Improvements of soil quality and cocoa productivity with agricultural waste biochar

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Abstract. National cocoa production has been decreasing, which was in 2017 down to 600,000 tons/year, only a third quarter of national need. The decline is due to a decrease in national cocoa production caused by lower productivity in smallholder cocoa. In 2003, the productivity was 1,100 kg/ha/year and in 2017 was only 820 kg/ha/year. The low productivity is caused by pod rot disease, pod borer, and vascular streak dieback (VSD). Not only that, soil degradation was also found to be a contributing factor. Compost or manure have been used as ameliorants, but they should be in high volume and have a short-term effect (3-4 months), easily decomposed, and produce CO₂ that damage the ozone layers. A more suitable solution is using biochar which is more resistant to decomposition (hundreds of years), can hold CO₂, water, and nutrients from being washed away by erosion. In addition, biochar does not require Cocoa farming generate organic waste that can be processed into biochar, such as cocoa pods, cocoa or shade trees from pruning. The biomass produced can reach up to 8-18 tons/year and is adequate to improve the soil fertility in cocoa plantations.

1. Introduction

National demand for cocoa beans increases significantly after the release of No.67/Permentan/OT.140/5/2014, which regulates the quality and distribution of cocoa. In 2017, 2018, and 2019, the demand for cocoa beans to meet 20 units of cocoa industries reached 800,000 tons/year. Unfortunately, national cocoa production in the same period decreased to 600,000 tons which 9 out of 20 units were closed due to inadequate raw materials even after importing 226,613 tons of cocoa beans in 2017 [1–3].

The production decrease is caused by lower cocoa plant productivity. In 2010, the productivity of smallholder cocoa was 822.43 kg/ha/year and decreased in the next year to 701.33 kg/ha/year [2]. The highest national productivity ever achieved is in 2001, up to 1,100 kg/ha/year. Soil nutrient content in cocoa plantations is very low. The results of soil analysis in cocoa plantations in the Central Lampung area show that the N, P, and K content in the soil is very low, only around 0.08%, 12.5% and 12.2%, while cocoa plants require very large elements, especially potassium [4]. At immature phase nutrition requirement of cocoa tree is 188 kg/ha (K₂O) and 140 kg/ha (N) [5].

Several factors in the declining cocoa production are pest and disease attacks, planting materials, post-harvest processing, and agricultural practice [6]. Harni [7] stated that pod rot disease causes yield loss as much as 20-30%, whereas the loss maybe 100% in areas with high rainfall. In some areas,, the disease attack causes farmers were unable to harvest at all.
Aside from that, the cocoa plantation is also undergoing degradation, a decrease in soil fertility and productivity [8]. This condition is caused by erosion, leached nutrients contents, improper agricultural practice, and exploited nutrients after harvesting. In each 1000 kg of cocoa beans harvested, 546 kg N, 96 kg P, 246 kg K, and other nutrients such as Mg, Ca, and Fe are also taken. Degraded soil in cocoa plantations causes fertilization ineffective despite the recommended dose as the fertilizer only saturates soil but cannot be absorbed by plants [9]. If not repaired, the degraded land will become critical land. Critical land area in 2018 reached 14.01 million ha, less than that of 2014, which reached 27.2 million ha [10].

Degraded soil can be repaired to restore its fertility. Amelioration of the degraded soil can be done using organic materials such as compost or manure. However, the application must be repeated and requires high volume (up to 12-25 tons/ha) [11] making it less efficient. Furthermore, it is easily decomposed, and the effect is short-term (3-4 months). Organic matter in the decomposition process also emits CO$_2$ gas, which has a greenhouse effect and contributes to the ozone layer damage of the atmosphere and global warming [1]. The CO$_2$ content in the atmosphere is always increasing which causes the greenhouse effect, the use of organic matter, the clearing of peatlands and emissions from industry as the cause. While relying on plants to absorb CO$_2$ is only temporary, because eventually it will die and decompose which also produces CO$_2$. The CO$_2$ content in the atmosphere continues to increase as a result of the decomposition of organic matter, clearing of peatlands, emissions from industry, and emissions from vehicle fuels. Control of CO$_2$ by planting plants is temporary, because it will die and decompose again and produce CO$_2$ into the atmosphere, as well as absorption by the earth and oceans which does not change over time. The increase in CO$_2$ in the atmosphere causes the greenhouse gas effect, and the earth's temperature rises. This increase in global temperature will affect the physical and chemical processes that exist both on earth and in the atmosphere and ultimately have an impact on climate change. It is estimated that the current CO$_2$ concentration is the highest concentration in the last 650,000 years. The rate of growth of CO$_2$ concentration continues to increase significantly. In terms of sources, in the period 1959-2006 the largest number of emissions came from the use of fuel oil, which reached 80%, while from changes in land use around 20%.

