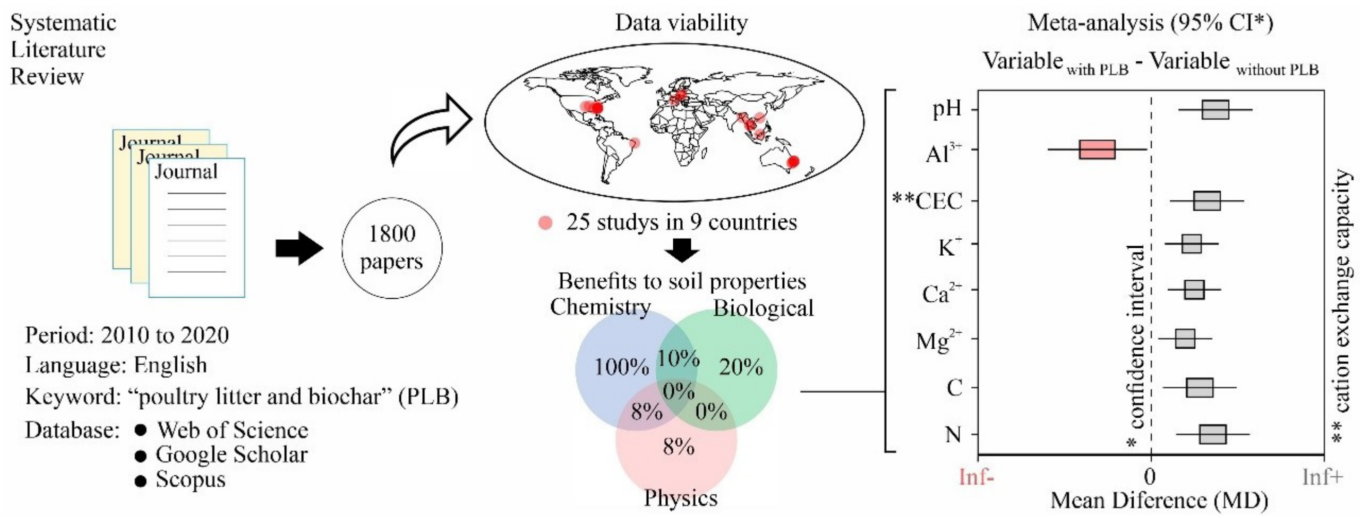
The significant difference between soil without (control) and with (treatment) PLB for each response variable was evaluated using MA to infer the degree of heterogeneity and the influences of fixed and random effect models by "meta" R package version 4.18-1 (Balduzzi et al., 2019). The standardized mean difference (MD) was used to compare significant differences between the contrasts at the 5% significance level and 95% confidence interval (CI).

In the case of p-values, the test of the null hypothesis indicated the probability of some degree of heterogeneity for low p-values. Heterogeneity between studies was quantified using the I^2 statistic, which measures the proportion of observed variance that reflects real differences in effect size, ranging from negative values to 100%, with a probability test equivalent to the p-value of Cochran's Q test (Higgins & Thompson, 2002). In other words, I^2 is the percentage of total heterogeneity resulting from variance among studies, which cannot be explained by sampling errors. When the value is negative, it is equal to zero: 0-40% may not be important, 30-60% may represent moderate heterogeneity, 50-90% may represent substantial heterogeneity, and 75-100% represents considerable heterogeneity (Dike et al., 2021). The extent of variation among the random effects observed in studies (between PLB conditions) is referred to as the tau-squared (τ^2) method (DerSimonian & Laird, 1986), which measures the dispersion of true effect sizes between studies and the scale of the effect size. The τ^2 was used to assign weights to the studies in the MA under the random effects (Re) model. Hence, if τ^2 was zero, the Re and fixed-effect (Fe) models were the same.

