Integrated use of biochar and lime as a tool to improve maize yield and mitigate CO₂ emission: A review

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ABSTRACT

Reducing greenhouse gas emissions and increasing agronomic productivity by sustaining soil organic matter and refining soil fertility have become the main concerns for agricultural scientists. There is a new approach to decrease greenhouse gas emissions, soil C sinks, and improve soil quality using biochar. Soil acidification is improved by applying lime or other acid-neutralizing materials. Additionally, Ca and Mg can increase by applying lime. The availability of Ca, Mg, and K in the soil is significantly affected by the application rate of biochar spread separately or combined with chemical fertilizers. Soil nutrients and maize (*Zea mays* L.) yield are highly influenced by the use of lime and biochar. Biochar can improve the ecosystem by reducing soil CO_2 emissions from agricultural practices. The inconsistent results and clarifications from various studies highlight the importance of relating the impact of different biochar rates on CO_2 emissions and maize yield. This review summarizes the properties of biochar, provides the scientific reference for its application to achieve high and good quality maize and reduce CO_2 emissions.

Key words: Acid soil, biochar, greenhouse gas abatement, lime, soil nutrients, *Zea mays*.

INTRODUCTION

Maize (*Zea mays* L.) is one of the leading cereal crops in the tropics, providing a source of food and oil for human beings and feed for animals along with diverse raw materials for agro-based industries (Zaidun et al., 2019). It is a vital crop worldwide and can grow in different types of soil and in a wide range of climates (Agegnehu et al., 2016). It is a very nutritious crop and provides us with phytochemical compounds and which can prevent many chronic diseases (Shah et al., 2016). The domestic production of the Malaysian maize crop was only 56 000 t in 2014, and the country imported approximately 3.2 billion tons of maize mainly from Argentina, Brazil, and India (Wahab and Rittgers, 2014). Global climate change and hunger have become crucial issues in current years. The main concern of agricultural scientists is to reduce greenhouse gas (GHG) emissions and increase agronomical fertility by increasing soil organic matter and developing soil quality (Agegnehu et al., 2016; Mandal et al., 2016; Yoo et al., 2016; Zhang et al., 2016). The largest part of solar energy radiated back into space and the anthropogenic GHGs adsorb and cause global warming (Kweku et al., 2017). The earth's temperature would be below -18 °C without global warming. This natural phenomenon warms the atmosphere so that life can exist on earth (Stepniewska and Kuzniar, 2013).

The application of biochar to the soil by converting organic waste is now one of the new eco-friendly management tools worldwide (Gonzaga et al., 2018). Biochar is a C-rich organic material that has undergone the pyrolysis process of biomass thermal decomposition when heated to temperatures usually between 300 and 1000 °C under low oxygen concentrations (Domene et al., 2014). Used as a soil amendment biochar can recover soil fertility and plant growth, improve C sequestration, assist waste management, and immobilize pollutants (Jeffery et al., 2017). Biochar has a high surface area and high organic matter. It is therefore an appropriate habitat for soil micro- and macroorganisms. It can therefore increase soil biota by improving soil quality (Lehmann et al., 2011).

Liming is one of the most efficient practices to neutralize or reduce agricultural soil acidity. Moreover, lime can increase the availability of Ca and Mg in soils (Joris et al., 2013). Lime can be applied to the surface or incorporated into the soil by tillage. Many studies have verified that surface application does not involve any problems for the soil; therefore, it is the most suitable scheme for lime application under no-tillage management (Yagi et al., 2014). Liming material can reduce acidification by increasing soil pH and Ca^{2+} concentration and by decreasing Al toxicity in the field (Shaaban et al., 2015).

