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Research article

Effects of soil amendments on soil acidity and crop yields in acidic soils: A world-wide meta-analysis

Siwen Zhang [a], Qichao Zhu [b,c,*], Wim de Vries [d], Gerard H. Ros [d], Xiaohui Chen [e], Muhammad Atif Muneer [a], Fusuo Zhang [b], Liangquang Wu [a,**]

[a] International Magnesium Institute, College of Resources and Environment, Fujian Agriculture and Forestry University, Fuzhou, 350002, China
[b] College of Resources and Environmental Sciences, National Academy of Agriculture Green Development, Key Laboratory of Plant-Soil Interactions, Ministry of Education, China Agricultural University, Beijing, 100193, China
[c] Sanya Institute of China Agricultural University, Sanya, 572000, China
[d] Wageningen University and Research, Environmental Systems Analysis Group, PO Box 47, 6700AA, Wageningen, the Netherlands
[e] Research Centre of Phosphorous Efficient Utilization and Water Environment Protection Along the Yangtze River Economic Belt, College of Resources and Environment, Anhui Agricultural University, Hefei, 230036, China

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ABSTRACT

Soil amendments, including lime, biochar, industrial by-products, manure, and straw are used to alleviate soil acidification and improve crop productivity. Quantitative insight in the effect of these amendments on soil pH is limited, hampering their appropriate use. Until now, there is no comprehensive evaluation of the effects of soil amendments on soil acidity and yield, accounting for differences in soil properties. We synthesized 832 observations from 142 papers to explore the impact of these amendments on crop yield, soil pH and soil properties, focusing on acidic soils with a pH value below 6.5. Application of lime, biochar, by-products, manure, straw and combinations of them significantly increased soil pH by 15%, 12%, 15%, 13%, 5% and 17%, and increased crop yield by 29%, 57%, 50%, 55%, 9%, and 52%, respectively. The increase of soil pH was positively correlated with the increase in crop yield, but the relationship varied among crop types. The most substantial increases in soil pH and yield in response to soil amendments were found under long-term applications (>6 year) in strongly acidic ($pH < 5.0$) sandy soils with a low cation exchange capacity (CEC, <100 $mmol_c\ kg^{-1}$) and low soil organic matter content (SOM, <12 $g\ kg^{-1}$). Most amendments increased soil CEC, SOM and base saturation (BS) and decreased soil bulk density (BD), but lime application increased soil BD (1%) induced by soil compaction. Soil pH and yield were positively correlated with CEC, SOM and BS, while yield declined when soils became compacted. Considering the impact of the amendments on soil pH, soil properties and crop yield as well as their costs, the addition of lime, manure and straw seem most appropriate in acidic soils with an initial pH range from <5.0, 5.0–6.0 and 6.0–6.5, respectively.

1. Introduction

Soil is the foundation of food production for human beings (Bünemann et al., 2018; Maharjan et al., 2020). While nutrient addition by fertilizers has enhanced crop yields worldwide, improper nutrient management caused substantial soil acidification with negative impacts on crop yields, in particular in China (Guo et al., 2010; Zhu et al., 2020). Nearly half of the world's arable soils have become acidic ($pH \leq 6.5$) and this areas is even increasing (Dai et al., 2017). A decline in soil pH can cause a series of adverse effects. It decreases the availability of soil nutrients (phosphorus, potassium, calcium and magnesium), affects the structure and functioning of microbial communities (Chen et al., 2013; Hao et al., 2020), and enhances the availability of toxic heavy metals (e.g., cadmium and lead) and other harmful elements (e.g., aluminum and manganese), especially at pH levels below 4.5 (Sun et al., 2019; Wu et al., 2014). These impacts subsequently threatens food security (Zhang et al., 2022). With a growing population and an increasing food demand, alleviating soil acidification is important.

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* Corresponding author. College of Resources and Environmental Sciences, National Academy of Agriculture Green Development, Key Laboratory of Plant-Soil Interactions, Ministry of Education, China Agricultural University, Beijing, 100193, China.
** Corresponding author.
E-mail addresses: qichaozhu@126.com (Q. Zhu), liangquan01@163.com (L. Wu).

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Various soil amendments, including lime, biochar, industrial by-products (e.g. phosphogypsum and caustic sludge), manure and straw, are capable of alleviating soil acidification in agricultural systems (Kätterer et al., 2019). Lime application is the most common practice worldwide to raise soil pH and neutralize excessive hydrogen ions (H^+) in soil solution and to promote crop productivity (Fageria and Baligar, 2008; Holland et al., 2018). However, negative impacts of lime application on soil properties and crop yields have also been reported. These include soil compaction and associated yield reductions especially if too much lime is used (Meng et al., 2004; Li et al., 2019). Manure application also ameliorates soil acidification by the addition of base cations and organic matter (Liu et al., 2020; Ning et al., 2020). During decomposition of organic matter in soil, the alkalinity (from base cations) is released via decarboxylation, which consumes H^+ and thus increases soil pH (Cai et al., 2018; Tang and Yu, 1999). In addition, manure application also reduces Al toxicity through the formation of Al-organic matter complexes (de Wit et al., 1999; Naramabuye et al., 2008). Similarly, the use of straw can reduce the impacts of acidification, but the effect is usually smaller than the effect of manure because of its low alkalinity (Dong et al., 2021; Siedt et al., 2021). In comparison, biochar has been recognized as a promising mitigation amendment to counteract soil acidification (Zhao et al., 2020). Biochar can be made from a wide range of carbon-based materials, such as wood residues, animal manure, crop residue (straw) and organic wastes, and usually has stronger effects on soil pH than raw materials (Farhangi-Abriz et al., 2021). Lastly, some industrial by-products with high alkalinity and low costs have also been promoted as promising amendments to ameliorate soil acidification (Blum et al., 2012; Garrido et al., 2003). Since various amendments are available for soil acidification improvement, quantifying their effects is necessary to support effective mitigation management in acidic soils.

Most of the aforementioned amendments also alter soil properties affecting soil health. Variable responses of crop and soils to amendments have been reported. For example, field application of manure on ultisols soil for 30 years increased not only the soil pH by 0.5 units (Ren et al., 2019) but long-term addition also increased the SOC content with more than 33% (Geisseler and Scow, 2014). These impacts on soil properties can affect crop yields as illustrated by Zhang et al. (2021a,b), who found that lime application in a continuous two-season pomelo field experiment increased soil pH by 0.4–1.1 units and crop yield by 16–30%. However, these effects of amendments likely vary with the initial soil properties such as the pH buffering capacity, texture and organic matter content as well as the crop type, the type and rate of amendments, and duration of the experiment (Du et al., 2020; Li et al., 2019). Wu et al. (2020), for example, found that biochar improved fruit quality compared with lime, although the effects on soil pH were comparable for strongly acidic soils ($pH < 4.5$). In addition, a four-year field study on apples showed that biochar amendment had a bigger impact on soil pH and yield than manure with an increasing impact over time (Safaei Khorram et al., 2019). Thus, the heterogeneity in soil properties, environmental conditions and experimental design makes it difficult to determine general crop and soil pH responses to amendment application (Liao et al., 2021).