Results and Discussion

Among the 1,800 scientific works on PLB, the vast majority were found exclusively on Google Scholar (89%) and others on the Web of Science and Scopus platforms (4.6%), while the remaining 6.4% were made available through publications surveyed over the past 10 years. Among the 25 studies used in the MA (Table 1), 44% were conducted in the Eastern Region of the USA, 24% in Eastern Australia, 20% in Southeast Asia (Bangladesh, China, Malaysia, and Thailand), 8% in Poland, and 4% in Northeast Brazil. Collectively, these were the only studies that presented viable data for the statistical evaluation of the effects of PLB on the major soil chemical variables using MA (Figure 1).

pH was the most selected variable for evaluating the effects of PLB on soil chemistry and was determined in 84%



CI - Confidence interval; CEC - Cation exchange capacity; C - Total carbon; N - Total nitrogen. A screening process was conducted using 1,800 scientific studies found across the three major global scientific search platforms, utilizing the access key phrase "poultry litter and biochar." The studies were conducted between 2010 and 2020. As a result, 25 datasets originating from all continents were filtered, enabling the statistical analysis of the impact of biochar on eight key soil attributes.

Figure 1. Summary of the systematic review and meta-analysis procedure

Table 1. Matrix showing the studies, countries, and variables that provided the data for the meta-analyses