In acidic soil, Al toxicity is one of the main restrictions on crop productivity, and 40% of worldwide arable land is affected. In Malaysia, phytotoxicity of the Al ion (Al^{+3}) and low pH are the two main aspects affecting maize production in tropical acidic soils (Rabileh, 2014). Nigussie et al. (2012) demonstrated that using 10 t ha^{-1} of maize stalk biochar can increase soil pH by 9%. This increase in soil pH was due to the unique properties of biochar, such as its large surface area and porosity characteristics. As a result these two features increase soil cation exchange capacity (CEC) , which is a consequence of the opportunity for Al and Fe to bind with the soil exchange sites; therefore, biochar applied to the soil reduces exchangeable Al and Fe. Syuhada et al. (2016) proved that the accessibility of K, Ca, and Mg in the soil significantly changed with the biochar rate when biochar was used, whether it was spread separately or mixed with inorganic fertilizer. Sorghum plant height increased by 20.1% and 13.7% after being treated with 5% and 10% biochar, respectively, compared with untreated soil (Ibrahim et al., 2020). When using four biochar rates, they also found that the 5% rate provided the best outcome for forage sorghum. According to Nigussie et al. (2012), soil CEC increased by 30% due to applying biochar to the soil. Cornelissen et al. (2013) reported an undisputable result when they detected a substantial enhancement of soil CEC by applying biochar in a maize farming location in Zambia. Biochar and lime application can positively influence maize yield and soil nutrients (Somchai et al., 2014). Plants can grow in a wide range of pH, but the ideal pH range is from 5.5 to 7.0 for healthy plant growth (Leonard, 2012). Soil enzyme activity was affected by the two main features of soil total N and exchangeable Ca. Biochar application has decreased soil exchangeable Ca and intensified soil organic C (SOC), exchangeable K, and total N (Xiubin et al., 2015). Njoku et al. (2016) observed a significant ($P < 0.05$) increase in maize height and grain yield with the biochar treatment compared with the control. Soil microorganisms, rooting patterns, soil aeration, water holding capacity, and bulk density were altered by applying biochar (Zafar et al., 2018). According to Asmare and Markku (2016), there are two essential features, phytotoxicity of soluble Al and Mn and an inadequate amount of trace elements, such as Ca, K, Mg, P, and Mo, which are responsible for preventing the productivity of acidic soils. Generally, N in biochar is a heterocyclic compound, and plants cannot uptake it as an available form. As a result, total N cannot significantly modify mineral N to the soil by applying biochar (Zhang et al., 2011). The H$^+$ concentrations increased by the extreme practice of N fertilizers, which account for soil acidity (Shaaban et al., 2016). This review focuses on the enhancement mechanism of maize yield and the decrease of CO_2 emissions by applying biochar and lime.

Nutritional value of maize

Maize is the leading staple food for humans in South America, Africa, and some parts of Asia and serves as livestock feed worldwide. In recent years maize has been the source of quality protein, which can play a significant role in reducing global vitamin A shortage and protein-energy malnourishment (Kumar and Jhariya, 2013). It can provide an energy density of 365 kcal 100 g^{-1} and contains approximately 72% starch, 10% protein, and 4% fat (Nuss and Tanumihardjo, 2010). The maize kernel provides approximately 70% of its weight as starch, which is the main dietary element. It also includes oil for human beings, which can decrease blood cholesterol (Kumar and Jhariya, 2013). Vitamin A as provitamin A carotenoids and vitamin E as tocopherols are the main components of fat-soluble vitamins originating from common yellow maize kernels (Nuss and Tanumihardjo, 2010). The third largest nutritional element of the kernel is fat along with

starch and protein, which can be found as oil and ranges from 3.5% to 6.0% of total kernel weight. This oil is used for cooking and in salads (Shah et al., 2016).

**Biochar production and characterization**
Biochar can be used as a modifier or conditioner for organic farming and recover soil productivity. Biochar has been developed from terra preta from the Brazilian Amazon. It is a C-rich organic material made by the pyrolysis process at relatively high temperatures (300 to 700 °C) and in the presence of low oxygen (Lehmann and Joseph, 2009). The residual biomass such as manure, crop residues, wood residues, forest, green and agricultural wastes such as straw, sawdust, husks, seeds, nutshells, peels, bark, bagasse, wood shavings, animal beds, corn cobs, and corn stalks, industrial wastes such as bagasse, distillers grain, and urban or municipal wastes are widely used to produce biochar (Novotny et al., 2015). Waste management also occurs while producing and using biochar (Kameyama et al., 2016).