Meta-analysis is a comprehensive method of analyzing a series of independent studies (He et al., 2021) and has been used to quantify the effects of single soil amendments on soil pH, crop yields and crop quality (Li et al., 2019; Farhangi-Abriz et al., 2021). For example, Farhangi-Abriz et al. (2021) identified the effects of biochar on grain yield, while Li et al. (2019b) investigated the effects of lime on soil pH and crop yield, depending on the type of lime, application method and crop type. In addition, Liao et al. (2019) assessed the effect of lime on both the yield and Cd uptake of rice. Due to the focus on single amendments in most experiments a thorough comparative assessment of the (cost) effectiveness of various amendments, accounting for the effects of soil and site properties, is missing. This limits the selection of the most appropriate amendment for use at farm level. To fill this knowledge gap, a world-wide meta-analysis was conducted to evaluate the response of soil pH and crop yield to different amendments in acidic soils while accounting for differences in soil properties. In addition, the costs of soil amendments application were calculated for situations differing in initial pH to guide the most cost-effective use of amendments to avoid and repair negative impacts of soil acidification on crop production in acidic soils.

2. Materials and methods

2.1. Data collection and data handling

We used Google Scholar (https://scholar.google.com/), Web of Science (http://www.apps.webofknowledge.com/), and the China Knowledge Network Infrastructure (https://www.cnki.net/) to search peer-reviewed publications from 1981 to 2021 reporting the effects of the application of amendments (i.e. lime, biochar, manure, industrial by-products and straw and combinations of them) on crop yield and soil pH. Specific search terms were used for literature screening, including "*soil amendments OR lime* OR biochar OR by-product OR straw OR manure*" and "*soil* pH *OR acid* OR yield.*" Data from both field and pot experiments were included, while the results from incubation or leaching experiments were excluded.

The data filtering process is shown in Fig. 1. To establish a complete dataset comprising all relevant factors affecting the impact of soil amendments, the following data was extracted: crop type, climatic conditions, experimental management (duration of amendments application, in years), soil properties (soil type, texture, initial pH, organic matter/carbon (OM) content, bulk density (BD), cation exchange capacity (CEC) and base saturation (BS)), and amendments properties (type and rate). The collected studies had to meet the following five criteria: (1) the experiment should have a control treatment without the application of amendments where all other agronomic practices remained unaffected (e.g. cropping intensity, fertilizer management and irrigation); (2) The materials and rates of soil amendments should be clearly reported; (3) the experiment includes at least one of the following target variables being affected by the soil amendment: soil pH, crop yield, CEC, BS, OM or BD; (4) The initial soil pH should be lower than 6.5 to exclude calcareous soils from the analysis; and (5) the means, standard deviation (SD) or standard error (SE) were reported. When SD was missing, SE was converted to SD by multiplying SE by the square root of the number of replicates.

Overall, 142 publications from 22 countries or regions were included (Fig. S1). Publication details of each paper are presented in the supplemental database. Results include changes for crop yield, soil pH, CEC, OM, BS and/or BD in response to amendment application. The GetData Graph Digitizer 2.26 was used to get numeric values from graphs or figures. The final dataset includes 832 paired observations for soil pH, 618 for crop yield, 204 for CEC, 292 for OM, 148 for BS and 80 for BD under different amendments application. Explanatory site properties controlling the response to amendments were grouped into categories described in Table 1.

In evaluating the impacts of pH, we used a standardized pH-H_2O with a 1:2.5 soil to solution ratio. The following equations were used to convert soil pH 1:2.5 KCl, 1:5 H_2O, or 1:5 $CaCl_2$ to 1:2.5 H_2O (Fotyma et al., 1998; Kabała et al., 2016; Minasny et al., 2011) before conducting the meta-analysis.

$$pH_{H_2O\ 1:2.5} = \left(pH_{H_2O\ 1:5} - 0.14\right) \times 0.99 \quad (1)$$

$$pH_{H_2O\ 1:2.5} = \frac{\left(11.58 \times log_{10}\left(pH_{KCl\ 1:2.5}\right) - 2.09\right)}{0.99} \quad (2)$$

$$pH_{H_2O\ 1:2.5} = 0.67 + 1.01 \times pH_{CaCl_2\ 1:5} - 0.12 \times \ln\left(EC_{H_2O\ 1:2.5}\right) \quad (3)$$

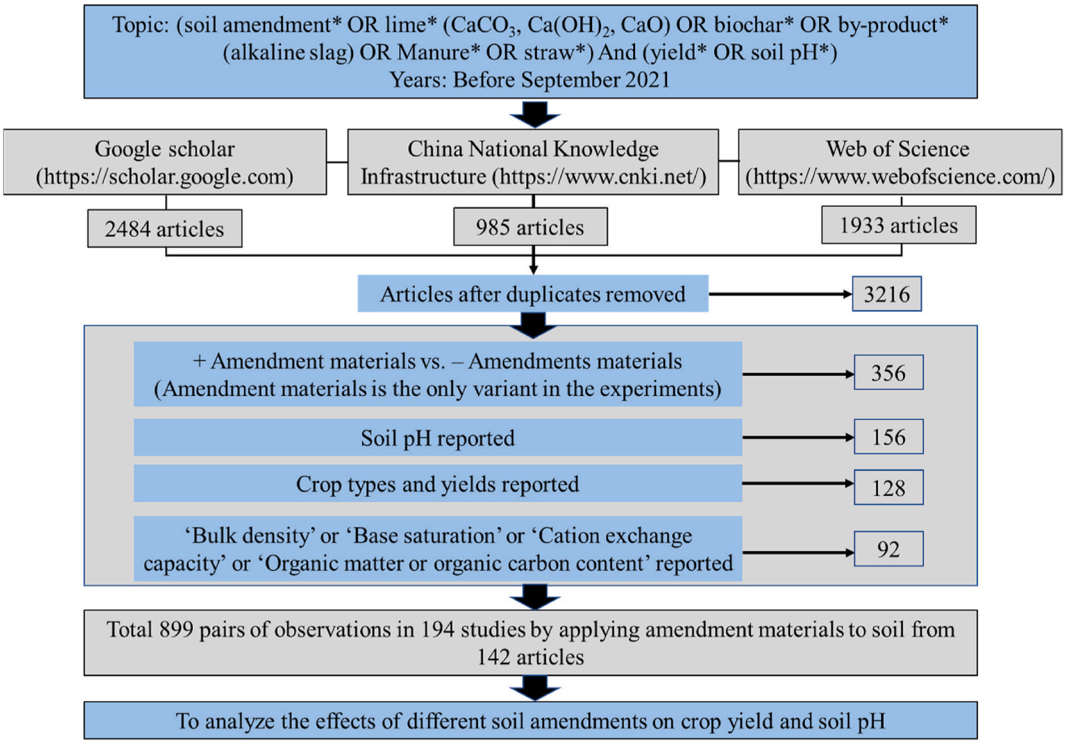

Fig. 1. Screening of soil amendments dataset by preferred reporting items for systematic reviews and Meta-analysis.

Table 1
Categorical grouping of variables which were used on meta-analyses.

	Variables	Categorical groups
Crops, experimental types and soil properties	Crops	Rice, Maize, Wheat, Fruits, Vegetables, Oil crops, Tubers, Tobacco, Tea, Cotton, Grasses, Others
	Duration (year)	<3, 3–6, >6
	Soil pH_{H2O}	<4.5, 4.5–5.0, 5.0–5.5, 5.5–6.0, 6.0–6.5
	Soil types	Ferralsols, Luvisols, Anthrosols, Fluvisols, Cambisols & Regosols, Phaozems
	Soil texture[a]	Clay, Loam, Sandy
	Soil CEC ($mmol_c$ kg^{-1})	<50, 50–100, 100–200, >200
	Soil OM (g kg^{-1})	<6, 6–12, 12–20, 20–30, >30
Amendment materials characteristics	Amendment types	Lime[b], Biochar, By-product, Manure, Straw, Combination[c]
	Amendment rates (t ha^{-1})	<1.5, 1.5–3, 3–6, >6 (lime); <10, 10–20, 20–30, >30 (biochar); <5, 5–20, >20 (by-product); <10, 10–20, 20–30, >30 (manure); <10, 10–20, >20 (straw); <5, 5–10, 10–30, >30 (combination[c])

[a] Clay (clay, sandy clay, silty clay), loam (sandy clay loam, loam, clay loam, silty clay loam) and sandy (sand, loam sand, sandy loam).
[b] Lime including $CaCO_3$, $Ca(OH)_2$, CaO, $CaMg(CO_3)_2$.
[c] Combination represents application of two or above amendment materials, with information on the included combinations being presented in Table S1.