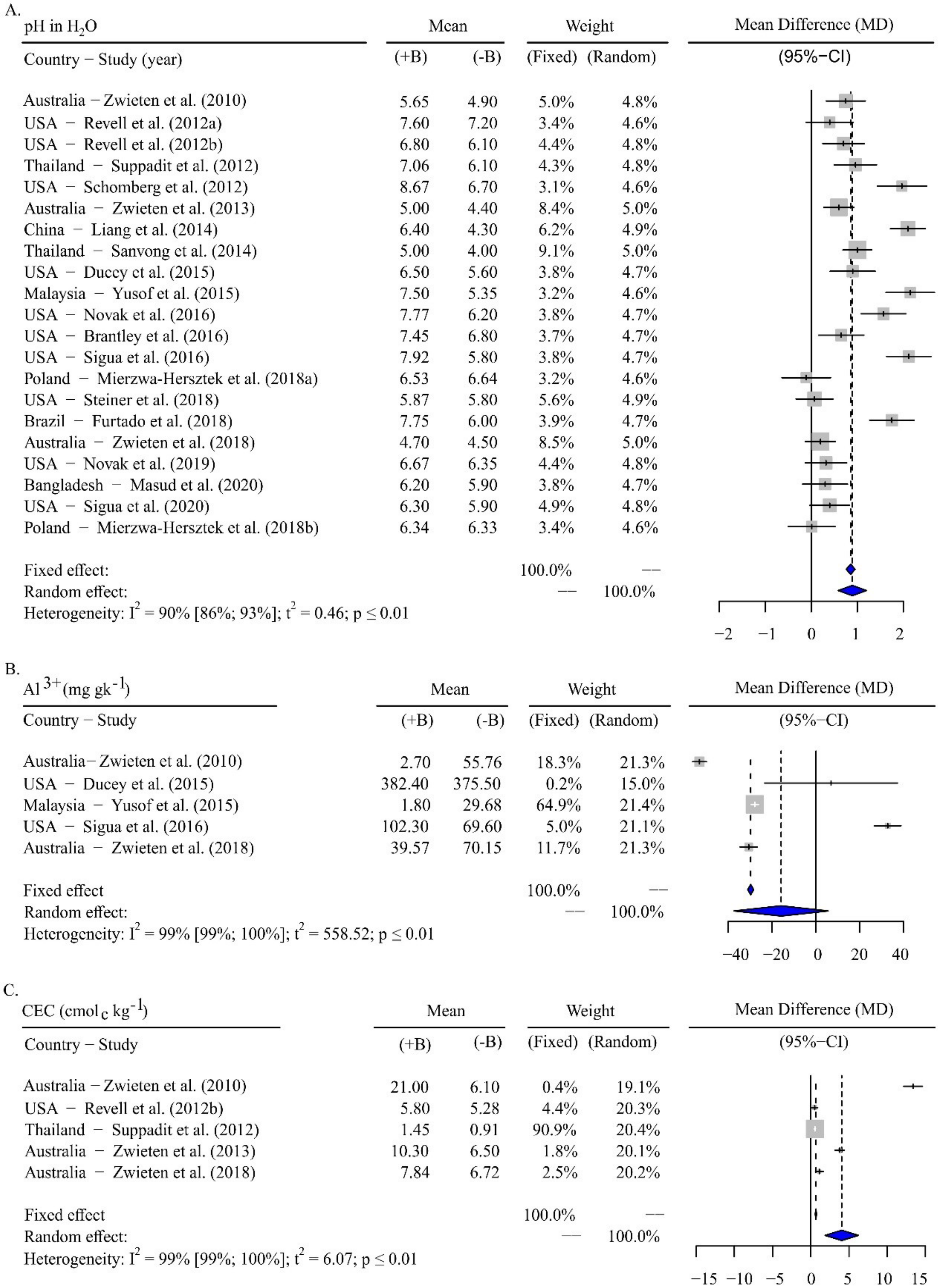
Author (year)	Country	pH	Al^{3+}	CEC	K^+	Ca^{2+}	Mg^{2+}	C	N	SD	FC	TOC	MBC	SBR	Beta	Ure
Zwieten et al. (2010)	Australia	x	x	x	x	x	x	x	x							
Revell et al. (2012a)	USA	x								x	x					
Revell et al. (2012b)	USA	x		x				x								
Suppadit et al. (2012)	Thailand	x		x	x	x	x	x	x							
Schomberg et al. (2012)	USA	x						x	x							
McLeod et al. (2012)	Australia							x	x							
Zwieten et al. (2013)	Australia	x		x				x	x							
Liang et al. (2014)	China	x			x	x	x	x	x				x	x	x	
Sanvong et al. (2014)	Thailand	x		x	x	x	x	x	x							
Ducey et al. (2015)	USA	x	x		x	x	x					x				
Yusof et al. (2015)	Malaysia	x	x		x	x	x		x			x				
Novak et al. (2016)	USA	x			x					x						
Brantley et al. (2016)	USA	x			x	x	x		x							
Rose et al. (2016)	Australia															
Sigua et al. (2016)	USA	x	x		x	x	x	x	x							
Mierzwa-H. et al. (2018a)	Poland	x						x	x							
Steiner et al. (2018)	USA	x			x	x	x	x	x							
Furtado et al. (2018)	Brazil	x			x	x	x									
Zwieten et al. (2019)	Australia	x	x	x	x	x	x	x	x					x		
Novak et al. (2019)	USA	x														
Masud et al. (2020)	Bangladesh	x			x	x	x									
Sigua et al. (2020)	USA	x							x							x
Novak et al. (2018)	USA				x											
Hersztek et al. (2018b)	Poland	x						x	x							
Singh et al. (2012)	Australia							x								
Total of studies:	25	21	5	6	14	12	12	14	15	2	1	2	1	2	1	1
Relative (%):	100	84	20	24	56	48	48	56	60	8	4	8	4	8	4	4

CEC - Cation exchange capacity; C - Total carbon; N - Total nitrogen; SD - Soil density; FC - Field capacity; TOC - Total organic carbon; MBC - Microbial biomass carbon; SBR - Soil basal respiration; Beta - Beta-glucosidase activity; Ure - Urease activity

of the studies, followed by total N (60%), total C (56%), K^+ (56%), Ca^{2+} (48%), Mg^{2+} (48%), CEC (24%), and Al^{3+} (20%). Other variables occurred in less than 9% of the observations and were insufficient for exploratory analysis via MA. These variables were soil density, total organic carbon, microbial biomass carbon, soil basal respiration, β-glucosidase, and urease enzyme activities.

