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Efficiency of biochar with mineral fertilizers on soil properties and crop growth

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Abstract
Biochar, derived from biomass pyrolysis, proves valuable in soil management due to its stable, carbon-rich composition and recalcitrant nature. It aids carbon sequestration, enhances water retention, alters soil properties, affects nutrient availability and crop productivity. Biochar has various beneficial properties such as has a highly porous structure that provides for a large surface area, high cation exchange capacity, which enhances the retention and exchange of positively charged ions (cations), which are essential for plant nutrient uptake. The slow decomposition of biochar, attributed to its aromatic structure, significantly contributes to long-term carbon sequestration. Mineral fertilizers are widely used since they address the nutrient deficiencies in soil. It helps in the formation of robust roots, leaves, and reproductive structures, leading to healthier and more resistant plants and contribute to increased crop yields. Urea is a widely used nitrogen source, while Diammonium Phosphate (DAP) is neutral and water-soluble, and Muriate of Potash (MOP) is rich in potassium. The mechanisms of nutrient elements within biochar (such as migration and transformation) impact nitrogen, phosphorus, and potassium dynamics in soil. Combining biochar with urea and DAP yields synergistic effects, moderating nitrogen mineralization and enhancing soil alkaline enzymes. This combination counters the negative effects of nitrogen addition on root growth and soil microbial activity. Biochar's interaction with DAP influences soil pH, aggregate stability, and nutrient availability, showcasing a pivotal role in soil management. The continuous use of mineral fertilisers alone have a certain negative impact on the environment and soil health. Moreover, they may not support the microbial activity crucial for maintaining a healthy soil ecosystem. This may lead to a decline in soil biodiversity and overall soil health. Overall, the properties and mechanisms of biochar, coupled with its interaction with various fertilizers, enhance soil properties and crop productivity.

Keywords: Biochar, carbon sequestration, mineral fertilizers, sustainable soil management

Introduction

Escalation in population, increased human pressure on land has converted natural landscapes into agricultural fields, which is causing a depletion in the land under agricultural use. The next decades will see more of the adoption of farming practices that reduce negative environmental impacts and adapt to climate change that improves sustainability and guarantees food security. It is estimated that by 2050, global population will reach 9.7 billion people. These 9.7 billion people will demand 70% more food than is consumed today. This demands for the establishment of an effective agricultural management system, that increases food production and counters the negative environmental impacts of intensive agriculture.

In order to provide sufficient healthy and nutritious food, methods to enhance and improve the resource use efficiency of the agri-food systems must be undertaken. Biochar is formed from the transformation of wastes into valuable and useful products for agriculture. It has a pivotal role in achieving environmental sustainability. Biochar enhances carbon sequestration in the soil, reduces farm waste, enhances crop yield, adsorbs certain toxic elements from the soil, thereby improving soil quality, ultimately leading to better crop growth. The solid product formed as a byproduct of pyrolysis, called "biochar" is a sterile, odourless, high carbon solid, having a highly heterogeneous material with chemical composition that varies depending on the feedstock and pyrolysis conditions.

The porous nature of biochar enhances it's surface area and cation exchange capacity (CEC). The application of biochar alters soil physical properties such as structure, pore size distribution and density, with implications for soil aeration, water holding capacity, plant growth, and soil workability (Downie *et al*. 2009) [12]. As a result, it reduces the overall bulk density of the soil which is desirable for plant growth and increases water holding capacity (Chan and Xu. 2009) [5]. This increase in surface area, porosity, and reduction in bulk density in mineral soil with biochar alters water retention and soil aggregation (Mbagwu and Piccolo. 1997) [15].

The organic amendments though efficient are not sufficient to feed the expanding population. Therefore, a balance must be maintained between the organic and inorganic amendments.

Feeding terrestrial ecosystems excessively with mineral fertilizers affects both plant biosphere and associated soil microflora. Here, comes the role and importance of mineral fertilizers. Mineral fertilizers are regarded as the salts, inorganic, industrial and mineral products that contain necessary elements for plant growth and development. The most important elements are carbon, oxygen, and hydrogen, which make up 90% of the dry mass of a plant; the most important of which are carbon, oxygen, and hydrogen, which make up 90% of the total mass of the plant. Nitrogen, phosphorus, potassium, calcium, magnesium and sulphur constitute 8-9% of the plant mass. These elements are regarded as macro-elements. The remaining elements comprise 1-2% of the plant mass. Plants require very small amounts of these (0.001-0.0001%). Therefore, they are regarded as microelements. These are is iron, zinc, copper, manganese, molybdenum, boron and chlorine.