2.2. Meta-analysis

In this study, we conducted a meta-analysis by using a random-effect model due to the significance of the residual heterogeneity of the observations (Schuch et al., 2016). The natural logarithm of the response ratio was used as the effect size since it quantifies the proportional changes in soil pH, crop yield, soil CEC, OM, BS and BD due to soil amendment by lime, biochar, manure, straw and industrial byproducts. Here, we abbreviate the 'natural log response ratio' as 'response ratio'. The natural logarithm of the response ratio (ln *RR*) reflects the relative change in one of the aforementioned properties due to application of a soil amendment: it is calculated by dividing the mean crop yield or soil property of an amended treatment by the mean of an unamended treatment (Hedges et al., 1999):

$$\ln RR = \ln\left(\frac{X_t}{X_c}\right) \tag{4}$$

where X_t represents the mean crop yield, soil pH, CEC, OM, BS and BD in the amended treatment and X_c represents the mean value of the control treatment (without amendments).

The variance (v) of lnRR was calculated as:

$$v = \frac{SD_t^2}{n_t X_t^2} + \frac{SD_c^2}{n_c X_c^2} \tag{6}$$

where SD_t and SD_c represent the standard deviations of the amended treatments and control, respectively, and n_t and n_c represent the associated sample sizes. Effect sizes were weighted by the inverse of the pooled variance.

2.3. Statistical analysis

The response ratio was calculated using the "metafor" R package (version 4.1.3). The mean effect sizes and the 95% confidence intervals (CIs) were presented in forest plots. Differences between amendment and no amendment are considered significant ($P < 0.05$) when the CIs do not overlap zero (Hedges et al., 1999). Spearman correlation analyses was performed to examine the relationship between the effect sizes for yield, soil pH, CEC, OM, BS and BD by using SPSS 21.0 (IBM, NY, USA). All figures were produced in Origin 2022b (OriginLab Corporation, Massachusetts, USA). Publication bias was analyzed by using the funnel plots and Egger's test. A well symmetric funnel plot and an insignificant Egger's test ($P > 0.05$) indicates that there is no obvious publication bias (Fig. S2). Otherwise we performed a trim and fill analysis on the funnel plot. Results (effect sizes) are also considered acceptable if there is no significant difference before and after trim and fill correction. In addition, the fail-safe number (NFs) was applied to test the robustness of the meta-analysis as recommended by Rosenberg (2005). If NFs exceeds 5 times the number of observations then the results can be considered highly robust and reliable (Table S2) (Lin and Chu, 2018; Niemeyer et al., 2020; Yuan et al., 2021). Our analysis showed that there was no significant publication bias (Fig. S2), leading to reliable results (Table S2).

2.4. Assessment of the costs of amendments

In order to evaluate the economic benefits of amendments application, the cost per hectare ($\$$ ha^{-1}) of 1% increases in soil pH or crop yield was calculated by dividing the total costs of the soil amendment (derived by multiplying the application rate (t ha^{-1}) and the price per ton amendment ($\$$ t^{-1})) by the percentage change in soil pH or crop yield due to the amendment. We set the costs of amendments at average market prices (Table S3), and the application rates of the amendments are the average values found from the dataset (Table S4).

3. Results

3.1. Soil pH and crop yield response to amendments application, their rates and duration

Application of soil amendments had a positive effect on soil pH and crop yield ($P < 0.01$), with an overall increase of 13 and 36%, respectively, compared to no amendment (Fig. 2). The effect on soil pH and yield varied greatly among the amendments, whereas the combination showed the best effect. Soil pH significantly increased by 15% for lime, 12% for biochar, 15% for by-products, 13% for manure, 5% for straw and 17% for a combination of amendments (Fig. 2A), whereas crop yield significantly increased by 29% for lime, 57% for biochar, 50% for by-products, 55% for manure, 9% for straw and 52% for a combination of amendments (Fig. 2B). The change in the soil pH was weakly and positively correlated to the change in crop yield (Fig. 7 and S2.), whereas the response for both soil pH and crop yield were highly crop dependent (Fig. S4.). For example, the application of amendments on soils with cash crops, such as tea, increased the pH on average by 26%, but the mean crop yield increased only by 10% (Fig. S4.). Inversely, the soil pH under acid-sensitive crops such as maize and wheat increased by 12–18% after amendment application (Fig. S4), whereas the yield increased on average by more than 50%. The response of both pH and crop yield mostly increased with the amendment application rates, but for by-products, manure and combined amendments the effect of application rate was generally not significant (Fig. 3). We also found that the percentage change of soil pH increased with a longer period of amendment application. The averaged soil pH increases by 8%, 12%, and 14% under durations of <3, 3–6 and >6 years, respectively (Fig. 2A). Similar trends were observed for crop yield (Fig. 2B) with the largest yield response when amendments have been applied for more than 6 years ($P < 0.01$). Continuous application of amendment materials could therefore alleviate soil acidity and enlarge the effect of yield increase.

3.2. Impacts of soil properties on pH and crop yield in response to amendments application

The response of soil pH and yield to soil amendment was largely affected by soil properties (Fig. 4). The highest impact was found in Ferralsols whereas soil amendments had only a minor impact in Phaoezems, Cambisols and Regosols. The highest impact of soil amendments was found in soils with a low pH ($pH < 5$) and a low buffer capacity, being the case for sandy soils with a low OM content and a low CEC (Fig. 4A). The average increase in yield due to the amendment ranged between 13% and 45% for soils with pH values below 5 (Fig. 4B). Soil texture strongly affected the soil pH and yield response ($P < 0.01$), with the largest increases of soil pH (15%) and yield (56%) found in sandy soil. Smaller but still substantial increases in pH (11%) and yield (28%) were observed in clay soils. Moreover, we found that soil pH and yield had lower responses in soils with CEC levels above 100 mmol + kg^{-1} and SOM levels below 20 g kg^{-1} (Fig. 4).