Majority of the studies on the meta-analysis, mainly dealt with soil chemical properties, while only 20% were on biological attributes, and 8%, on some physical properties. Among these studies, 10% evaluated the chemical and biological properties together and 8% evaluated the chemical and physical properties. No study has simultaneously investigated all three properties or their biological and physical properties. MA revealed high heterogeneity ($I^2 = 90\%$) and a low p-value ($p < 0.01$) among the studies of the variables (Figure 2). Biochar from poultry litter mainly modified pH (Figure 2A), Al^{3+} (Figure 2B), and CEC (Figure 2C) for MD between soils without (-B) and with (+B) PLB.

PLB increased the pH of the studied soils by 16%, from 5.7 to 6.6, with the difference being significant both in the fixed effects model (Fe) and in the random effects model (Re) (Figure 2A). The Al^{3+} content in the soils decreased from 52 to 15 mg kg^{-1} (71% reduction) after using PLB biochar (Figure 2B).



CI - Confidence interval; I^2 - Heterogeneity between fixed effects of the two contrasting conditions (larger, more heterogeneous); t^2, statistic of uniformity of the random weights assigned to the studies (larger, more heterogeneous)

Figure 2. Meta-analysis of the effect of poultry litter biochar on pH (A), Al^{3+} concentrations (B), and the cation exchange capacity (C) in soil with (B+) and without (B-) poultry litter biochar

Conversely, soil CEC increased from 5.1 to 9.3 $cmol_c\ kg^{-1}$ (by 82%) (Figure 2C). The values of t^2 tended to zero, indicating a more balanced contribution of the weights between the studies associated with the Re model. Therefore, the estimated standard deviation of the true underlying effects across studies was the lowest for pH, followed by CEC and Al^{3+}.

The increase in CEC was accompanied by a high degree of heterogeneity (I^2 = 100%) and significant MD values for K^+, Ca^{2+}, and Mg^{2+} concentrations (Figure 3). Here, the Re model demonstrated a more relevant explanation for the contrasts between -B and +B. Inconsistent with that for CEC, the resulting cations demonstrated high t^2 values (much greater than zero), indicating substantial deviations from the true effects between studies associated with Re.

Overall, studies that evaluated K^+, Ca^{2+}, and Mg^{2+} in soils after receiving biochar demonstrated a weight contribution with amplitudes varying between 6 and 11% of the total explanation of the real variability. Under these conditions, on average, the use of PLB increased the K^+ concentration from 61 to 449 mg kg^{-1} (636%) (Figure 3A), Ca^{2+} from 649 to 928 mg kg^{-1} (43%) (Figure 3B), and Mg^{2+} from 43 to 130 mg kg^{-1} (202%) (Figure 3C). The addition of PLB increased C content in all selected studies (Figure 4A). Similarly, the N content in soils that received PLB increased compared to that in the treatments without biochar addition (Figure 4B).

In this study, an extensive literature search was conducted to assess whether PLB improves soil quality in different regions worldwide. Many studies have suggested that different types of biochar increase the soil pH (Medeiros et al., 2020; Lima et al., 2021). Here, we observed a significant increase in pH and CEC in soils with incorporated biochar, which consequently increased nutrient availability (Medeiros et al., 2020). When evaluating the use of PLB, the average soil pH was 6.65, with the highest value (8.67) derived from a study by Schomberg et al. (2012), who evaluated the influence of biochar on the fractions of nitrogen in coastal plain soil. The increase in pH may have been the major effect of PLB addition.

In this MA, an increase in pH ranging from practically zero (Mierzwa-Hersztek et al., 2018) to 2.15 units (Yusof et al., 2015) was observed. Sigua et al. (2016) and Liang et al. (2014) also approached this scale; PLB raised the pH by 2.15 and 2.10 units, respectively. In the first case (Sigua et al., 2016), highly weathered soil in the coastal plain region of the USA was studied by applying 40 Mg ha^{-1} of pine and PLB. In the second study (Liang et al., 2014), the influence of PLB on drought resistance and resilience in tropical soils in Guangdong Province, China, was investigated.

