A META-ANALYSIS ON INFLUENCE OF OXIDIZED-BIOCHAR ON CROP YIELD

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Abstract
Application of oxidized-biochar as one of the most controversial issues of sustainable agriculture and consequently improving crop production needs to a meta-analysis investigation due to conflicting studies that covers representative crop yields datasets. Based on results, crop yields increased by 6.7%, 11.8%, and 18.1% in low (<15 ha), medium (15-25 ha), and high (>25 ha) rates of oxidized-biochar, respectively. While produced-biochar at 350-500 °C and >500 °C temperature significantly enhanced crop yield by 20.2% and 15.7%, respectively, there wasn't a significant change in yield with biochar pyrolyzed at < 350 °C. Also, using oxidized biochar caused to increase crop yield in soils with high value (>2.5% kg^{-1} soil) of organic matter and clay texture by 23% and 22% increase, respectively. Overall, altering these factors can notably boost crop yield efficiency, because they play important roles in nutrient, water and air supply as well as in biogeochemical cycling in agricultural ecosystems.

Key words: *soil organic carbon, pyrolysis temperature, aging, oxidation.*

INTRODUCTION

In recent decades, special attention has been paid to increasing crop production efficiency by application of biochar in the direction of sustainable agriculture (*Asadi et al., 2021*). Due to its porous structure and creating a suitable substrate to retain water, nutrients (*Ghorbani et al., 2019*) and prevent the absorption of contaminants such as heavy metals by plant roots (*Amirahmadi et al., 2020*), the crop yield has been significantly enhanced (*Ghorbani et al., 2021*). Recently, this attention has been enhanced by boosting the surface properties of biochar, such as the cation exchange capacity (CEC) due to oxidation (*Yang et al., 2019; Li et al., 2020*). Most scientific publications refer to the initial properties of fresh biochars. However, these properties are changing over time when biochars have been exposed to a moisture-containing environment, as it is the case after application to soil. This process is referred to as "ageing (oxidation)" (*Beusch, 2021*). Oxidation of biochar can be defined as dissociation in biochar structure and altering in its biochemical characteristics. These basic changes can be effectively caused to the dissolution of organic compounds, absorption of dissolved compounds from the soil, and the neutralization of alkaline conditions in soil over time (*Mia et al., 2017*; *Hung et al., 2021*). It has been studied that the degradation of biochar due to the aging process can be derived into two-part as follows; a) biotic oxidation (activities and respiration of microorganisms) and abiotic oxidation (chemical aging in lab, and photooxidation) (*Bakshi et al., 2016*; *Feng et al., 2018; Yang et al., 2019*). The addition of oxidized-biochar in soils may be more advantageous than fresh biochars, because the degradation in characteristics of the biochars during oxidation may extent the capacity of water and nutrient sustain in soils (*Shi et al., 2015*; *Mia et al., 2017*).

It has been demonstrated that oxidized-biochar can improve soil water storage in drought conditions (*Mia et al., 2017*; *Hung et al., 2021*). Meanwhile, oxidized-biochar can improve carbon sequestration due to the mineralization of organic carbon (*Li et al., 2020*). Surface characteristics of biochar are playing important roles in altering absorption behavior in soil (*Asadi et al., 2021*; *Hung et al., 2021*). Organic matter in biochar tends to be converted to low molecular weight compounds by chemical interactions over a long period of time (*Pan et al., 2021*). The chemical oxidation of biochar is one of the best promising ways to degradation of physicochemical characteristics of biochar and thus, enhance the CEC of biochar as the result of more negatively charge and oxygen-containing functional groups on the surface (*Huff et al., 2018*; *Yang et al., 2019*). On the other hand, it has been shown that using oxidized-biochar without fertilization may even diminution crop yields due to immobilization of N (*Tam-meorg et al., 2014*). A considerable increment in quinoa (*Chenopodium quinoa L.*) yield was reported (*Kammann et al. 2015*) when a mix of compost and biochar was applied to the soil. The substance of compost-biochar was significantly nutrient-loaded and had absorbed substantial amounts of nitrate. Also, there wasn't a significant improvement in maize yield when oxidized-biochars were applied for two years'

field study (*Rogovska et al., 2014*). A labile fraction of oxidized-biochar which is rapidly mineralized by the extension of soil respiration is the main reason (*Haider et al., 2017*). Therefore, it's hypothesized that decreasing nutrient availability may also be correlated with the complex absorbent behavior of biochar (*Kanthle et al., 2016*).
Increment of phenolic hydroxyl groups and aromatic ethers on biochar surface due to oxidation is inevitable (*Li et al., 2020*). However, the magnitude of degradation on the surface area isn't clear, and different studies have reported conflicting findings of either enhancement or a scarce reduction in functional groups. Notwithstanding, the manipulating of oxidized-biochar in agricultural systems has been implemented by many studies, it seems existence of contradictory data regarding the changes in crop yields needs a meta-analysis study. Therefore, the aim of this meta-analysis is clarification the role of oxidized biochar in crop efficiency influenced by pyrolysis condition and soil properties.