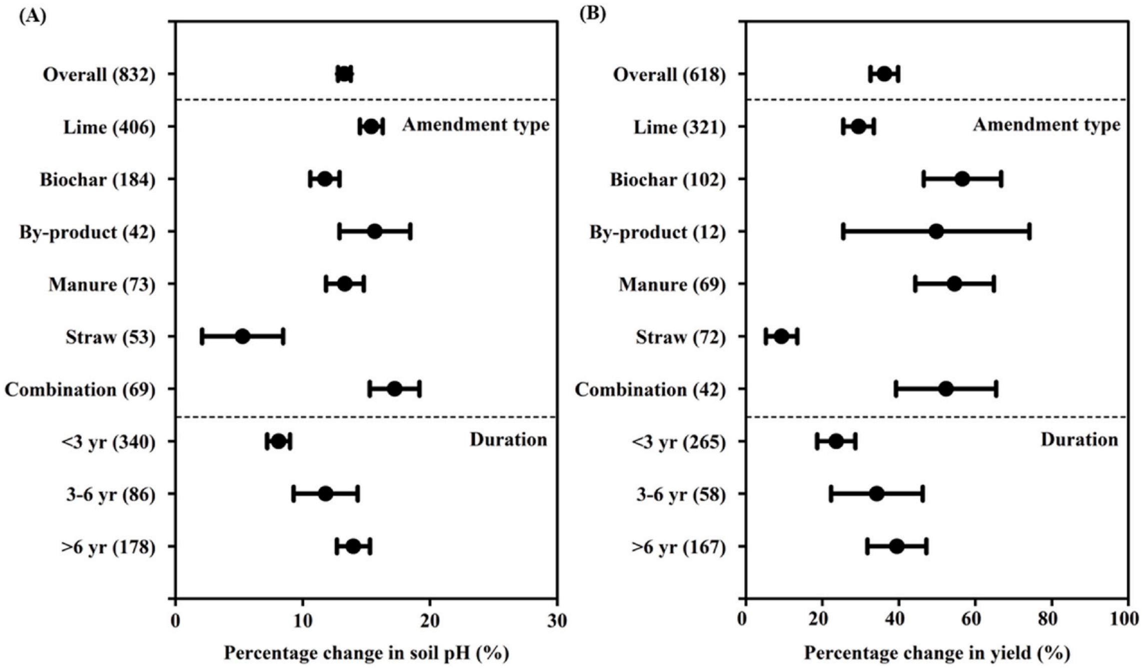

Fig. 2. The percentage change in soil pH (A) and crop yield (B) in response to amendments application (amendment type, application duration). The dots and error bars indicate the mean percentage change and 95% confidence interval (CI), respectively, with effects being significant if the CI does not overlap with the 0 line ($P < 0.05$). The number in parentheses indicate the numbers of observations.

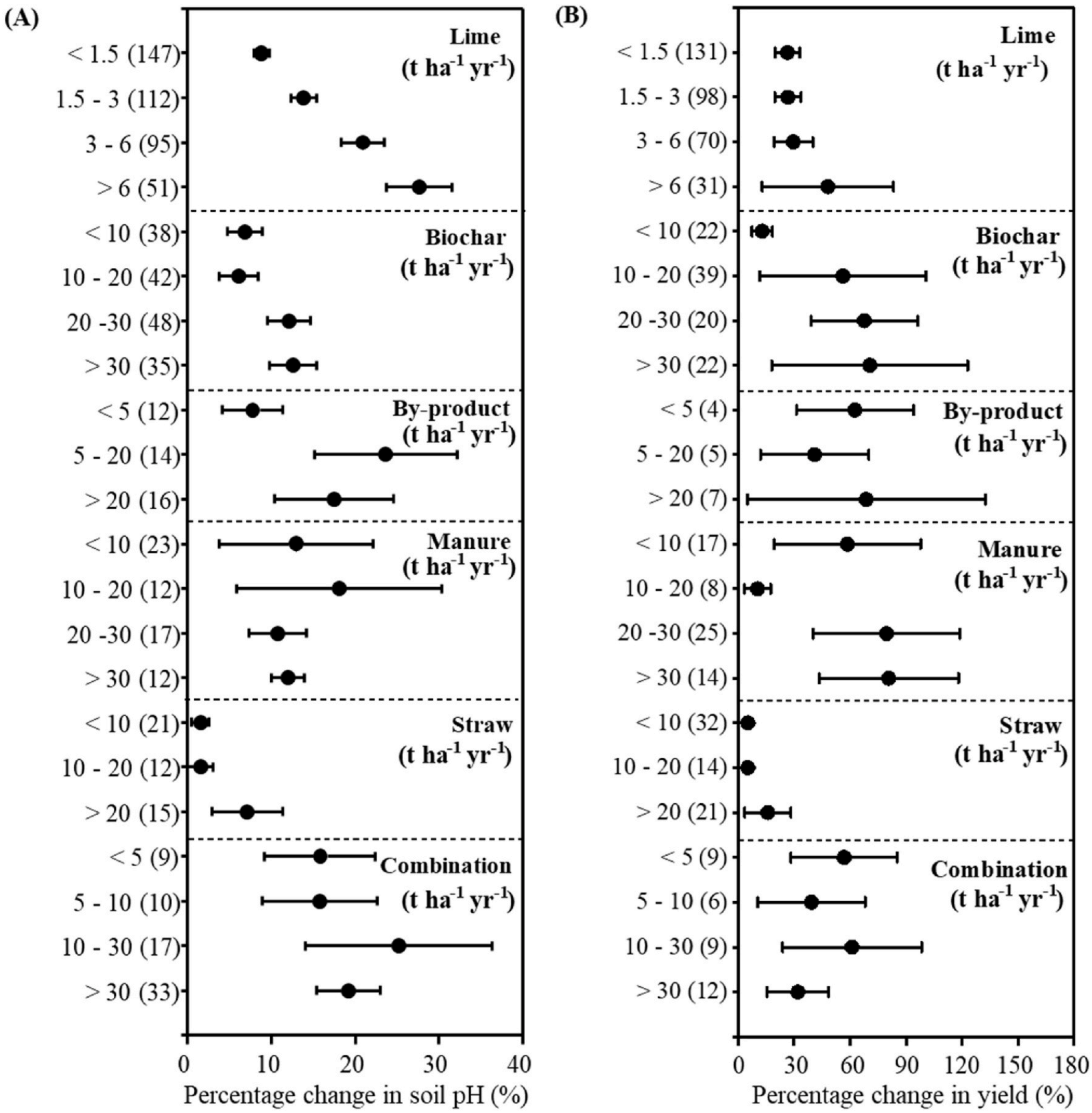

Fig. 3. The percentage change of different application rates (t ha^{-1}) of amendments in soil pH (A) and crop yield (B). The dots and error bars indicate the mean and 95% confidence interval (CI) of the percentage change, respectively, with effects being significant if the CI does not overlap with the 0 line ($P < 0.05$). The number in parentheses indicate the numbers of observations.

3.3. Soil property changes in response to amendments application and their relation to changes in crop yield

Soil amendments increased soil CEC, OM and BS by 27%, 27% and 65%, and decreased soil BD by 6%, respectively, compared to no amendments ($P < 0.01$, Fig. 5). All amendments increased soil CEC by 15–34% (Fig. 5A) and BS by 5–81% (Fig. 5C). The highest increase in CEC was observed after biochar application, followed by the application of combined soil amendments. Strongest increase of BS was observed when soil amendments were combined with lime. Soil OM responded positively ($P < 0.01$) to the application of biochar (50%), by-product (12%), manure (26%), straw (26%) and combined materials (40%), but showed no effect to lime alone (Fig. 5B). The soil BD declined with 10%, 1%, 6% and 12% when biochar, by-products, manure and combined soil amendments were applied, respectively. In contrast, liming increased soil BD by 1% ($P < 0.05$) (Fig. 5D).

Spearman correlations between the response of yield and soil properties to the application of soil amendments showed that the increase of yield was weakly and positively correlated with the change in soil pH ($P < 0.05$), CEC, OM and BS ($P < 0.01$) but negatively correlated with BD ($P < 0.01$, Fig. 6). The increase of soil pH was positively correlated with CEC, OM and BS ($P < 0.01$), but not with BD ($P > 0.05$; Fig. 6).