The pH-corrective characteristics observed in biochar can be explained by its high concentration of minerals, primarily K^+, Ca^{2+}, and Mg^{2+} carbonates (Domingues et al., 2017) serving as an alternatives to limestones. The increased availability of these cations displaces the H^+ and Al^{3+} ions adsorbed onto the negatively charged soil colloids (Sigua et al., 2016). Consequently, the proportion of H^+ and Al^{3+} ions at the cation exchange site decreases, and base saturation increases (Sigua et al., 2014), explaining the close relationship between pH, Al^{3+}, CEC, K^+, Ca^{2+}, and Mg^{2+}. However, biochars from different types of organic matter can vary in properties (Lima et al., 2021; Silva et al., 2021a; Silva et al., 2021b). Furthermore, biochar produced from the same type of matter may exhibit different characteristics depending on the production temperature. The PLB produced in Brazil at 450 °C, with pH 10.2, changed the soil pH from 6.4 to 8.28 after application of the highest dose (15% = 1,100 g per pot) (Furtado & Chaves, 2018). This difference was due to the biochar production temperature and elemental composition of the poultry litter used. This was reflected in the final pH of the biochar, which showed a value of eight.

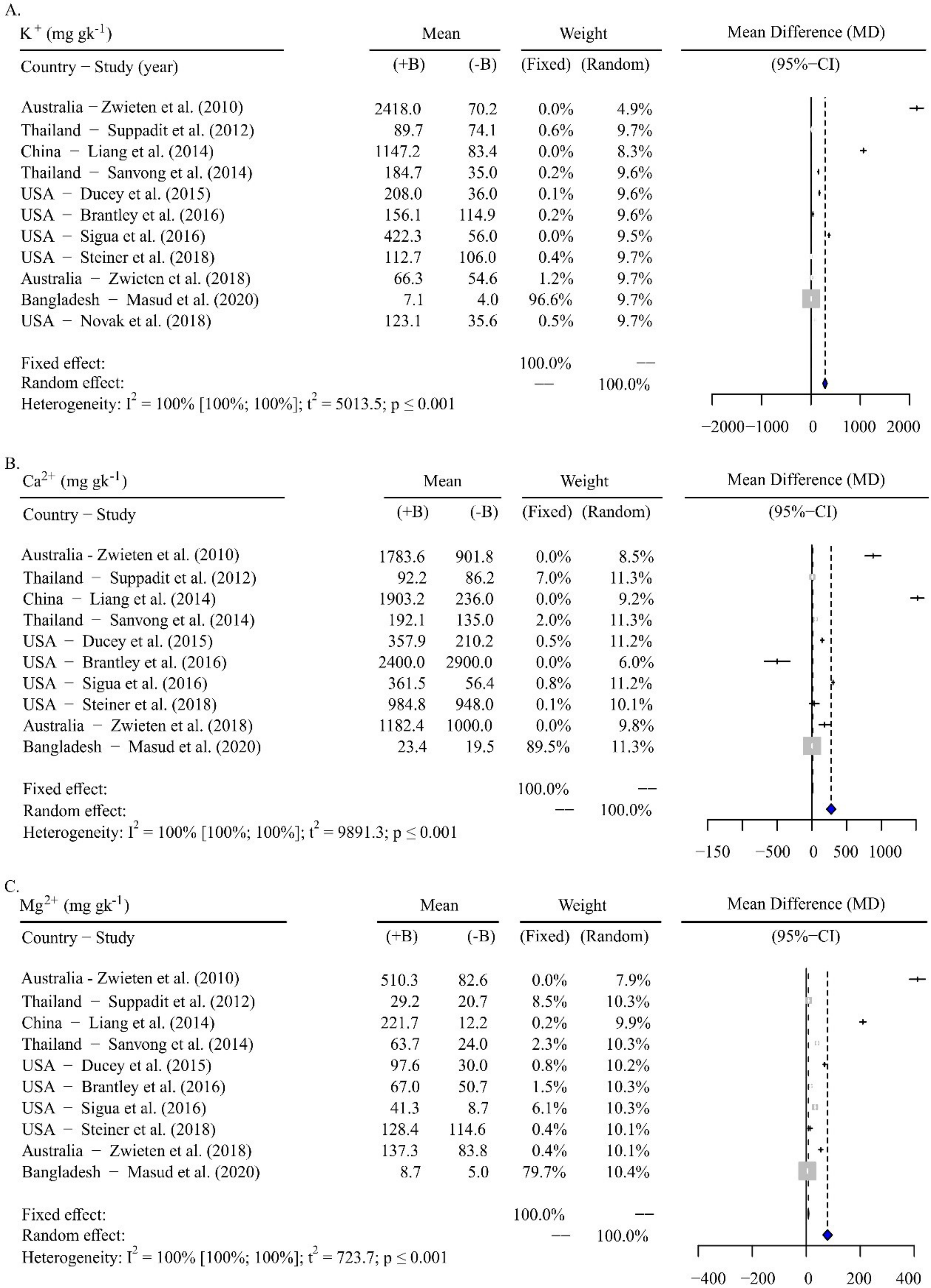
Zwieten et al. (2019) evaluated the effects of two contrasting biochars on N_2O emissions, soil ammonium (NH_4^+) and nitrate (NO_3^-) status, and pasture productivity, demonstrating that PLB was more efficient than hardwood biochar in soil liming, and this was due to a higher $CaCO_3$ percentage found in PLB (13% $CaCO_3$) than that in hardwood biochar (7.3% $CaCO_3$).