The biochar characteristics depend on which materials are used and the process used for conversion (Figure 1). Biochar physical properties positively influence soil health because it is a way to control the living world (Ajema, 2018). Biochar characteristics vary depending on the pyrolysis process and feedstock (Bird, 2015). The type of soil and the biochar physicochemical properties can determine the biochar rate and application technology. Han et al. (2019) studied Mollisols soils in China and found that soil available P was affected by the types of feedstock and pyrolysis temperatures during biochar production. A large specific surface area and microporosity are unique properties of biochar. They are related to temperature and when temperature increases, these two characteristics of biochar also increase. Pore-size distributions, particle density, and surface area are the physical characteristics of biochar. However, pH, total C, and total N, P, exchangeable cations, acid neutralizing capacity, CEC, conductivity, and designated nutrient and contaminant trace elements are its important chemical characteristics (Agegnehu et al., 2016).

Biochar as soil amendment
The primary concerns in promoting the innovation of the cultivation system are food safety, restored soil productivity, sustainable crop production, and global warming. Biochar is progressively becoming an option approved by scientists and policymakers because of its prospective ability to reduce GHG emissions, C sequestration, waste mitigation, renewable energy, and as soil amendment (Beesley et al., 2011). Biochar has two unique features that make it superior to all other organic materials. The first and foremost is its high stability against decomposition. It can exist for an extended period in the soil and provides it with long-term benefits. It also defines the long-term impact of GHG emissions from the pedosphere and contributes to the mitigation of global warming. The potential for nutrient retention is the second important quality of biochar (Mensah and Frimpong, 2018). Furthermore, biochar-amended soil assists nutrient uptake for adequate plant growth by maintaining root growth and biomass and the root/shoot ratio (Zhu et al., 2018).

Figure 1. Biomass sources and conversion methods to obtain final products (Beluri et al., 2018).
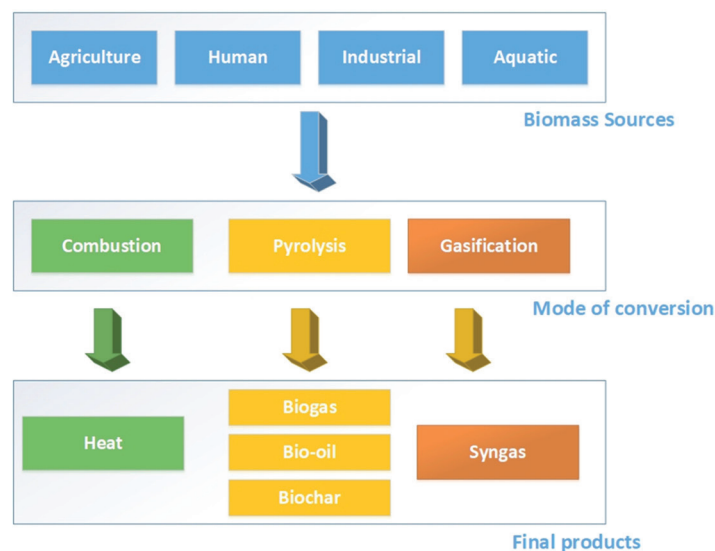
Impact of biochar on greenhouse gases (GHGs) and microbial activity

Biochar has been foreseen as a new opportunity for the mitigation of GHG emissions, C sequestration, and crop yield expansion (Jeffery et al., 2011). Biochar has the potential to address the problems of global climate change by raising the stable organic matter fraction, which is known as SOC (Sohi et al., 2010; Atkinson et al., 2010). According to Ventura et al. (2013), biochar can decrease nutrient leaching from the soil and GHG emissions (Kammann et al., 2012; Cayuela et al., 2013). Biochar can mitigate climatic change by increasing soil C because it is a solid charcoal-like material (Lal, 2011). According to Zhang et al. (2011), the application of biochar decreased N_2O emissions while CH_4 emissions increased. The emission of N_2O from ruminant urine patches decreased N by 50% with a combination of 30 t ha^{-1} biochar (Taghizadeh-Toosi et al., 2011). Cayuela et al. (2014) reported that soil N_2O emissions decreased by 54% on average in laboratory and field experiments using different biochar feedstocks between 2007 and 2013. Meanwhile, the emission of N_2O increased in a rice field when applying biochar (Shen et al., 2014).