MATERIALS AND METHODS

Literature survey and selection criteria

Based on published literature, this meta-analysis was implemented. We identified papers that reported agricultural crop yield in non-oxidized (control) and oxidized (treatment) biochar using the online database search engines Web of Science and Google Scholar. Keywords used for literature search were combinations of terms such as biochar, pyrolysis, feedstock, oxidation, aged biochar, soil, surface area, porosity, functional groups, CEC and crop yield. Also, two criteria were considered to select proper studies as follows: a) all studies were conducted in agricultural environments, and b) all studies reported results from a non-oxidized (control) and oxidized (treatment) biochar.

Collection of data

We reviewed over 50 papers and found that 12 of them met our selection criteria. In total, 864 observations or 432 pairs of observations (effect sizes) were extracted from those studies meeting our criteria and were used in this meta-analysis. These datasets consisted of crop yield in t ha^{-1} affected by oxidized and non-oxidized biochar, pyrolysis temperature, and soil texture and soil organic carbon (SOC).
The rate of biochar application was grouped as low for <15 ha, medium for 15-25 ha, high for >25 ha. Pyrolysis temperature were classified as low (<350 °C), medium (350-500 °C), and high (>500 °C). Soils with the texture of sandy loam, loamy sand, and sand were categorized as sandy. Also, studies that contained soils with the texture of loam, silt loam, clay loam, and silty clay loam were categorized as loamy, as well as, clay and silty were grouped as clay texture. SOC was categorized as low (<1 %), medium (1-2.5 %), and high (>2.5 %).

Meta-data analyses

Meta-analysis calculates the magnitude of change of a variable and the significance of this change in response to a treatment. The natural logarithm of the response ratio (RR) was used to evaluate the value of change which defines as effect size (*Hedges et al., 1999*):

$$\ln(RR) = \ln\frac{X_T}{X_C}$$

where X_C and X_T represent the average of the variable in the control and treatment, respectively. The RR can be considered as the percentage change after applying oxidized-biochar as ($e^{\ln(RR)}$ -1) × 100 (*Nave et al., 2010*). For generating confidence intervals (CIs) around effect sizes, we recorded standard deviation (SD) and number of replicates (n) of crop yield for the control and treatment. The statistical significance was tested using 95% CI for each effect size. If the 95% CIs didn't overlap with the zero line, the change was statistically significant at $P \leq 0.05$. Also, doesn't overlap between groups represent significant differences. A non-linear regression test was used for SOC versus biochar rate and for soil texture versus biochar rate, because the data were not normally distributed. Data collection and organization as well as all calculations (i.e., effect size and CIs), regression analyses and creation of forest plots were performed by Microsoft Excel 2020.
For assessing the presence of publication bias, the Spearman rank correlation test in order to clarify the correlation between the replicates of each study and the effect size was conducted (*Holden and Treseder, 2013*). No publication bias was inspected in the crop yield data for any of the factors.

RESULTS AND DISCUSSION

Based on meta-analysis of data, oxidized-biochar caused crop yield changes across all investigated influencing factors and in total significantly increased crop yields up to 14% at $\alpha = 0.05$ (Fig. 1).