3.4. The costs of amending soil acidification by different materials in different pH ranges

Considering that the responses of pH and yield response to amendments varied greatly depending on the initial pH (Fig. 7), the application cost of soil amendments was calculated for situations differing in initial pH (Fig. 8). Among the evaluated soil amendments, the application of lime was the most cost-effective method to increase soil pH, followed by straw and manure. (Fig. 8A). The cost-effectiveness of these amendments to improve crop yield, however, slightly differed (Fig. 8B). Lime was the most cost-effective amendment in soils with pH values below 5.0, while both lime and manure were equally cost-effective when the soil pH ranged between 5.0 and 6.0. When the initial pH exceeded the pH of 6 then straw amendment was the most cost-effective method (Fig. 8B). Biochar was the most expensive amendment and therefore

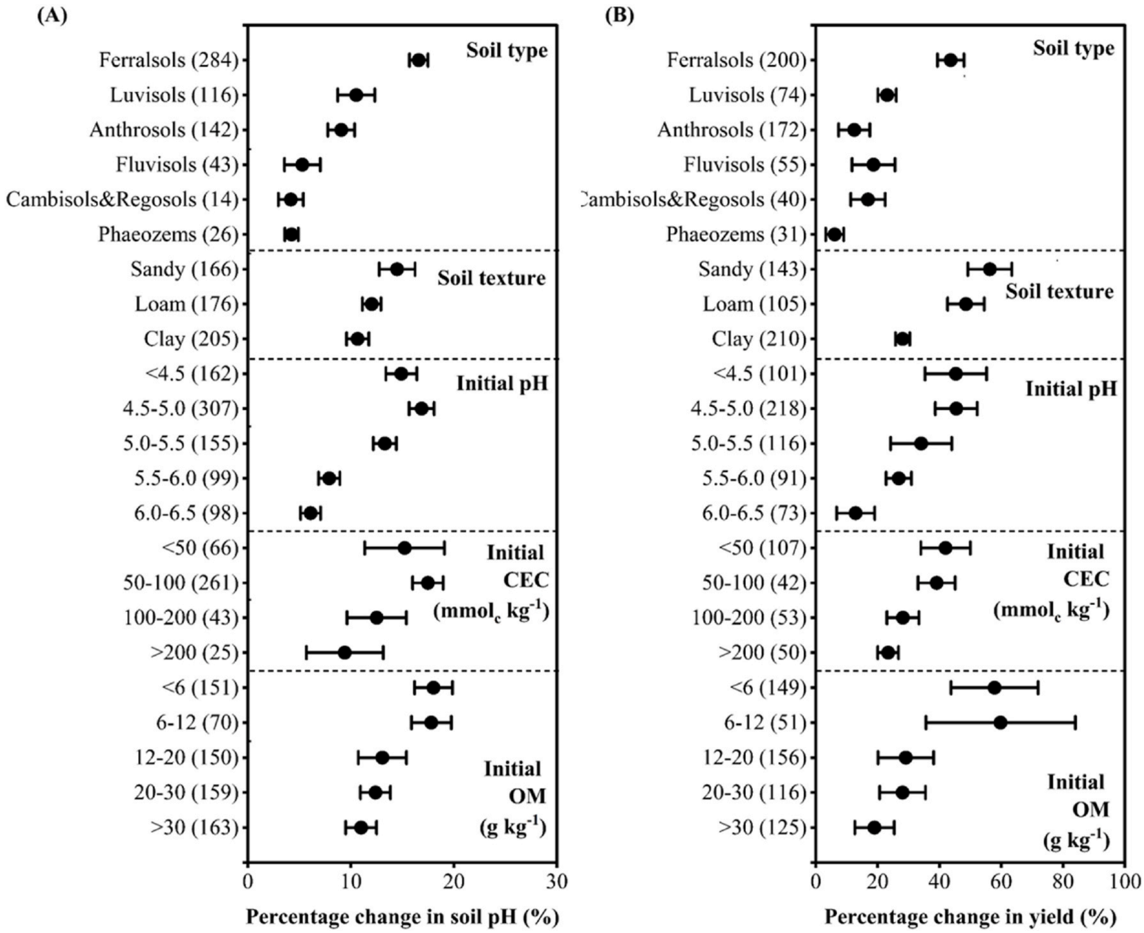

Fig. 4. The percentage change in soil pH (A) and crop yield (B) in response to amendments application as affected by soil property ranges (soil type, texture, initial soil pH, CEC, OM). The dots and error bars indicate the mean percentage change and 95% confidence interval (CI), respectively, with effects being significant if the CI does not overlap with the 0 line ($P < 0.05$). The number in parentheses indicate the numbers of observations.

financially not attractive to increase crop yields (Fig. 8). Lastly, manure and straw were most cost-effective for soils with pH values ranging between 5.0-6.0 and 6.0–6.5, respectively (Fig. 8B).

4. Discussion

4.1. Effect of soil amendments on soil acidification mitigation and yield improvement

An appropriate soil pH is an important factor to obtain and sustain high yield of crops in view of its great effect on metal toxicity, nutrient availability and soil microbial community (Zhao et al., 2022). Previous studies have shown that application of amendments in acidic soils can increase soil pH, although the effect varies greatly with the amendment applied (Siedt et al., 2021; Zhao et al., 2020). In this study, the quantitative effect of soil amendments on soil pH was analyzed (Fig. 2A). Our results showed that lime application had a greater and more stable pH raising effect (16%) than any other single amendment (Fig. 2A). This is probably due to types of lime, which are mainly oxides, hydroxides and carbonates of Ca (Li et al., 2019a; Wang et al., 2021) and its anions (chemically speaking, a “base”) undergo a chemical neutralization reaction with soil acidity (H^+) quickly (Farhoodi and Coventry, 2008; Holland et al., 2018). Therefore, lime application has always been regarded as the most effective practice to reduce soil acidity in previous studies and in the acidity amendment actions (Goulding, 2016). Similar to lime, by-products are also inorganic substances, but their composition is more complex, such as phosphogypsum, which, in addition to the main component $CaSO_4$, also contains large amounts of sulfur, phosphorus, and fluorides (Garrido et al., 2003). On the other hand, the dataset of by-products included alkali slag, steel slag and other industrial waste. This leads to a large compositional variation, being reflected in the huge variation in soil pH responses after amendment (Fig. 2A). Biochar had a stronger effect on soil pH than other organic amendments (i.e. manure and straw) due to its alkaline nature and high pH buffering capacity . In addition to being rich in base cations, biochar also contains functional groups such as –COO− and O−, and these functional groups can also react with H^+ and then increase the soil pH (Xu et al., 2012). Manure and straw, due to their alkalinity, can also increase soil pH, the extent of which depends on their content of base cations released during decomposition (Shi et al., 2019). Cai et al. (2018), for example, found that the ash alkalinity of swine manure was around 2 times that of soybean and maize straws, thus resulting in a much higher pH increase. This observation is in line with this meta-analysis showing that manure had a more substantial impact on soil pH than straw (Fig. 2A). In addition, whether straw can improve acidic soil pH has been controversial since its effect is usually limited (Cai et al., 2018; Siedt et al., 2021).