Different types of living things, including bacteria, fungi, nematodes, protozoa, arthropods, and earthworms, are the essential microorganisms that significantly contribute in an eco-friendly environment. By making space for soil microorganisms, soil microbial respiration increased along with soil density, and soil biodiversity increased by applying biochar (Slapakova et al., 2018). The application of biochar substantially contributes in influencing soil microbes, increasing microbial activity, and biomass (Thies and Rillig, 2009).

Influence of lime on greenhouse gases, yield, and nutrient availability

The application of chemical fertilizers, such as N fertilizer, has increased N_2O emissions. In contrast, the application of dolomitic limestone has decreased N_2O emissions (Shaaban et al., 2016). The emission of cumulative N_2O was markedly reduced between 4.6% to 32.7% in an experiment with either the separate or combined use of biochar and dolomitic limestone, whereas cumulative CO_2 emissions increased when applying both biochar and dolomitic limestone. In this case, biochar was the only relevant amendment (Oo et al., 2018).

Liming is a well-known agricultural technique to improve soil acidification. Organic matter mineralization, nitrification, denitrification, and soil N transformation are significantly influenced by lime (Bolan et al., 2011; Shaaban et al., 2014). The concentrations of soil available P and alkali dissolved N decreased when applying lime (Yao et al., 2019). One of the limiting factors for maize production is soil acidity. In a study by Mwangi et al. (2000) in a Kenyan acidic soil, maize yield increased significantly (6.68 t ha^{-1}) with lime-treated soil compared with untreated soil. Similarly, a significant increase in maize yield was found by Opala et al. (2018). According to Onwuka et al. (2009), maize production using 8 t ha^{-1} calcium carbonate significantly ($P < 0.05$) increased soil pH from 5.20 to 8.04. In contrast, for different liming elements using 8 t ha^{-1}, pH varied between 6.05 and 6.55. Soluble P forms a complex with Ca when soil pH is > 6 for the high lime rate and results in decreased available P. However, when pH is low, a low lime rate is inadequate to remove soluble Al and Fe, which fix P (Opala, 2017).

Effect of biochar on global warming and CO_2 emissions

The CO_2 emissions from agronomic soil are responsible for their ecological impact. As a result, C sequestration in soils is reduced, and the final consequence is global climate change (Dhadli and Brar, 2016). In 2014, CO_2 emissions accounted for 81% of total emissions, methane for 10.6%, N_2O for 5.6%, and F-gases for 2.9% (Kijewska and Bluszcz, 2016). In the 1800s, the concentration of CO_2 emissions was approximately 280 ppm, whereas it now accounts for approximately 400 ppm. Since the start of the Industrial Revolution until today, atmospheric CO_2 concentrations have increased by more than 40% (EPA, 2009-2012). The concentration of GHGs, mainly CH_4, CO_2, and N_2O, in the environment has significantly increased due to human actions, for example, applying different types of chemicals in agriculture, debris from incineration processes, bushfires, and other manufacturing activities (Kweku et al., 2017). It has been predicted that the CO_2 concentration will increase by 30% to 150% by 2100 (Belic, 2006).