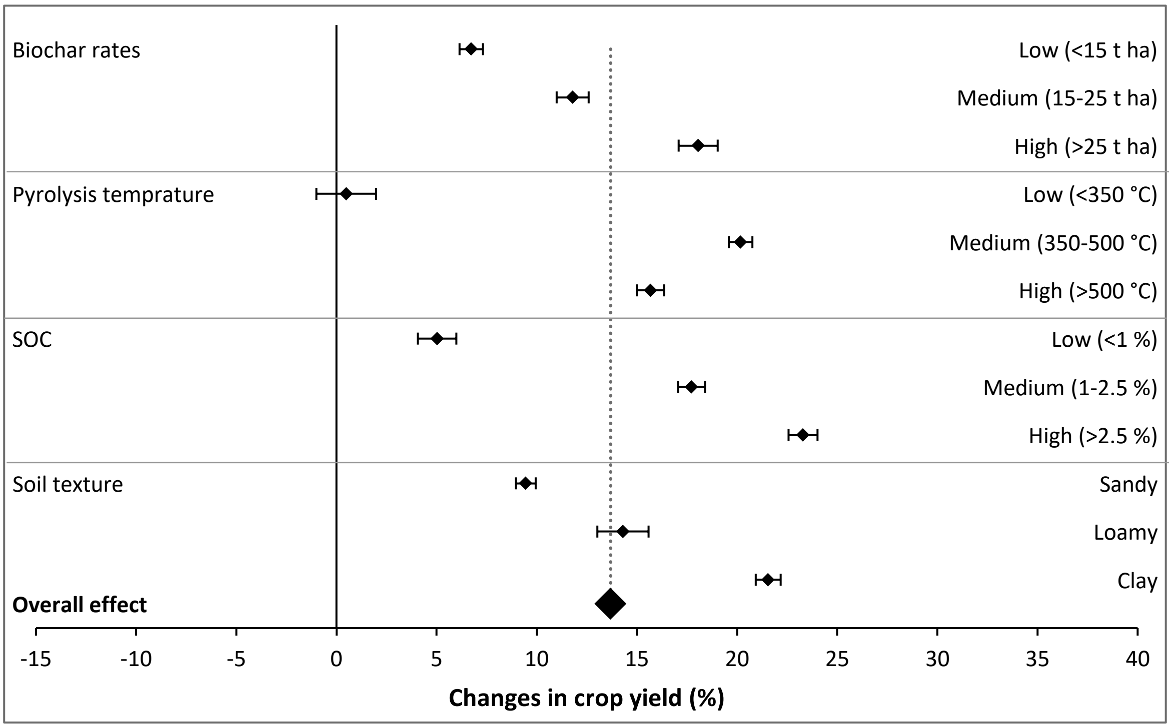

Fig. 1 Crop yield changes due to application of oxidized biochar, influenced by biochar rate, pyrolysis temperature, SOC, and soil texture. Results are presented as mean effect sizes ± 95% confidence intervals. Groups with confidence intervals overlapping the reference line (0% change) indicate no statistically significant change in crop yield due to using oxidized biochar at $\alpha = 0.05$.

Influence of biochar application rates

Crop yields increased by 6.7%, 11.8%, and 18.1% in low, medium, and high rates of biochar, respectively, due to oxidation, which were significantly different from each other. Greater effectiveness in higher grades means more porosity and negative charges on the biochar surface, resulting in more water and nutrients available to the plant's roots. Adding oxidized-biochar to the soil stimulates the development of acidic functional groups (*De la Rosa et al., 2018*), and the accumulation of basic functional groups on the biochar surface will decline for the long term (*Rechberger et al., 2017*). Furthermore, the negative surface charge is increasing with oxidation, leading to a high surface charge density and enhanced CEC (*Mia et al., 2017*). One of the main reasons for the increase in crop yields at higher rates of oxidized-biochar is adding nutrients and required ions to the soil than furthermore. Enhancement in atomic concentrations of sulfur (S), N (nitrogen), sodium (Na), aluminum (Al), calcium (Ca), manganese (Mn), and ferric (Fe) was detected at the surface of oxidized-biochar (*Mia et al., 2017*; *De la Rosa et al., 2018*). In particular, the changes in the surface chemistry may alter the adsorption properties of oxidized-biochars and consequently more nutrient retention in soil (*Ren et al., 2016*). However, due to the increment in CEC, oxidized-biochars may provide a superior potential to sustain cations and elevate crop yields (*Mia et al., 2017*).

Influence of pyrolysis temperature

Oxidized biochar which produced at medium (350-500 °C) and high (>500 °C) pyrolysis temperature significantly enhanced crop yields by 20.2% and 15.7%, respectively. While adding oxidized biochar that derived from low pyrolysis temperature (< 350 °C) wasn't significantly affected by oxidation. In general, ageing processes are enhanced with increasing temperatures and duration of exposure (*Heitkötter & Marschner, 2015*) and in particular affect the biochar surface (*Sorrenti et al., 2016*). Pyrolysis temperature is a key factor that most of the biochar characteristics are depending on its changes (*Ippolito et al., 2020*; *Das et al., 2021*). Higher temperatures caused to increment of C content (*Yuan et al., 2011*), specific surface area, and porosity (*Al-Wabel et al., 2013*), inorganic element concentrations (*Chen et al., 2019*), ash content (*Ippolito et al., 2020*), CEC (*Zhao et al., 2013*), and aromaticity (*Chen et al., 2019*). With the rising temperature, more volatile ingredients have been lost, and as a result, the value of biochar yield will be diminution (*Al-Wabel et al., 2013*). Moreover, higher temperatures foster decomposition of acidic functional groups like phenolic hydroxyl and carboxyl groups, while carbonyl groups form (*Chen et al., 2019*). Also, decreasing zeta potential with increasing pyrolysis temperatures has been reported, which indicating less negative surface charges for high-temperature biochars than for low-temperature biochars (*Yuan et al., 2011*). This is the main reason that biochar divided from 350-500 °C had the best result in oxidized-biochar efficiency.

