Analysis of The Impact of Biochar Application on Soil Fertility and Productivity

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Abstract. The increase agricultural production through intensification and extensification programs does not only provide solutions to food security, but it raises several challenges in sustainable production. In addition to increasing greenhouse emissions which have an impact on global warming, increased production also escalate the production of biomass waste. Although biomass waste is more environmentally friendly than oil-based waste, without proper treatment, this solid waste will have a negative impact on the environment and the sustainability of agricultural production. The conversion of biomass waste into new technology must be adapted to the characteristics of the biomass. Several studies have shown that biomass waste has the potential to be converted into products of higher value such as biochar. Biochar is a material converted from organic waste or agricultural / plantation waste that is rich in carbon, used to increase soil productivity. The long-term advantage of biochar application for the availability of plant nutrients is related to the high stability of organic carbon. The effectiveness of biochar application depends on the biochar production process, the amount of biochar that applied, the soil characteristic, the type of crop being cultivated.

Keywords: Biomass Waste, Biochar, Soil fertility, Soil Productivity

1. Introduction

World population growth in 2050 is predicted to reach 9-11 billion people [1], of which around 6 billion people are residents of developing countries [2]. Population growth must be followed by an increase in agricultural production to meet food needs. Over the past 50-60 years, agricultural research and development has focused on maximizing yields, coupled with increased specialization in production and expansion of agricultural land [3].

Increasing agricultural production through intensification and extensification does not only provide solutions to food security, but raises several challenges in sustainable production. In order to meet food needs for the next 40 years, agricultural emissions will increase by around 60% [4]. Apart from increasing greenhouse emissions which have an impact on global warming, increased production also increases the production of biomass waste. The agricultural, forestry, domestic and industrial sectors produce around 10 billion tons of waste per year on a global scale, and 2 billion tons of total waste constitute agricultural waste whose numbers tend to increase over time [5]. Although biomass waste is more environmentally friendly than oil-based waste, without proper treatment, this solid waste will have a negative impact on the environment and the sustainability of agricultural production.

The conversion of biomass waste into new technology must be adapted to the characteristics of the biomass. Several studies have shown that biomass waste has the potential to be converted into products of higher value such as biochar. Biochar is a charcoal that is formed by biomass pyrolysis. The conversion of chemical composition in biomass into biochar occurred in the absence or restriction of oxygen supply at particular temperatures and pressures. The highly porous structure of biochar can contain quantities of extractable, humic-like and fluvic-like substances [6]. Meanwhile, the molecular structure of biochar show high degree of chemical and microbial stability.
The basic structure of biochar typically contains carbon, nitrogen, hydrogen, and some lower nutrients, such as K, Ca, Na, and Mg [8]. Biochar has a high specific surface area and a variety of polar or non-polar compounds that have a good attraction to inorganic ions such as heavy metal ions, phosphates and nitrates. The majority of biochar compound is suitable in soil quality improvement for agriculture purposes.

Biochar was reported to improve the soil chemical and physical properties [9]. Besides, Biochar also able to improve the soil microbial properties [7]. Many studies have shown that the combination of biochar and soil is able to improve soil structure, increase porosity, reduce bulk density, and increase aggregation and water retention [10]. Further, Biochar is also increase soil electrical conductivity [11], cation exchange capacity [12], reduce soil acidity [11], increase soil biology community composition, and increase microbial biomass [13]. It is indicated that Biochar is potentially component for increase the agriculture productivity through increase the soil fertility.

The majority of Indonesian agricultural soils are acidic and low in both total and available phosphorus [14]. Approximately 104 million ha (68 per cent) out of a total of 148 million ha are acidic and mainly found in Sumatra, Kalimantan and Papua [15]. The utilization of Biochar in soil productivity for many Indonesia agriculture commodities still less discussed. In this review study, we addressed objectively the effect of biochar on soil fertility and productivity.

2. Production of Biochar

The high quality of Biochar is produced from biomass with the proper process. Common strategy for production of Biochar for high yield agriculture product showed in Fig 1. There are various thermochemical processes for the processing of biochar along with their characteristics. Each of process resulted different Biochar characteristic product and yield.