PLB allowed the reduction of Al^{3+} in all soils of the evaluated studies; this chemical species is one of the major limiting factors for agricultural production in acidic soils (Masud et al., 2020). Mehmood et al. (2018) observed that biochar decreased the exchangeable acidity of soil through an alkalization process and contained functional groups with oxygen radicals that formed complexes with Al^{3+}. The biochar results for pH and Al^{3+} concentrations corroborated the findings of the soil CEC in MA, which were closely correlated (Zwieten et al., 2019). In addition, the variability in CEC is linked to factors that affect the surface properties of biochar, such as the carbonization temperature and raw material (Suliman et al., 2016). According to Sigua et al. (2016), by conditioning the soil through increased cation availability and low relative cost, PLB can be considered a viable biofertilizer for agricultural use. Despite the overall positive results, the study by Revell et al. (2012) did not show a significant effect of PLB on CEC in the three soils studied, even at application rates of 4.5 9 Mg ha^{-1}.

The positive effect of PLB on exchangeable bases (K^+, Ca^{2+}, and Mg^{2+}) was expected as poultry litter is rich in nutrients. Novak et al. (2018) evaluated the release of P and K by biochars based on a mixture of lignocellulosic materials and poultry litter and demonstrated a better use of pyrolyzed biochar with 100% poultry litter. Masud et al. (2020) observed an increase in the availability of K^+, Ca^{2+}, Mg^{2+}, and P when testing the use of PLB to improve corn growth in acidic soils with notable leaching losses.

