Vol. 18, No. 1, pp. 14-20 (2018)
Journal of Agricultural Physics
ISSN 0973-032X
http://www.agrophysics.in

Review Article

A Decadal Overview of Biochar Research in Agriculture

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ABSTRACT

Application of biochar in modern agriculture is fascinated by its multifaceted benefits. The importance of biochar in various sector of agriculture recently gained priorities through various cutting-edge research although it has been felt earlier through discoveries of terra-preta soils in Amazon Basin also called as *Amazonian dark earth* or *Indian black earth*. The impact of biochar application in agricultural research includes not only on soil and nutrient management, soil fertility and productivity but also on soil carbon sequestration and mitigation of global climate change. The trend of biochar related research has increased rapidly since 2005 as the importance of biochar to solve many problems in soils has recently been realized. The report says that the most number of studies were conducted are related to soil management. However, application of biochar in agricultural research can incur some associated problem such deterioration of air and water quality, deficiencies of some micronutrients, negative impact on some microbes including fungi and human health in general. Biochar researches are mostly limited to the laboratory to greenhouse set-up, hence more research involving field studies will give robust and concrete output.

Key words: Biochar, Carbon sequestration, Field application, Soil management, Remediation

Introduction

The term biochar refers to a predominantly stable and recalcitrant organic carbon (C) compound, created by pyrolysis, an energy conversion process when biomass (feedstock) is heated to temperatures usually between 300 and 1000°C, under low (preferably complete or near absence) concentration of oxygen (Verheijen *et al.*, 2010). Understanding the origin, distribution, and properties of naturally occurring biochar i.e., "Terra Preta de Indio" or Brazilian Dark Earth in the Brazilian Amazon region allowed scientists to evaluate and promote biochar uses in agricultural soils (Lehman *et al.*, 2003). The two-fold interest of biochar use includes the supply of enormous amount of organic carbon by biochar-type substances (Glaser *et al.*, 2001) and the benefits of biochar in soil fertility in Terra Preta de Indio soils (Lehmann *et al.*, 2003).

This article is an overview of research conducted and published in various scientific journals and popular articles such as technical articles and newsletters. The intended readers of this article, agricultural producers, crop professionals, researchers, and extension personnel, will get a broad idea of the general trend of biochar research activities conducted in the field of agriculture during the past decade, and the potential benefits and negative impacts of biochar

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uses. This review article will be a useful documentation of the use of biochar in the various fields of agriculture given its suitability for nutrient retention and amelioration of contaminated soils.

Current Knowledge on Relevance of Biochar in Agriculture

The multi-faceted functionality of biochar incorporates not only carbon sequestration but also global climate change mitigation, soil management, environmental remediation, waste management and renewable energy generation (Fig. 1). The two most important aspects of biochar use include soil fertility enhancement and as an environmental remediation tool to remove organic and inorganic pollutants, heavy metals, and nutrients. During the past few years, biochar has attained considerable importance as a soil amendment in agriculture. The consequences of biochar applications on soil properties, soil and water quality, plant production and productivity, microbial activities, water and nutrient retention has become pivotal in sustainable environmental studies to explore the potential of biochar for applying in agricultural fields.

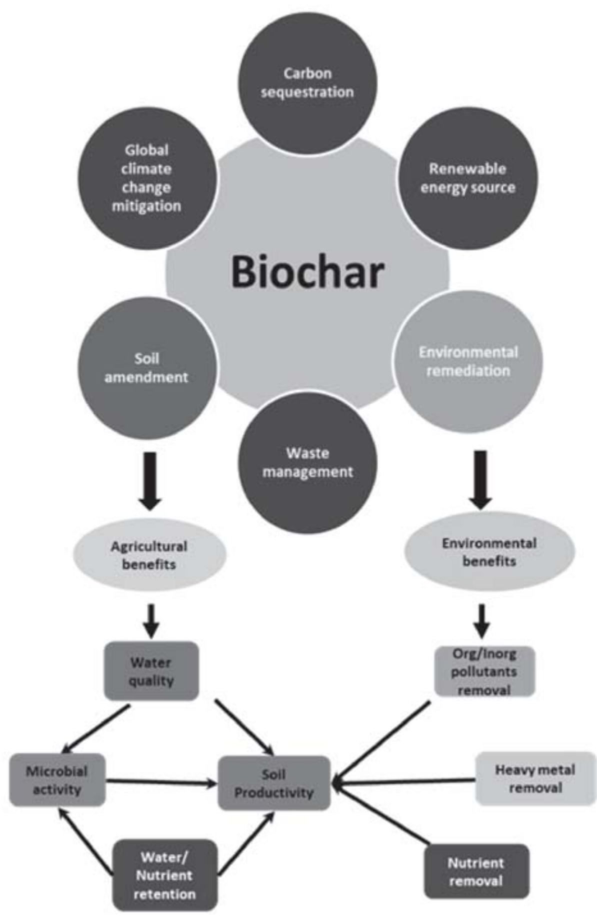

Fig. 1. Schematic of multifaceted uses of biochar in various sector of agriculture.