Plants meet their carbon, oxygen, and hydrogen requirements from air and water, while the rest from the soil. Most of the elements are removed by the crop and as such not returned back to soil. Moreover many soil elements are washed away by water and interact with soil components that makes it difficult for the plant to assimilate. This leads to paucity of plant nutrients and decreases soil fertility. Therefore, fertilizers need to fill the gap of these lost elements.

Effect on soil properties

Much of the work done on biochar has resulted in better crop performance and improved soil properties (Laird *et al*. 2010; Herath *et al*. 2013; Abrol *et al*. 2016) [10, 9, 1]. Biochar has also shown enhanced crop yield (Basso *et al*. 2012; Carlsson *et al*., 2012; Herath *et al*., 2013; Mukherjee and Lal, 2013; Martinsen *et al*., 2015; Hansen *et al*. 2016; Blanco *et al*., 2017) [2, 4, 9, 13, 11, 8, 3]. Mensah and Frimpong (2018) [12] reported that the biochar amendment improves soil health by increasing pH, water retention capacity, CEC and microbial flora.

The highly porous nature of biochar is attributed to the retaining the cell wall structure of the biomass feedstock. Coarse textured soils have shown positive impact on moisture content on the application of biochar (Glaser *et al*. 2002) [7]. The International Biochar Initiative (IBI) promotes ubiquitous use of biochar as a soil amendment, advocates for inclusion of provisions favourable to biochar use in national and global climate mitigation policies, promotes biochar commercialization, and aspires to a global system that sequesters 2.2 Gt C/yr by 2050.

Amalgamation of organic materials with more dense mineral fractions of soil decreases bulk density. The increase in organic matter content leads to increased total porosity and reduction in soil bulk density (Tejada *et al*., 2008) [20]. Therefore, incorporating organic materials with synthetic fertilizers reduces nutrients losses (especially nitrogen; leaching losses) and improves fertilizers use efficiency through improving microbial activity. As a result, bulk density is reduced and total porosity of soil is increased. (Yadav *et al*. 2019) [21].

The addition of mineral fertiliser increases porosity in soil. This is attributed to an increase in the amount of rounded pores, defined as “biopores”. Thus, the organic or mineral sources modify the wettability of soil surfaces (Oades, 1993) [14].

Effect on crop growth

Biochar has proven to have caused positive effects on nutrient retention, cation-exchange capacity (CEC), water-holding capacity (Glaser *et al*. 2002) [7]. Biochar addition causes an increase in the C: N ratio. The addition of N regulates the same. Biochar coming from an organic source causes an increase in soil organic matter (SOM) content and soil fertility. This leads to increased plant growth. Significant interactions between biochar and N fertilizer on rice grain and straw yield are seen (MacCarthy). Similar interactions on rainfed rice, are seen in yield and yield components (Oladele). In two-year field experiments, biochar and N applications significantly increased grain yield and the above ground biomass of maize.

The co-application of biochar with inorganic fertilizers is a sustainable and environmentally friendly solution to improve soil fertility, plant nutrient availability and crop yield. Moreover, in aim of the widespread adoption and integration of biochar with farming operations, formulations that combine biochar with inorganic and/or organic fertilizers are likely to have high nutrient-use efficiency and to be the most cost-effective.

Thus, there happens to be an overall positive effect of co-application of biochar mineral fertilizers on soil properties and crop growth.