We found that amendment materials increased soil pH by 13% on average (Fig. 2A) and they stimulated crop yield by 36% in acidic soils (Fig. 3B and S3). The increase in crop yield has been linked to alleviated Al^{3+} toxicity and increased soil nutrients availability (e.g., Ca, Mg, and P) under amendments application (Tang et al., 2003; Zhang et al., 2021a,b). As previously reported, the response of yield varies among crops due to crop specific sensitivity to low pH conditions (Caires et al.,

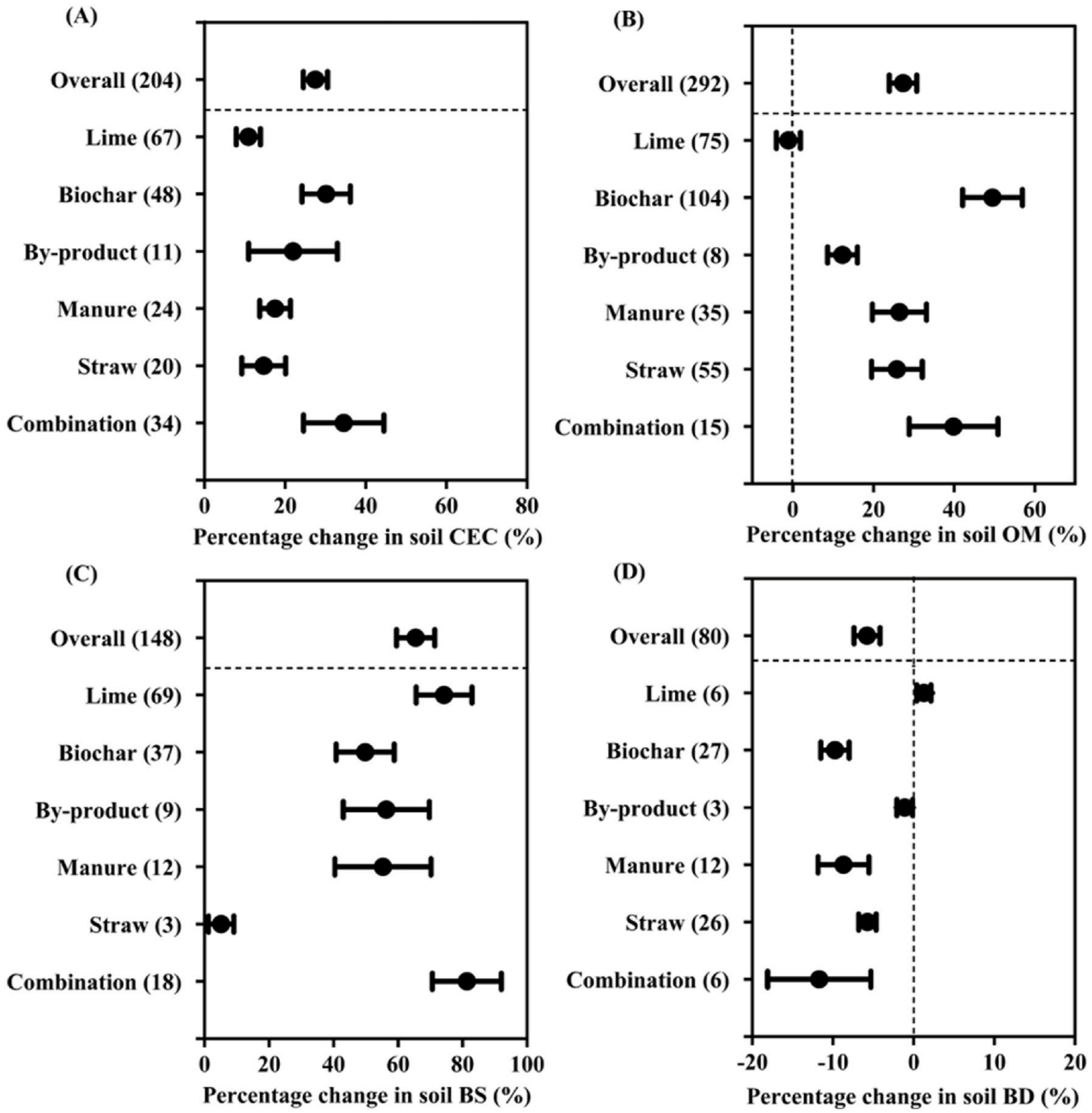

Fig. 5. The percentage change in soil CEC (A), OM (B), BS (C) and BD (D) under different amendments. The dots and error bars indicate the mean percentage change and 95% confidence interval (CI), respectively, with effects being significant if the CI does not overlap with the 0 line ($P < 0.05$). The number in parentheses indicate the numbers of observations.

2008). Our results showed much higher responses to soil amendments for maize and wheat than for tea (Fig. S4). Given the crop sensitivity and potential impact of soil amendments, their application needs more attention in cereal crop productions compared to cash crops like tea.

In addition, the positive impact of soil amendments on crop yield was positively related to the increase of soil CEC, OM, BS, and the decrease of BD (Fig. 6). As previously reported, amendments in acidic soils improves soil nutrient availability and promotes nutrients uptake, thereby increasing crop yields (Holland et al., 2019). Differences in elemental composition can therefore explain the potential benefits of the amendments evaluated (Wang et al., 2015; Wu et al., 2020). The main component of lime is Ca, which supplements large amounts of Ca^{2+} for crops. Long term application of lime however may also cause soil hardening (Wang et al., 2016) and affect the uptake of other cations by antagonism (i.e. Mg^{2+} and K^{+}) (Álvarez et al., 2009; Aye et al., 2016). Our results showed that lime application increased soil bulk density (BD) by 1% (Fig. 5D) ($P < 0.05$), which means the soil is slightly more compacted after lime addition (Du et al., 2020). This likely explains that sometimes other soil amendments are preferred to ameliorate soil acidification even though the lime impact on soil pH is the highest among the soil amendments evaluated (Chen et al., 2022; Li et al., 2019a). Organic amendments, such as biochar, manure and straw, contain abundant nutrients and binding agents that not only provide nutrients (e.g. N, P, K, Ca and Mg) to crops and increase organic matter, but also improve soil structure (Cai et al., 2018; Wang et al., 2017) and soil functions affected by organic matter (Ros et al., 2022). In our study, SOM responded positively ($P < 0.01$) to the application of biochar (50%), manure (26%) and straw (26%) (Fig. 5B). The use of straw as soil amendment was also reported to be insufficient to reduce the negative effects of acidification on the short term (Cai et al., 2019; Ma et al., 2019), being conformed by the limited increase in crop yields by straw application in our study (Fig. 2B).

Our study also quantified the effects of amendments application duration and soil properties on crop yield under amendment materials application (Figs. 2B and 5B). Positive yield effects from soil amendments were greatest (39%) in areas where the practice has lasted for more than 6 years (Fig. 2B). This is consistent with previous studies reporting that the effects of soil amendments like lime, biochar or