Greenhouse gases, such as CO_2 and N_2O emissions, have a substantial effect on global climate change and environmental chemistry. Biochar application is a possible option to decrease GHG emissions through C capture and N_2O mitigation (Wu et al., 2018). Biochar created from the thermochemical alteration of living matter subjected to the presence of low oxygen (Sohi et al., 2010) is responsible for the successful outcome of reducing CO_2 and N_2O emissions (Lehmann et al., 2011; Cayuela et al., 2014). However, for individual biochar and various soil categories, there are different types of

effects reduced GHG emissions (Taghizadeh-Toosi et al., 2011). Both He et al. (2016) and Song et al. (2016) indicated substantial increases in CO_2 emissions, 19% and 22%, respectively, while Liu et al. (2013) found nonsignificant effects of biochar on soil CO_2 emissions. The CO_2 emissions increase due to the mineralization of SOC when applying biochar (Luo et al., 2011; Cely et al., 2014). In contrast, decreased CO_2 emissions resulted from the prevention of SOC mineralization (Kuzyakov et al., 2009; Singh and Cowie, 2014). Biochar application can inhibit soil CO_2 emissions produced under temperatures between 400 and 510 °C (Spokas and Reicosky, 2009). Soil respiration is restricted by biochar application during maize cultivation (Liu et al., 2011; Shen et al., 2017) due to the labile C sorption from the large surface area and porous characteristics of the biochar (Lehmann et al., 2011). According to Weng et al. (2017), rhizodeposits absorbed by biochar and enzymes in the soil inhibit microbial activity, which is responsible for soil C degradation. Thus, CO_2 emissions decreased using biochar soil.

Aluminum toxicity and nutrient availability
In the field environment, there was an interactive consequence on soil nutrients due to the integrated application of biochar and lime, which resulted in improved soil health, enhanced plant growth, and reduced chemical fertilizer practice; this improved water holding capacity and modified soil structure (Trupiano et al., 2017). However, in many instances, the separate biochar application did not supply a considerable volume of nutrients (Glaser and Birk, 2012).

When pH is < 5 in a soil solution, the Al ion concentration strongly influences the plant roots. This soil level comprises 40% or more of the potentially arable land worldwide. The toxicity of Al is one of the key drivers that stimulate plant root development. The restriction of cell division and cell extension of root development is responsible for Al toxicity in acidic soil (Zhang et al., 2007). In an Ultisol, growing maize restricted more than 60% of saturated Al; for this reason, cell division and elongation are obstructed due to the inhibition of root growth by a high Al concentration in acidic soils (Rabileh, 2014; Rabileh et al., 2015). The N and P deficiencies and Al toxicity decreased maize yield by 30%, 28%, and 16%, respectively, in Kenyan soils as reported by Kisinyo (2016). Major et al. (2010) reported the impact of the dietary value and yield of maize in a savanna Oxisol in Colombia. The application studied a substantial reduction of exchangeable Al and Fe at rates of 8 and 20 t ha^{-1}.

Rabileh et al. (2015) indicated that the value of soil pH increased from 4.82 to 5.17 by applying the empty fruit bunches (EFB) of palm oil biochar at an increasing rate of 5 to 10 t ha^{-1}, respectively. The biochar pH was approximately 9; it therefore helped increase soil pH. They also found that, with or without lime application, CEC significantly increased when applying EFB biochar. The CEC value increased from 13.30 to 15.30 cmol$_c$ kg^{-1} when applying 10 to 20 t ha^{-1} EFB biochar, respectively. In a maize plot, soil available P increased by 28% when applying biochar (Widowati et al., 2012). Nigussie et al. (2012) indicated the same result and mentioned that available P increased by 10 t ha^{-1} in garden lettuce when applying maize stalk biochar. Adding 10% biochar increased the soil P concentration from 81.8 to 445 mg kg^{-1} (Fellet et al., 2011), and according to Widowati and Asnah (2014), the P concentration significantly increased by 179% to 208% for biochar application. By applying 10 and 20 t ha^{-1} biochar, soil exchangeable K increased from 64.30% to 111.57%, respectively, compared with the control soil. The control soil without biochar exhibited the lowest soil exchangeable K, approximately 10.98 mg kg^{-1} (Zaidun et al., 2019). In soil treated with urea and 20 and 40 t ha^{-1} biochar, Zhang et al. (2011) indicated increased SOC from 25% to 42%, respectively, compared with the control. In the same experiment, without the addition of urea, SOC increased from 44% to 58% when applying 20 and 40 t ha^{-1} biochar, respectively.