Figures and graphs

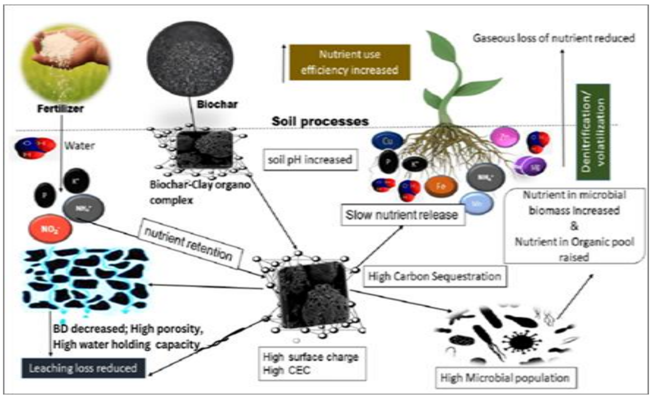
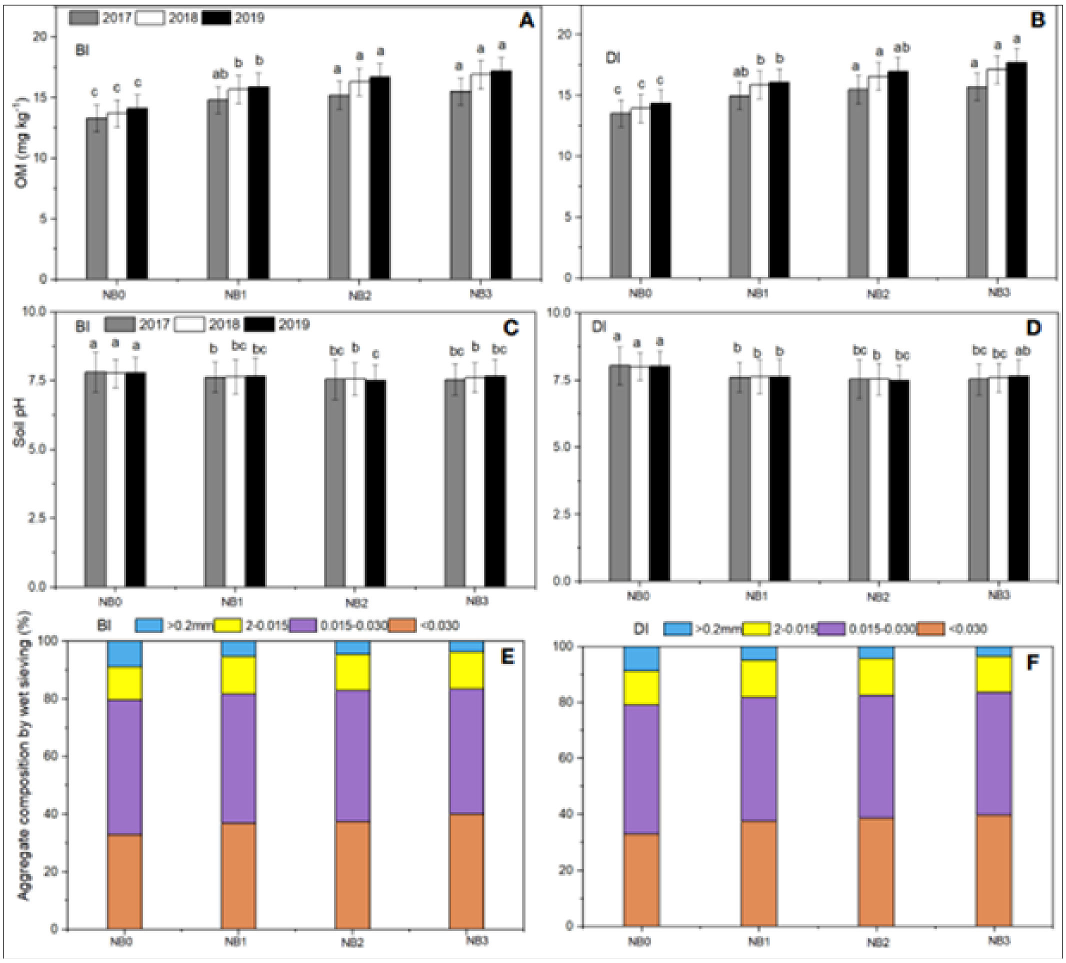
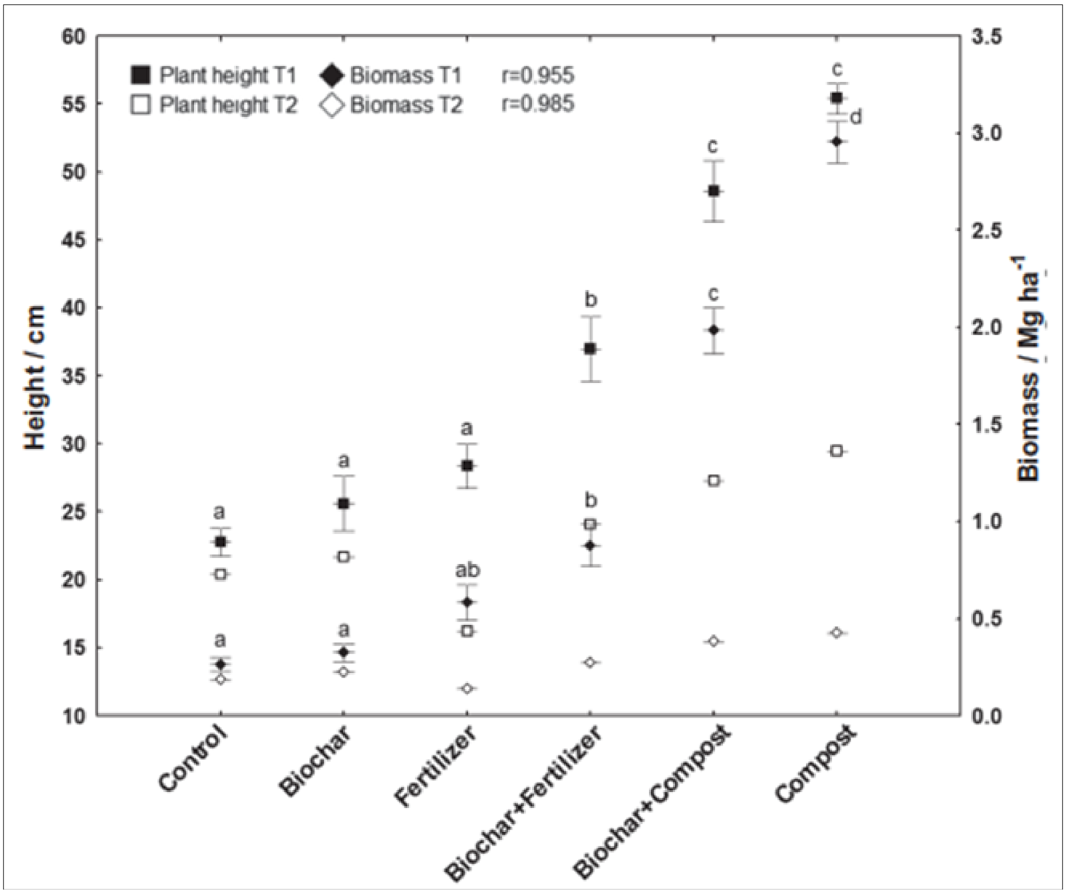