Field Application of Biochar

A myriad of literature is available on biochar and its application in diverse sub-areas under agriculture such as soil fertility, crop productivity, nutrient sorption, soil amelioration, green-house gas emission and carbon sequestration (Fig. 1). The available literature on higher agricultural crop yield involves main two mechanisms such as liming effect (increase in soil pH) and water holding capacity of the soil along with improved crop nutrient availability which are applicable in acidic (14%) and neutral pH soils (13%), and in soils with a coarse (10%) or medium texture (13%) for agricultural research (Jeffery *et al.*, 2011). The biochar applications rate of 100 t ha^{-1} (39%) has shown greatest positive results in term of agricultural crop production. Poultry litter showed the strongest (significant) positive effect (28%) towards crop productivity as compared to biosolids, which were the only feedstock showing a statistically significant negative effect (-28%) (Jeffery *et al.*, 2011).

Different soil-specific scenarios have been produced by low-temperature derived biochar (having acidic pH) compared to high-temperature produced biochar (Lehmann and Joseph, 2009). The bichar produced from higher temperature showed increase in sorption of nutrient elements by changing the composition of surface functional groups (acidic to basis group) and more bioavailable C imparting stabilized microbial decompositions as compared to biochar produced from low-temperature (Ippolito *et al.*, 2012). The mechanism behind this temperature-driven behavior of biochar is still unclear.

Very little has been documented about the pros and cons of applying biochar in field studies such as spatial (weathering situation, temperate or tropical climate) and temporal (short-term or long-term) variability of using biochar in those research areas and the fertility status of the soil on which the experiments were conducted. Application of biochar for agricultural purposes were mostly reported in highly weathered tropical or sub-tropical climate and infertile soils (Ippolito *et al.*, 2012), and less has been explored in temperate climates. The currently available data on agricultural research are limited to periods of 1 to 2 years. The feasibility of extending the short-term laboratory-oriented experiment into long-term field experiments is also questioned.

Dimension of Biochar Related Studies

A brief review of articles (including both popular articles such as technical reports, and newsletters and research articles) published since 2000 to present date (Fig. 2) showed an increased interest on biochar studies in the area of agriculture. The number of publications may not be absolute as they were obtained from a single search engine (google scholar), but the trend is obvious. Most of the publications used to derive the trend graph were on either laboratory- or field experiments on various aspects of biochar-application in agriculture. The general trend shown in the graph indicates less concern about biochar-related studies in agricultural research during the 2000 to 2005 period. Scientists, researchers and environmental consultants throughout the world showed their increased interest in biochar studies from 2006 to 2010. The trend showed a steep increase in the publication rate from 2010 to till date with maximum research and publications being conducted in 2012, 2013 and 2014.

Biochar plays an important role in soil fertility and crop productivity, soil amendments, nutrients retention, greenhouse gas emission, carbon sequestration etc. The pie diagram (Fig. 3) represents the contribution of various fields of biochar in agriculture in recent studies (data from