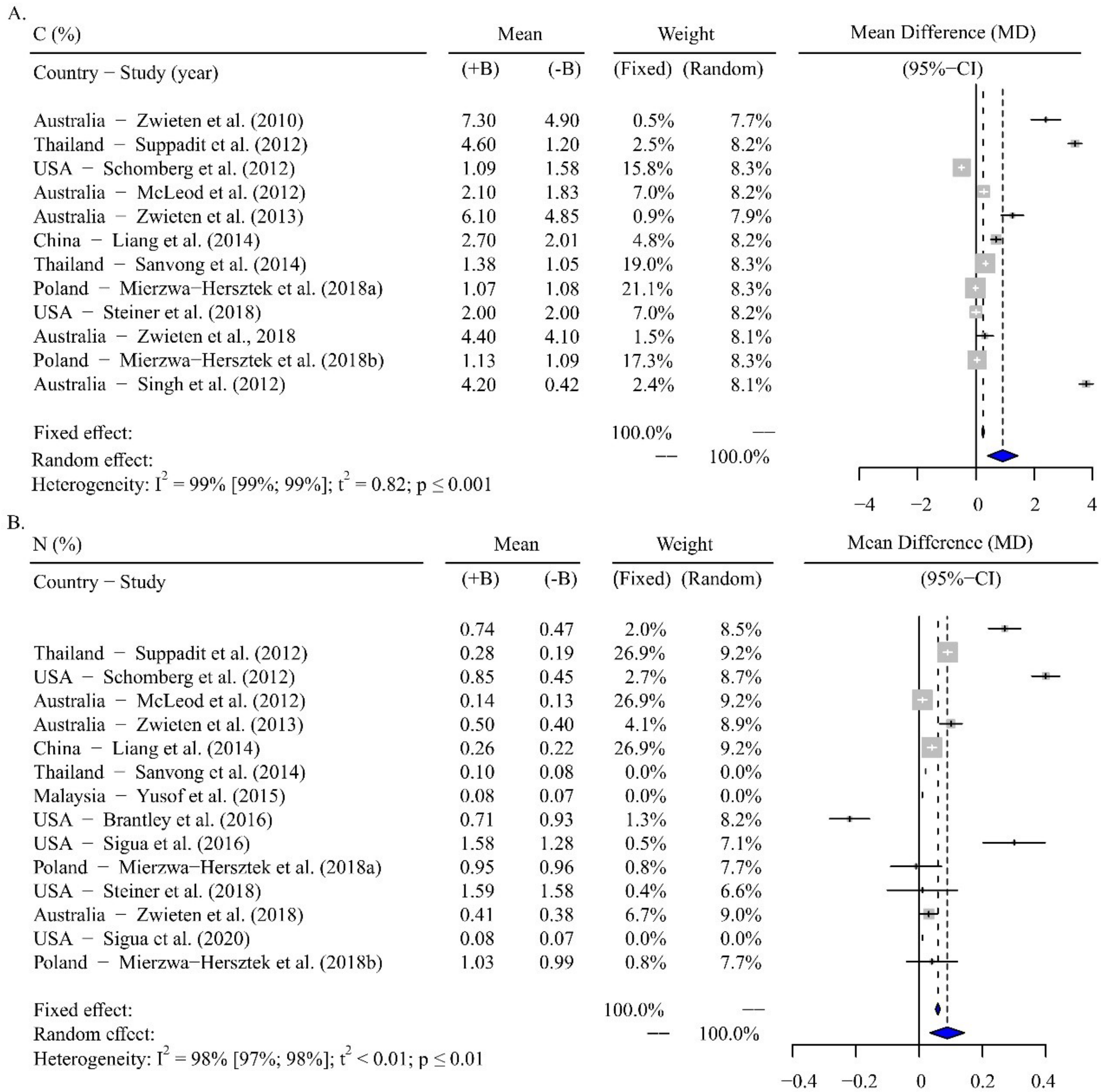
The significant increase in the soil C content was observed as one of the major results in the studies where PLB was added to the soil. However, some studies did not detect any differences, considering that the biochar C content varies depending on the type of raw material and pyrolysis process used (Zwieten et al., 2019). When studying the effect of PLB on the chemical properties and nutrient absorption in soil cultivated by *Oryza sativa* L, Yusof et al. (2015) observed that the percentage of total C in PLB (63.7%) was higher than that in poultry litter ash (0.4%), demonstrating the effect of the pyrolysis process on this element.