Fig 1: Sole and interactive effects of biochar and mineral fertilizers in soil and the mechanisms underlying Murtaza *et al*., 2013 [23]



Graph 1: Effect of biochar and mineral fertilizer on soil "physical", "chemical" and "biological properties" Wang *et al.*, 2023 [10]



Graph 2: Plant height and plant biomass after the first harvest (T1) and after the second harvest (T2) Schulz *et al.*, 2011 [17]

Table 1: Growth and yield parameters of wheat crop as influenced by chemical fertilizer (CF) and biochar produced from farmyard manure (FMB) Sadaf *et al*. 2017 [24]

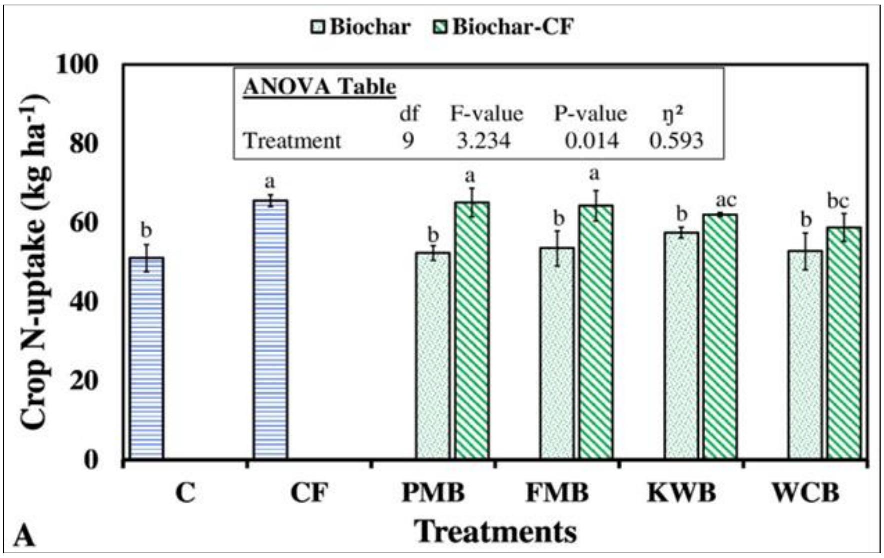
Parameters	Unit	Control	CF	FMB	FMB-CF
Plant height	cm	67.7 ± 4.8	72.5 ± 4.9	68.6 ± 3.1	71.1 ± 3.4
Root biomass	kg ha^{-1}	493.6 ± 38.4c	779.4 ± 10.3g	329.9 ± 38.6a	646.2 ± 9.1d
Biological yield	kg ha^{-1}	5699 ± 123ab	7679 ± 141f	5378 ± 241ab	6956 ± 71d
Grain yield	kg ha^{-1}	2258 ± 63c	2866 ± 52e	1980 ± 24a	2924 ± 31e
Harvest index	%	39.6 ± 1.0bg	37.3 ± 0.7bh	36.9 ± 1.3bh	42.0 ± 0.1cdg

Table 2(a): Soil properties as influenced by biochar and inorganic fertilizers before transplanting (T1) Rivelli *et al*. 2022 [16]

Parameters	Units	B0	Bw	F0	IF	B0F0	B0IF	BwF0	BwIF
pH	Unitless	7.6 ab	7.6b	7.6a	7.6b	7.6ab	7.6ab	7.7ab	7.5b
EC	dSm^{-1}	1.2 a	1.0b	0.6c	0.8b	0.6d	0.9c	0.5d	0.6d
NH_4^+	mg kg^{-1}	5.7a	3.0c	0.0b	13.5a	0.0d	17.2a	0.0d	9.0c
Ca^{+2}	mg kg^{-1}	325.3	332.8	258.6c	378.4a	287.1bc	351.5ab	245.1c	404.9a
Mg^{+2}	mg kg^{-1}	22.7b	24.2ab	19.9cd	26.8a	19.9cd	22.9bcd	17.9d	27.5ab
Total N	Total N, % dw	0.2a	0.1b	0.1b	0.2a	0.2ab	0.2a	0.1b	0.1b
Corg	Corg, % dw	0.7c	2.2a	1.4c	1.6b	0.6d	0.7d	1.8c	2.5b

Table 2(b): Soil properties as influenced by biochar and inorganic fertilizers at the end of the growing season (T2) Rivelli *et al.* 2022 [16]

Parameters	Units	B0	Bw	F0	IF	B0F0	B0IF	BwF0	BwIF
pH	Unitless	7.9a	7.9ab	7.9a	7.9a	7.9bcd	8.0ab	7.9bcd	7.8cd
EC	dSm^{-1}	0.5b	0.5b	0.7a	0.6b	0.4d	0.7b	0.4d	0.7b
NH_4^+	mg kg^{-1}	0.5	0.5	0.5	0.5	0.5	0.5	4.0d	0.5
Ca^{+2}	mg kg^{-1}	234.6b	251.9a	222.8b	255.4a	218.2e	265.7b	248.4c	281.9a
Mg^{+2}	mg kg^{-1}	17.2c	19.1a	17.6c	18.0b	16.3g	17.2f	20.1a	19.4b
Total N	Total N, % dw	0.1ab	0.1b	0.1	0.1	0.1b	0.1b	0.1b	0.0b
Corg	Corg, % dw	0.8c	2.2b	1.6c	1.7b	0.8cd	0.7d	2.1b	2.1b



Graph 3: Crop nitrogen uptake (A) from biochar and chemical fertilizer treatments Sadaf *et al*., 2017 [24]

Conclusion

Biochar has a positive impact on soil physicochemical and biological properties. It significantly aids in carbon sequestration. Properties and mechanisms of biochar, coupled with its interaction with various fertilizers, enhance soil properties and crop productivity.

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