Effect of biochar on maize growth and grain yield
Parameters related to pH, base saturation, exchangeable K, and Ca/Al ratio were mostly responsible for crop yield. Soil acidification mitigated by cocoa shell biochar in an Ultisol had a beneficial impact on crop yield. Applying 15 t ha^{-1} cocoa shell biochar every third season sustained soil quality and increased yield (Yargholi and Azarneshan, 2014). The study of a savanna Oxisol in Colombia reported that maize yield increased from 28% to 140% as compared with the untreated soil 2 to 4 yr after applying 20 t ha^{-1} biochar (Major et al., 2010). Plant leaf number and size decreased because of moisture deficiencies throughout the growing season, which reduced grain yield when the photosynthesis rate decreased (Lobell et al., 2013). Major et al. (2010) reported a Colombian savanna soil using biochar at a rate of 8 and 20 t ha^{-1} that reduced exchangeable Al and Fe and significantly increased maize yield. In acidic soils, biochar-treated soil increased soil pH and nutrient availability and decreased phytotoxic Al; it has been recommended to increase crop

yield (Kookana et al., 2011). The damage of Ca^{2+}, K^+, and Mg^{2+} from the root cells and the rupture of the cell wall are responsible for Al toxicity, but a low Al rate influenced leaf growth, which prevented the growth of maize roots (Wang et al., 2015). Biochar application at 20 and 40 t ha^{-1} without N fertilizer increased maize yield by 15.8% and 7.3%, respectively, and it increased by 8.8% and 12.1%, respectively, when combined with N fertilizer (Zhang et al., 2011).

The response of maize DM increased by 3% for every g kg^{-1} biochar-treated soil with or without fertilizer (Syuhada et al., 2016). These authors also reported that maize height increased 2.45 cm for every g kg^{-1} of biochar added. There was no substantial change when applying biochar at the low rate of 5 g kg^{-1}, but change was detected at the higher rates of 10 and 15 g kg^{-1}. Maize yield and growth usually increased with the combined application of biochar and fertilizer compared with only applying biochar. In sandy soil, maize DM remarkably increased by applying biochar processed from cow manure incorporated with chemical fertilizer compared with only applying chemical fertilizer. However, there was no change at a low rate (10 t ha^{-1}) (Uzoma et al., 2011). These authors also explained that the application of biochar at the higher rates of 15 and 20 t ha^{-1} increased maize grain yield by 150% and 88 %, respectively, compared with an untreated plot.

There was a significant ($P < 0.05$) increase in maize height and grain yield due to biochar application compared with the control (Njoku et al., 2016). These authors also detected that increased biochar rates increased maize grain yield and height. They reported that biochar-treated plots ranged from 600.0 to 666.67 kg ha^{-1} maize grain yield, whereas 511.11 kg ha^{-1} was observed in the control. Likewise, the lowest maize height value was recorded in the control at 109.50 cm. This experimental value in the control was less than maize height by 27%, 42%, and 81%. Among the different maize parameters, ear length is a vital parameter that contributes to yield; it significantly influences both the number of grains per ear and the size of the maize grain yield. Thousand-grain weight is essential among the numerous parameters promoting the commercial maize yield (Yigermal et al., 2019).

CONCLUSIONS

The rapid growth of the world population creates pressure on limited natural resources. The use of biochar undoubtedly plays a vital role in sustainable crop production, soil health restoration, and climate change mitigation. Biochar has established a clear and substantial positive effect by supplying essential nutrients, increasing soil physicochemical properties such as pH, cation exchange capacity, water retention capacity, and influencing microbial soil activity. However, it has been pointed out that the biochar treatment has been widely studied as a prospective technology, and the application rate is no less important. Many aspects of biochar and lime application on CO_2 emission mitigation and increased maize yield still need further study because existing results are inadequate and inconsistent.

ACKNOWLEDGEMENTS

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