![Figure 1. Strategy to produce Biochar for high yield agriculture product](image)

2.1 Pyrolysis

Pyrolysis is a method for decomposing organic materials thermally under depleted oxygen conditions within a temperature range of 300 ~ 900 °C [16, 17]. The cellulose, hemicellulose and lignin in biomass undergo their own reaction mechanisms, including cross-linking, depolymerization and fragmentation at their own temperature, creating solid, liquid and gaseous materials, during its thermal decomposition [18]. The factors that influence the quality of products in pyrolysis processes include the reaction temperature, heating rate, and residence time. Meanwhile, the yields of the pyrolysis products rely on the characteristics of the raw biomass materials and the pyrolysis processes adapted [18]. Therefore, the proper pyrolysis process will determined quality of Biochar resulted. There are 2 type of pyrolysis methods in Biochar production process, including slow pyrolysis and fast pyrolysis [19]. Slow pyrolysis is a process in which biomass is decomposed at a comparatively mild temperature, which gives ample time for biomass pyrolysis vapor. "Slow" in the slow pyrolysis process implies a low heating rate; meanwhile, the "optimum carbon forming temperature area" [20].
### Table 1. The yield and biochar composition from pyrolysis process

| Biomass            | Yield   | Biochar Composition (Wt. %) | Reference |
|--------------------|---------|----------------------------|-----------|
|                    |         | C  | H  | N  | S  | O  |         |
| Coffee husk        | 39.82   | 69.96 | 3.63 | 3.58 | 0.24 | - | [21] |
| Pine wood          | 43.7    | 71.3  | 4.7  | -  | -  | - | [22] |
| Wheat straw        | 26      | 56  | 2.3  | 1.0 | -  | - | [23] |
| Cow manure         | 58.0    | 51.30 | 4.52 | 1.70 | -  | - | [24] |
| Sweet sorghum      | 23.8    | 69.03 | 2.78 | 0.59 | -  | 27.6 | [25] |
| Rice husk          | 38.86   | 44.73 | 1.80 | 0.73 | -  | 7.69 | [26] |
| Brown macroalga    | 56.08   | 30.67 | 2.72 | 2.09 | -  | 64.53 | [27] |

In contrast to slow pyrolysis, fast pyrolysis occurred in very high heating rates, about 1000 °C/min, to the pyrolysis temperature around 500 °C, and the residence time of vapor is normally <2s [27]. Biomass particles are rapidly decomposed to produce pyrolysis vapors and biochars (10–15 wt.%) in fast pyrolysis process [18]. The yield and biochar composition from biomass conversion process was showed in Table 1.

#### 2.2 Gasification

The thermochemical partial oxidation process, called gasification, is converting carbonaceous materials to gaseous products using agents. Gasification typically occurs at a temperature of 700–1000 °C [18]. The biomass undergoes incomplete combustion of different gasifying agents in such temperature condition [20]. The gasification process can be divided into several stages including drying, pyrolysis, oxidation and gasification (Fig 2.). Each step could not be clearly distinguished from the others in terms of temperature and pressure [18].

![Figure 2. Gasification process](image)

In the drying step, the biomass will be evaporated and the energy used in this step will not be recovered. This step is required to introduce the biomass into the gasifier when the moisture content is too high. After that, the biomass will be heated in pyrolysis process. It takes place over the temperature range, 150-400°C. In this process resulted the product include H₂, CO, CO₂, H₂O and CH₄. Reaction temperature, pressure and temperature rising rate will determine the product composition in this step. Oxidation and combustion of some gas species and char are important sources of energy required for gasification reactions. The carbon formed during the pyrolysis step is converted to CO, CH₄, and H₂ by a variety of gasification reactions. More oxygen molecules in the gasification process can cause a strong removal of biochar, reduce its mechanical strength and yield, and increase its ash content.

#### 2.3 Torrefaction

Torrefaction is a mild form of pyrolysis at temperatures typically between 200 and 320 °C of biomass into better fuel quality for combustion and gasification applications. This thermal-chemical process is able to produce char product that can be used as a fuel and/or soil amendment [28]. Besides, this thermal-chemical process is usually used to improve the thermochemical properties of biomass used for combustion, gasification, and co-combustion with coal. There are several biomasses that used for Biochar production with torrefaction process, including stem wood, sugarcane base, corn stover and bamboo (Table 2).
Table 2. Biochar from torrefaction process of biomass

| Biomass Sources           | References |
|--------------------------|------------|
| Stem wood                | [29]       |
| Sugarcane bagasse        | [30]       |
| Corn stover              | [31]       |
| Rice straw               | [32]       |
| Bamboo                   | [33]       |

3. Application of Biochar to Improve Physical and Chemical Properties of Soil

Soil fertility and land productivity are two important aspect in agriculture activity. The improvement of physical properties of soils by biochar occurred through its high total porosity [34], its impact on increase of available water capacity [35], formation and stability of soil aggregates [36], its impact on increase soil pore structure [37], and its impact on ameliorate compaction [35]. Until now, several studies have focused on the use of biochar to the physico-chemical properties of different soils (Table 3).