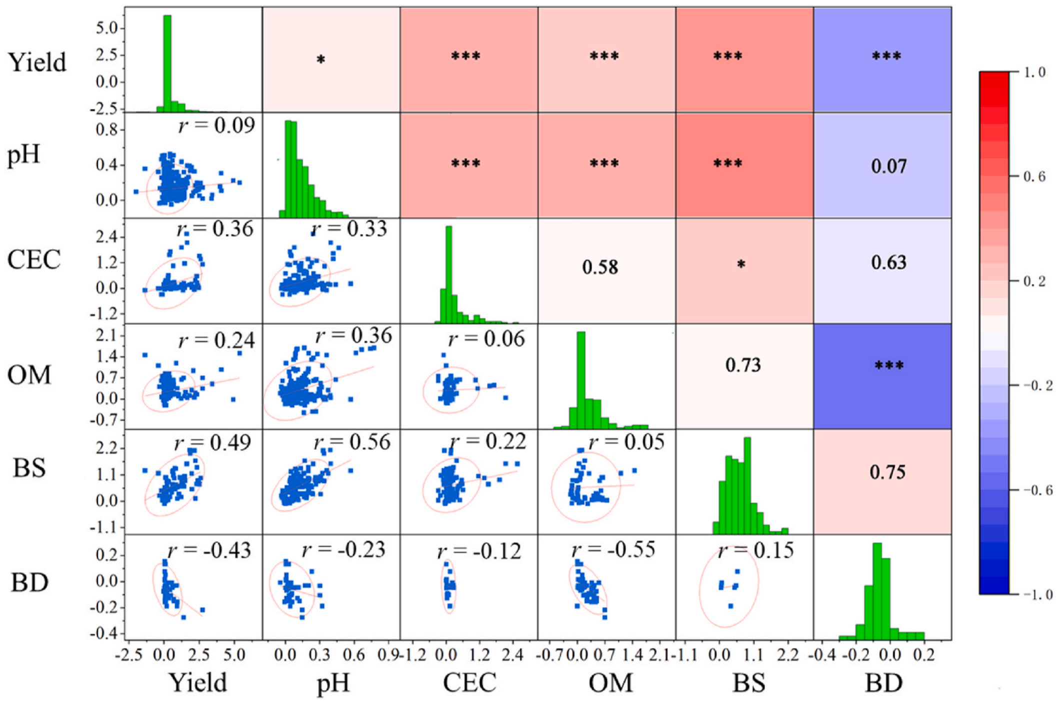

Fig. 6. Spearman correlations between the effect size of yield, soil pH, CEC, OM, BS and BD. The upper right triangle shows the correlation significance, i.e, *, *** at $P < 0.05$ and $P < 0.001$, respectively. For non-significant, showed the P values. Blue and red colors indicate negative and positive correlation, respectively. The lower left triangle shows the correlation coefficient (r) values. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

manure on soil fertility and yield increases when these amendments are frequently applied (Farhangi-Abriz et al., 2021).

4.2. Effects of site conditions on pH and yield response to amendments application

Initial soil properties strongly affect the response of soil pH and crop yield to amendments application (Zhao et al., 2022) as shown for soil type, texture, pH, OM and CEC (Fig. 4). Although soil pH and yield showed positive effects with amendments application on all soil types, the higher increase was observed on Ferralsols. These soils are usually extremely acidic and rich in Fe^{3+} and Al^{3+}. The strong acidity can be neutralized with amendments application, thereby reducing the Al toxicity risk on crops (Shi et al., 2019), explaining the observed strong increase in yield (Fig. 4B). Since the pH of most amendments is higher than that of acidic soils, exhibiting alkaline characteristics (Li et al., 2019), the response of soil pH to amendment application to was greater in strong acidic soils with pH values below 5.0 (Fig. 4A).

The magnitude of yield increases in response to amendments application was smaller in soils being high in CEC and SOM (Fig. 4B). This corresponds to the known impact of soil organic matter and clays controlling the pH buffer capacity as well the pH itself (He et al., 2021). Increasing SOM and related CEC reduces the pH decline in response to proton production (defined as soil acidification). Amending soils with organic amendments like biochar, manure or compost decreases therefore the sensitivity of a soil to acidification (Cai et al., 2019). Because clays also contributes to the buffer capacity and buffers the impact of amendments, we observed that changes in pH were more pronounced in sandy soils (Fageria and Baligar, 2008) (Fig. 4). Next to soil properties, climate also affects the sensitivity of a soil to acidification, since high rainfall rates are associated with higher leaching rates of base cations, thereby enhancing soil acidification and the need for soil amendments to reduce the acidification (S. Zhang et al., 2022). A higher positive response on yield was observed under tropical climate, perhaps because higher temperature and moisture conditions enhance photosynthesis and stimulate soil microbial activity (Lee et al., 2019), which in turn accelerate nutrient transformations. However, there is no clear mechanism to assume an impact of climate on the pH response to an amendment.

4.3. Materials recommendations for soil acidification amendment

The identification of best soil amendment and application rates have been debated in view of soil acidity management and crop sustainable production (Farhangi-Abriz et al., 2021). Our meta-analysis showed that the optimum application rate varies per product to maximize the crop yield response (Fig. 3) varied from around >6 tons ha^{-1} for lime, 5–20 tons ha^{-1} for industrial byproducts, 20–30 tons ha^{-1} for manure, 20–30 tons ha^{-1} for biochar, >20 tons ha^{-1} for straw and 10–30 tons ha^{-1} for optimum combinations (Fig. 3). Most previous studies on the appropriate rate of soil amendments showed similar doses, as being illustrated by an optimum lime dose of 6–16 t yr^{-1} in Goulding's (2016) Fertiliser Manual when the initial soil pH is below 5.0. In addition, field experiments showed an optimum dose of 11–25 tons for biochar (Liu et al., 2013; Yan et al., 2021). Besides, Gai et al. (2016) found that the application of 23 t yr^{-1} manure can substantially improve soil pH and yield compared with chemical fertilizers in vegetable production. The agreement of our estimates with these studies show that the recommended rates of the meta-analysis might be useful for practical guidance.

Soil amendments might also lead to economic benefits. Therefore, the costs of amendments under different soil conditions are also worth considering when recommending amendments. As previously reported, lime has been identified as the most effective amendment to raise soil pH with limited costs (Li et al., 2019a; Li et al., 2019b). Our quantitative analysis confirms this observation for soils having a pH value lower than 6 (Fig. 8). Compared with other amendments, biochar has the highest costs per 1% increase of soil pH and crop yield (Fig. 8). Robb and Joseph (2015) reported that the cost of biochar varied between US$ 100 and 250 per ton, limiting its use in conventional farming systems even