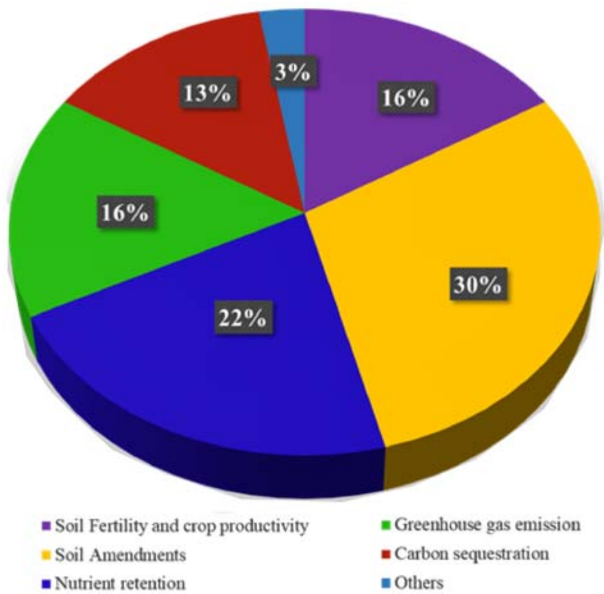

Fig. 3. Distribution of biochar articles published in agriculture

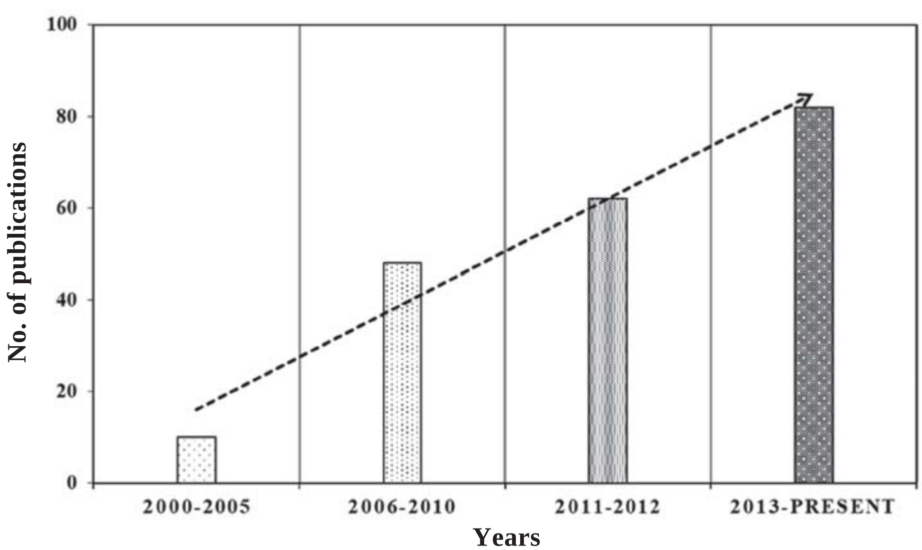

Fig. 2. Publications trends of biochar research in agriculture (~2000 to the present).

google scholar search engine). The evidence from literature showed a substantial amount of research (approx. 30% of total publications in agriculture) were conducted in soil amendments and nutrient retention fields. Almost an equal number of publications have been reported for biochar use on soil fertility and greenhouse gas emission studies. Approximately 13% of total number of publications in the agricultural field involves research related to application of biochar on greenhouse gas emission studies.

Sources and Byproducts of Biochar in Agriculture

The feedstock used by various sectors to prepare biochar in the laboratory or on a large-scale includes crop residues or agriculture and forestry by-products are presented with some examples in Table 1. Biochar is a habitat for soil microorganisms. The amount of plant-available nutrients increases with biochar application with a decrease in nutrient losses via leaching and volatilization. The physico-chemical properties of synthetically produced biochar (e.g., composition, particle and pore size distribution) depend on conditions of pyrolysis and characteristics of feedstock. The suitability of biochar application as well as its behavior, transport and fate in the environment is determined by the feedstock used in the preparation of biochar. Although structurally amorphous, biochar contains some crystalline structure of highly conjugated aromatic compounds, which facilitates the characteristics of high surface area of biochar, particularly when prepared at high temperatures.

Biochar Effects on Agricultural Soils

The physical and chemical properties of biochar used for experiments determine the effects of biochar application in different agricultural studies. Experiments have been conducted ranging from laboratory-based batch experiments and column studies to greenhouse trials and field scale studies. Temporal scale includes 7 days to 4 months under laboratory situation generally up to 2-3 years under long-term field experiments. The particular rate of mixture of different biochar with soil samples for various experiments depends on the purpose of the experiments. The findings obtained from laboratory- and field based experiments on application of biochar in agriculture has been presented in a tabular form (Table 2).

Benefits of Biochar Use in Agriculture

Biochar is used in agriculture for multiple purposes which can be listed as follows:

i. Promoting long-term soil carbon sequestration
ii. Enhancing crop production
iii. Improving soil fertility and tilth
iv. Improving water retention
v. Acting as surface sorbent

Table 1: List of feedstock used in biochar preparation.

Sources of feedstock	By-product for biochar preparation	References
Agricultural by-products or crop residues	Nut shells, rice hulls, wood chips, wood pellets, tree bark rapeseed straw and stalk	Filiz *et al.* (2000)
	Empty fruit bunches	Salleh *et al.* (2010)
	Corn stover, yard waste and switchgrass	Roberts *et al.* (2010)
	Winter wheat straw, miscanthus and switchgrass	Gaunt and Lehmann (2008)
	Pine, oak and grass	Mukherjee *et al.* (2011)
	Brazilian pepperwood and peanut hull	Yao *et al.* (2012)
	Black locust, bamboo charcoal	Uzoma *et al.* (2011)
Industrial by-products	Bagasse from the sugarcane industry	Cao *et al.* (2009)
Animal wastes	Poultry litter	Chan *et al.* (2007)
	Chicken litter	Hass *et al.* (2011)
	Dairy manure	Cao and Harris (2010)