Table 3. Biochar application effect on physico-chemical properties of different soils

| Biochar rate          | Soil type            | Incubation | Location                          | pH  | Available N | Available K | Available P | Cation exchange capacity | Reference |
|-----------------------|----------------------|------------|-----------------------------------|-----|-------------|-------------|-------------|----------------------------|-----------|
| Cocoa Peel (15 t/Ha)  | Red clay soils       | 42 Days    | Lampung, Indonesia               | 4.27| 0.09%       | -           | 14.87 ppm   | 0.32 ppm                  | [38]      |
| Rice Husk(15 t/Ha)    | Red clay soils       | 42 Days    | Lampung, Indonesia               | 4.07| 0.087%      | -           | 12.43 ppm   | 0.04 ppm                  | [38]      |
| Chicken manure        | Peat land            | 5 Months   | South Kalimantan, Indonesia      | 3.6 | 1.1%        | -           | 62.66 ppm   | 0.44 (cmol(+) kg-1)       | [39]      |
| (16.7%) + Biochar from coconut shell | Peat land | Vegetative Phase | South Kalimantan, Indonesia      | 4.15| 1.02%       | 1012%       | 156.58%     | -                         | [39]      |
| Galam stem (16 t/Ha)  | Peat land            | Vegetative Phase | South Kalimantan, Indonesia      | 4.11| 1.02%       | 1118%       | 296.37%     | -                         | [39]      |
| Rice husk (16 t/Ha)   | Peat land            | Vegetative Phase | South Kalimantan, Indonesia      | 4.19| 0.96%       | 0.561%      | 160.38%     | -                         | [39]      |
| Palm midrib (16 t/Ha) | Peat land            | Vegetative Phase | South Kalimantan, Indonesia      | 4.29| 1.02%       | 0.651%      | 129.96%     | -                         | [39]      |
| Coconut shell (16 t/Ha)| Peat land           | Vegetative Phase | South Kalimantan, Indonesia      | 6.6 | -           | -           | -                       | -          |
| Wood—450, 50 t ha−1 | Sandy clay loam      | Year 3     | Abergyngreyn, Wales              | 7.4 | -           | -           | -                       | -          |
| Peanut hull—500, 2 %  | Sandy soil           | Day 120    | Southeastern USA                 | 6.83| -           | -           | -                       | -          |
| Pineapple peel—500, 3 %| Red soil            | Day 100    | Hangzhou, China                  | 5.07| -           | -           | 10.8 (cmol kg−1)        | [43]      |
| White lead trees—700, 5 %| Acidic soil         | Day 105    | Pingtung, Taiwan                 | 5.07| -           | -           | -                       | -          |
4. The effect of biochar application on soil productivity

The effectiveness of biochar also depends on the amount of biochar that applied and the type of crop being cultivated. The amount of biochar to be applied depending on the degree of soil degradation and its characteristics such as pH, cation exchange capacity (CEC), soil texture and C-organic content [38]. In addition, the effect of biochar on crop productivity such as corn can be seen in Table 4.

| Biochar Rate | Soil                     | Location                  | Yield (ton/ha) | References |
|--------------|--------------------------|---------------------------|---------------|------------|
| Without biochar | Biochar of rice husk—7.5 | Typic Kanhapludult. Lampung, Indonesia | 0.37 2.31 | [44]        |
|              | Biochar of coconut shell—15 | Sandy loam Lombok Utara, Indonesia | 4.50 5.20 | [45]        |
|              | Biochar of legume---5 ton/ha | Alfisol Indonesia | 4.17 6.57 8.15 | [46]        |
| Biochar of legume --- 10 ton/ha |                          |                           |               |             |
| Biochar of paper fiber sludge and grain husks—20 ton/ha | HaplicLuvisol Malanta, Slovakia |                           |               | [47]        |
| Biochar of wood | Oxisol Llanos Orientales, Columbia |                           |               | [48]        |

5. Conclusion

Biochar is promising agent in soil fertility and productivity improvement. The different thermochemical process will resulted different characteristic of Biochar products. Moreover, the use of Biochar will also affect on pH, available N, P, K, and cation exchange. On the other hands, the improvement of physical and chemical properties of soil will also affect to its productivity.
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