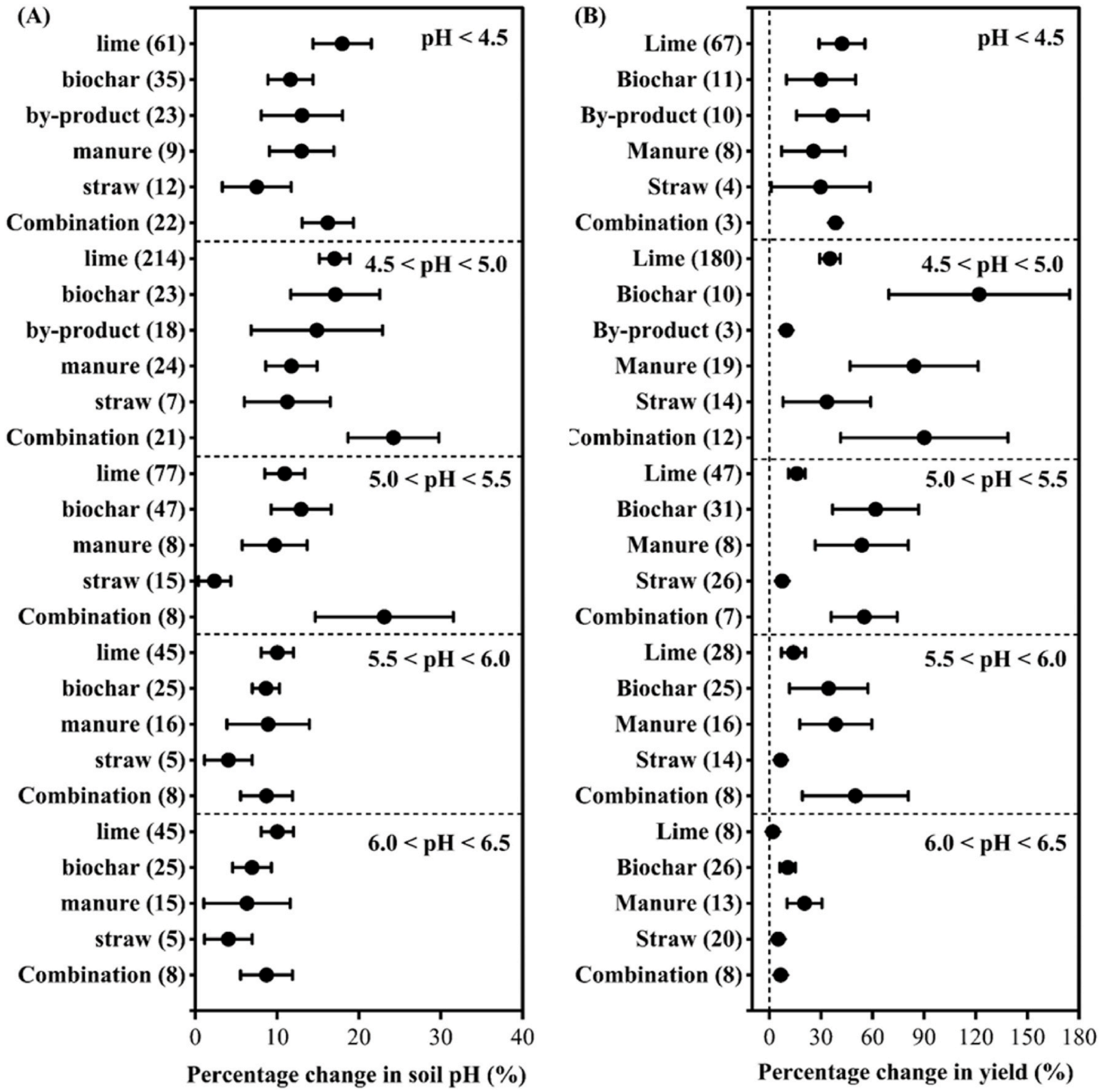

Fig. 7. Percentage change in soil pH (A) and crop yield (B) of different amendment s application under different pH ranges. The dots and error bars indicate the mean percentage change and 95% confidence interval (CI), respectively, with effects being significant if the CI does not overlap with the 0 line ($P < 0.05$). The number in parentheses indicate the numbers of observations.

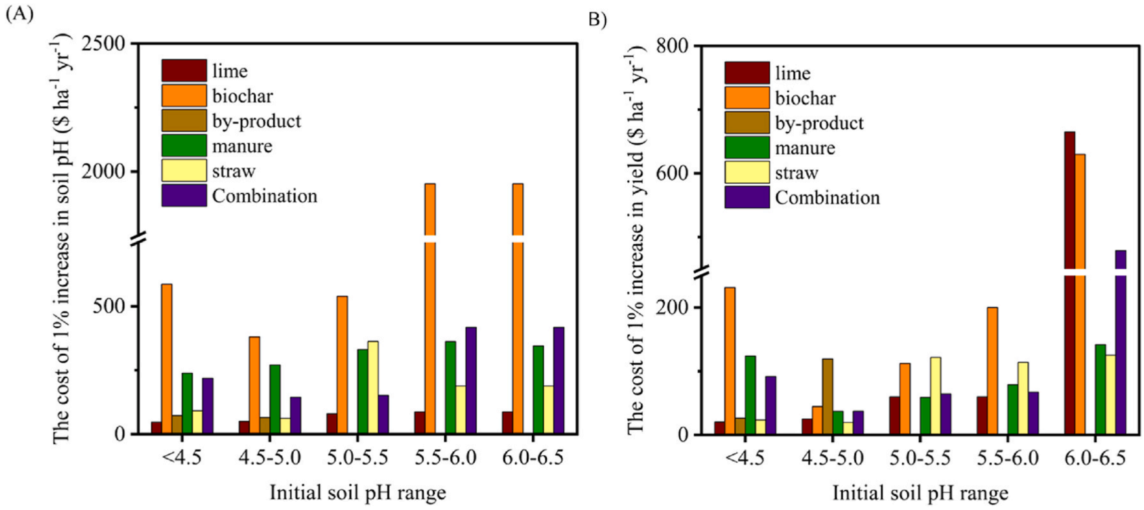

Fig. 8. The cost of 1% increases in soil pH (A) and crop yield (B) of different amendments in different initial soil pH ranges.

although it might have many advantages for soil health and acidity amelioration (Farhangi-Abriz et al., 2021). In contrast, manure and straw are often cheaper and therefore a cost effective alternative to increase soil pH, in particular when the pH exceeds the pH value of 4.5 (Fig. 8). Note that only a few industrial by-products have been included in our meta-analysis, whereas their impact is highly variable due to their elemental composition. The effect and cost of by-products in raising pH are on average comparable to those of lime, but due to their relatively complex compositions, they are not as effective as lime (Blum et al., 2012).

Al toxicity has become the main constraint in strongly acidic soils (pH < 4.5) restricting crop production by damaging the root system (Baquy et al., 2018; Zhang et al., 2020). Therefore, rapidly increasing soil pH is the main strategy when the soil pH is less than 4.5 (Zhu et al., 2020). Combining the amendment properties with the amendment costs to improve soil pH and yield, lime (>6 t ha^{-1}) should be recommended for soils when the pH declines below 4.5, as it can quickly eliminate the toxicity of Al^{3+} to crops (Aye et al., 2016; Conyers et al., 2003; Li et al., 2019) and it is cost-effective (Fig. 8). In slightly acidic soils ($4.5 < pH < 6.5$) the crop yield decline due to acidification is often smaller (Du et al., 2020) allowing one to use soil amendments that improves soil fertility and the buffer capacity of soils to minimize the risks of acidification (Cai et al., 2018). Under these conditions the use of manure (20–30 t ha^{-1}) and straw (>20 t ha^{-1}) should be recommended, with a preference for straw in conditions where soil pH exceeds a pH value of 6. Our analysis shows that an optimized acidification management scheme should account for the initial soil properties, crop types, and amendment properties (Liu et al., 2013; Siedt et al., 2021) and the recommended practices based on our analysis might help to design robust and optimal amendments application strategies to ameliorate soil acidity and to improve crop yield in agroecosystems.

5. Conclusions

Our meta-analysis on the effects of the application of different amendments on soil pH and crop yield showed that combining soil amendments leads to the highest effects with an increase of 17% for pH and 52% for crop yield. Amendments are most effective in enhancing soil pH and crop yield in strongly acidic, sandy soils that have a low acid buffer capacity. The average yield increase ranged from ca. 10% at an initial soil pH above 6–45% when the soil pH falls down below 4.5. Most amendments had positive effects on soil CEC, soil organic matter content and base saturation (increase) and soil bulk density (decrease), being positively correlated with crop yield. However, long-term lime application leads to small negative effects on soil organic matter content (decrease) and bulk density (increase, due to soil compaction). The most appropriate amendments to reduce soil acidification and enhance crop yields differ in different pH ranges. Considering the effects on soil pH and crop yield and costs of the amendments, lime, manure or straw being seem the most appropriate amendments when the initial pH is < 5.0, 5.0–6.0 and 6.0–6.5, respectively.

Credit author statement

Siwen Zhang: Conceptualization, Data collection, Writing – original draft, Formal analysis, Visualization; **Qichao Zhu**: Conceptualization, Writing – review & editing, Supervision; **Gerard Ros**: Formal analysis, Review and Editing; **Wim de Vries**: Supervision; Writing – review & editing; **Xiaohui Chen & Muhammad Atif Muneera**: Formal analysis; **Fusuo Zhang & Liangquan Wu**: Supervision; Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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