Table 2. Effects of biochar application in agricultural studies

Roles of biochar	Effects	References
Soil fertility & crop productivity	Increase soil pH, Organic Carbon (OC) and ex. Cations but reduction of soil strength	Chan *et al.* (2007)
Soil amendment & remediation	i) Increase adsorption of heavy metals like copper, zinc & cadmium	Lima and Marshall (2005)
	ii) Increase adsorption of lead & Atrazine from soil	Cao and Harris (2010)
	iii) Increase soil pH, Carbon (C), Nitrogen (N) and available Phosphorus (P) but reduce in soil strength	Chan *et al.* (2008)
	iv) Increase soil pH, increase Mehlich-3 extractable micro-and macronutrients, no increase of nitrate in leachate but increase sulfate, dissolved organic carbon, and potassium	Hass *et al.* (2011)
	v) Enhance retention & reduce transport of tylosin in soils	Jeong *et al.* (2011)
GHG emission	i) Greater emission of Carbon-di-oxide (CO_2)	Gaunt and Lehmann (2008)
	ii) Effect on Nitrous oxide (N_2O) emission	Toosi *et al.* (2011)
Carbon sequestration	i) Long-term increase of C sequestration & renewable energy generation	
	ii) Increase C sequestration, crop yield & energy production	Roberts *et al.* (2010) Lehmann *et al.* (2003)
Nutrient retention	Remove phosphate from aqueous solutions	Yao *et al.* (2011)
Crop production	i) Negative yield responses	Lentz and Ippolito (2012)
	ii) Increase crop yield	Spokas *et al.* (2012)
	iii) No crop yield benefit, poor recovery of nutrients & negative nutrient balance	Schnell *et al.* (2012)

vi. Adsorbing organic pollutants from waste water

vii. Reducing soil erosion and vulnerability to degradation

viii. Reducing need for fertilizer inputs

ix. Enhancing agricultural adaptation to climate change

x. Reducing Nitrous oxide and Methane emission

xi. Improving water quality through reduction in ammonium ion leaching and run off of P

xii. Facilitating rehabilitation of contaminated wetlands and management of algal blooms in aquatic ecosystems through adsorption/ retention of nutrients.

Limitations of Biochar Use in Agriculture

In spite of the benefits of biochar use in various sub-areas of agriculture, there are concerns on the negative aspects of biochar by soil scientists and environmental specialists. Biochar uses result some challenges in agricultural research:

i. Hazards of air quality (air pollution)

ii. Nutrient loss from the soil and thereby impacting water quality of receiving waters

iii. Micronutrients deficiencies and unfavorable environmental conditions for fungi and bacteria in soil by biochar application with increasing pH

iv. Dust in transportation and application

v. General health and safety issues of workers working with biochar in the laboratory

Research Gaps

The following research gaps have been identified based on the available literature:

i. Biochar researches are mostly set up in laboratories (short-term) either as batch or incubation studies or column experiments and greenhouses. Assessment of biochar application in field on large scale must be merged with laboratory researches with respect to yield and crop production.

ii. Biochar applications for sequestering nutrient elements (like C, Cu, etc.) in a soil, should take into account the potential problems associated with other elemental loss like P from soil. This is particularly important for sandy soils of the southeastern USA where P leaching is a major problem and land application of biochar should be minimized or perhaps considered in co-application with a P retaining material.

iii. The proper appreciation of effects of biochar on soil biota should explore the interaction between biochar-types and soil microbial communities with some basic manipulative experiments.

iv. Liming effect (increasing pH of soil) of biochar on neutral and acidic soils result in crop yield improvement. The harmful effect of increased pH for an alkaline soil has never been mentioned.

v. A detailed consideration is needed to document the effect of time on increasing cation exchange capacity of a soil by biochar application.

vi. Specific mechanism of water retention, macro-aggregation and soil stability after biochar application is poorly understood.

vii. Long term studies are needed on the fate and transport of nutrients after biochar application. The underlying mechanisms need to be investigated on basic soil chemistry regarding adsorption and release of any nutrients or contaminants in/from soil.

viii. Biochar researches are mainly focused on highly weathered and infertile soils.

ix. Socio-economic constraints of biochar application are not adequately addressed.

Implications of Biochar Application to Soils

Despite the gaps in biochar research, current knowledge suggests that biochar addition for agricultural and environment purposes will be useful if biochar production is tailored for specific uses as indicated by Lehmann and Joseph, 2006. Future research should focus on biochar production on a large scale based on the information currently available, taking into consideration both the agricultural and environmental benefits and problems associated with land application of biochar. Biochar research in agriculture need an elucidation of mechanisms as differentiated by environmental and management factors which will include experiments over longer time run.

Acknowledgments

Authors gratefully acknowledge Dr. P.K. Nair and Dr. Vimala D Nair for their academic guidance at the preparation of this manuscript.

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Received: January 05, 2018 Accepted: February 21, 2018