Thermochemical transformation through pyrolysis transforms organic waste into safer and more stable compounds for agricultural land applications (Medeiros et



CI - Confidence interval; I^2 - Heterogeneity between fixed effects of the two contrasting conditions (larger, more heterogeneous); t^2 - Statistic of uniformity of the random weights assigned to the studies (larger, more heterogeneous)

Figure 3. Meta-analysis of the effect of poultry litter biochar on K^+ (A), Ca^{2+} (B), and Mg^{2+} (C) content in soil with (B+) and without (B-) biochar



CI - Confidence interval; I^2 - Heterogeneity between fixed effects of the two contrasting conditions (larger, more heterogeneous); t^2 - Statistic of uniformity of the random weights assigned to the studies (larger, more heterogeneous)

Figure 4. Meta-analysis of the effect of poultry litter biochar application on carbon (A) and nitrogen (B) stocks in soils soil with (B+) and without (B-) biochar

al., 2020). This type of transformation has several advantages, mainly in the so-called negative carbon process, in which net greenhouse emissions can be reduced to zero, making the carbon cycle fully renewable, as inferred by Yang et al. (2016). The pyrolysis treatment promotes the resynthesis of the source material, adding previously nonexistent attributes. Properties such as water retention capacity, CEC, presence of ash, alkaline pH, and low molar ratios (H:C and O:C ratios), in addition to the suppression of biological contaminants, are the major advantages of using this technique (Li et al., 2021; Rodriguez et al., 2021).

The significant increase in N in soils with PLB was one of the most unexpected results owing to the high volatility of this element. The pyrolysis temperature and raw materials also influenced this response. In general, higher pyrolysis temperatures (600-700 °C) result in an increase in alkalinity, fixed carbon content, and the amount of basic functional groups; while lower temperatures (100-300 °C) result in an increase in adsorption capacity, porosity, biochar yield, and amount of acidic functional groups (Sun et al., 2017). The primary entry route of N into the soil is through biological fixation; however, the addition of mineral fertilizers or organic matter is responsible for increasing the N content in the soil. Under these conditions, MA revealed that PLB substantially increased the N content in the soil, especially when poultry litter was subjected to pyrolysis.

This study demonstrated that PLB can significantly improve soil quality by increasing soil pH, cation exchange capacity (CEC), and nutrient availability. The pH-correcting characteristics of the PLB can be attributed to its high concentration of minerals, particularly K^+, Ca^{2+}, and Mg^{2+} carbonates. Additionally, PLB was found to reduce Al^{3+} concentrations in the soil, which is a major limiting factor for agricultural production in acidic soils. The properties of PLB can vary depending on the type of organic matter used and the production temperature. Furthermore, the use of PLB was found to significantly increase soil carbon and nitrogen contents owing to the pyrolysis process, transforming organic waste into safer and more stable compounds for agricultural land application. Overall, PLB can be considered a viable biofertilizer for agricultural use. However, a knowledge gap in understanding the long-term effects of biochar, its optimal use, its interactions with soil carbon, and its impact on the environment and human health, (Nepal et al., 2023) remains.

Conclusions

1. The meta-analysis (MA) revealed that the application of poultry litter biochar (PLB) significantly changed several key soil properties, including pH; cation exchange capacity (CEC); and nitrogen, carbon, potassium, calcium, magnesium, and aluminum contents.

2. PLB can be used for pH correction, reduction of Al^{3+} in acidic soils, and as a biofertilizer for significantly increasing the cation exchange capacity owing to high concentrations of K, Ca, and Mg.

3. Despite the significant impact of PLB on soil chemical properties, only a limited number of studies have investigated its influence on soil physical attributes and biological components. This review underscores the need for additional research to elucidate the effects of biochar on soil microbial communities.

Contribution of authors: Avete V. Lima performed the study, investigation, methodology, data collection, and wrote the original draft. Diogo P. da Costa performed the statistical analysis. Lucas R. Simões worked on the literature review, data curation, and corrections to the original draft. Jamilly A. de Barros performed the literature review, data curation, and corrections of the original draft. Vanilson P. da Silva performed the literature review, data curation, and corrections of the original draft. José Romualdo S. Lima worked on the conceptualization, and supervision. Claude Hammecker worked on the methodology, formal analysis, and data curation. Erika V. de Medeiros worked on the conceptualization, supervision, funding, literature review, and corrections of the original draft.

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