Influence of soil organic matter and texture

Application of oxidized biochar significantly increased crop yields up to 5%, 18%, and 23% in soils with low (<1%), medium (1-2.5%), and high (>2.5%) values of SOC, respectively, which have shown significant differences from each other. Crop yields significantly increased by 22%, 14%, and 9% in clay, loamy and sandy soils, respectively, due to oxidation. Also, there were significantly different between soil textures. It has been widely corroborated that biochar significantly affects the accumulation of organic carbon and nitrogen at soil aggregate fractions (*Xiu et al., 2019*; *Ghorbani et al., 2019*; *Joseph et al., 2020*). After adding oxidized-biochar to the soil biochar surface is coated and the pores are linked with organic and mineral components of soils (*Ren et al., 2016*; *De la Rosa et al., 2018*), leading to an increase of aggregation and improving soil structure (*Xiu et al., 2019*). The clay particles apparently play the main role in formation of soil aggregates through binding organic molecules by bi- and trivalent cations (e.g. Ca^{2+}, Fe^{3+} and Al^{3+}) (*Juriga et al., 2018*). That is why soils with clay texture showed the best perform in increasing crop yields. Regarding Fig. 2, a significant positive correlation between changes in biochar rate and SOC (R^2= 0.49), as well as, biochar rate and soil texture (R^2= 0.56) in response to adding oxidized-biochar proves that claim.

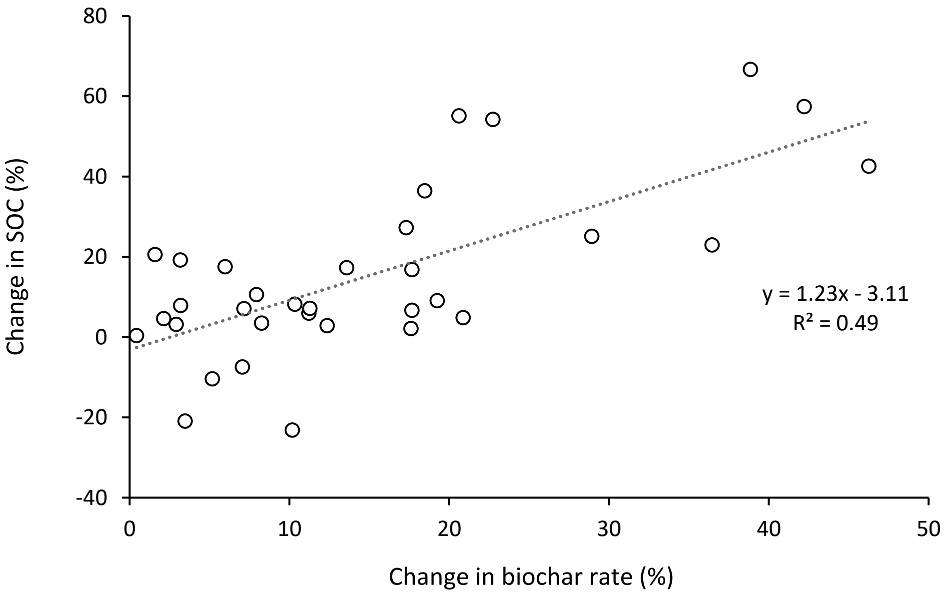

Fig. 2 The correlation between the percentage changes in biochar rate (n = 33) and soil organic carbon (SOC). The correlation was statistically significant at α = 0.05.

CONCLUSIONS

This meta-analysis evaluated the impact of oxidized-biochar on crop yields in agricultural ecosystems affected by two amendment factors (biochar rate and pyrolysis temperature and two soil factors (SOC and texture). Despite contradictory reports in previous literature, the meta-analysis showed that the application of oxidized-biochar significantly increased crop yields up to 14%. The positive effect of oxidized-biochar on efficiency of crop yield is largely depends on the pyrolysis temperature. This means that increasing the pyrolysis temperature increases the porosity of biochar structure. This helps to increase the specific surface area and oxygen-contained functional groups during the oxidation and then supply more nutrients, water and air for plant root's area. Accompanied with the fact that clay texture soils hold more water and create organo-mineral bridges with soil organic matter, specific consideration should be paid when oxidized-biochar are used, with the intention to improve the efficiency of strategic agricultural products.

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