Biochar can be used as a material to repair degraded soil. In corn crops, the administration of biochar from corn cobs as much as 20-30 kg/ha can improve soil fertility and water-saving capability, so production increased by 65.48% [11]. Biochar can affect the soil’s ability to hold nutrients, groundwater, and CO$_2$ so that it does not escape into the air and increase the activity of soil microorganisms [12]. In addition, biochar is more resistant to decomposition and does not require as much volume as manure, making it easier to apply and with a longer effect. Carbonization is an incomplete pyrolysis (combustion) process with limited air from carbon-containing materials. In this process the formation of the pore structure begins. The high number of pores has a high absorption capacity. The base material is heated with various temperatures up to 1300°C. Organic material is decomposed leaving carbon and other volatile components evaporated [13]. The carbonization process is a process in which volatile components will be released from the carbon and the carbon will start to form pores. In the carbonization process, many non-carbon elements such as oxygen, hydrogen, and nitrogen are removed as volatile gases by pyrolytic decomposition of the starting material [2]. The carbonization process is influenced by the length of carbonization time and the carbonization temperature. The charcoal obtained is then activated. Activation aims to enlarge the pores, namely by breaking hydrocarbon bonds or oxidizing surface molecules so that the charcoal undergoes changes in properties, both physical and chemical, namely increasing the surface area and affecting absorption [14]. The activation method commonly used is the method of making activated charcoal, namely physical activation and chemical activation.

Physical activation is the process of breaking the carbon chain from organic compounds with the help of heat, steam and CO$_2$. These gases function to expand the structure of the cavity in the charcoal so that it expands its surface, removes volatile constituents and removes the production of tar or hydrocarbon impurities in the charcoal.

Chemical activation is the process of breaking the carbon chain from organic compounds with the use of chemicals. Chemical activation usually uses activating ingredients such as potassium chloride.
salt (CaCl$_2$), magnesium chloride (MgCl$_2$), zinc chloride (ZnCl$_2$), sodium hydroxide (NaOH), potassium hydroxide (KOH), sodium carbonate (Na$_2$CO$_3$), sodium chloride (NaCl), Phosphoric acid (H$_3$PO$_4$), Nitric acid (HNO$_3$), Hydrogen Peroxide (H$_2$O$_2$), Potassium Permanganate (KMnO$_4$), Ammonia Sulfate ((NH$_4$)$_2$SO$_4$), Hydrochloric Acid (HCl). The absorption of biochar is getting stronger to increase the concentration of the added activator. This gives a strong influence to bind tar compounds out through the pores of the biochar so that the surface of the biochar gets wider which results in the greater absorption of the biochar.

Biochar or often called activated charcoal, is a type of carbon that has a very large surface area. Biochar is a porous solid containing 85-95% carbon, which is produced from carbon-containing materials by heating at high temperatures. When heating takes place, efforts are made to prevent air leakage into the heating room so that the carbon-containing materials are only carbonized and not oxidized.

Biochar results from thermally burnt decomposed biomass at 300-600°C, with a very low oxygen content or without oxygen, known as pyrolysis [15]. Biomass can be derived from rice husks, cocoa or shade tree wood from pruning, cocoa pod, coconut shell, coffee husk, and high carbon-containing biomass. Making biochar can be done by using a tight lid drum or a bunker made of cement. In some areas, farmers have produced biochar in bulk which gives them an additional source of income. The productivity of smallholder cocoa is decreasing, and one of the reasons is the declining soil fertility. If not improved, the cocoa plants will not absorb the fertilizer, and productivity will not increase.

2. Biochar and Improved Soil Quality

2.1. Physical properties

The properties of biochar from husk of rice were: 4.96% (water content), 8.70 (pH), 0.12% (P), 17.57 cmol kg$^{-1}$ (CEC), 0.20% (K), 0.41% Ca, 0.62% (Mg) and 1.40% (Na) [16]. Applying biochar to degraded soils can improve soil structure, retain water, prevent soil erosion, and enrich organic carbon in the soil, increasing soil pH, thereby indirectly increasing crop production [17,18]. The increased temperature of charring is increase the physical properties of soil e.g. the capacity exchange and surface area. Nutrient availability and retention was found higher as well due to the capacity exchange and surface area was increase. The research results by Masulili, Utomo, & MS [16] showed that the application of biochar to acid sulfate soils decreased bulk density of soil from 1.24 Mg m$^{-3}$ to 1.17 Mg m$^{-3}$. The low bulk density of soil generally improved the porosity with the aggregation of soil. The increased of soil porosity incline with water retention.

2.2. Chemical properties

The application of biochar is not to add nutrients to the soil but to hold nutrients from being washed away or washed away with erosion. The application of rice husk biochar on maize plantations can withstand the loss of K nutrients up to 65.48%, so that the nutrients that plants can absorb increase to 35%, and the dose of K fertilization can be reduced to 75% [19]. It is similar to the nutrients N and P. Biochar can increase the soil's buffering capacity against leaching or leaching of N, P, and K and increase the ability of the soil to exchange cations. According to Mateus et al. [20], besides stable organic C-organic, biochar also contains many organic compounds in the form of organic acids that play a role in the liberation and release of nutrients. Biochar has a high carbon content. The application of biochar can increase the content of organic matter in the soil and is used as an indicator of soil quality, such as maturity of retention soil aggregates and availability of nutrients [11].

The research results by Nuridiyati & Mariati [21] show that biochar application can increase soil pH by up to 23%. An increase in pH causes the solubility of aluminum to decrease in acid soils that develop in the tropics. Therefore, the solubility of aluminum is often a limiting factor for crop production [17]. Biochar application increases soil pH and the availability of nutrients for plants, such as C, K, Ca, Mg, Na, and P. On the contrary, it will reduce the solubility of iron and aluminum [16]. Lehman [22] stated that the application of biochar into the soil is most affected by its affinity for nutrients and its resistance ability.
Biochar can maintain the concentration of CO₂ in the atmosphere as well, whether to remain stagnant or decrease. Biochar potent to store CO₂ in the soil and simultaneously improve the soil material (amendment). Sarwono [23] stated that biochar is a recalcitrant that is difficult to oxidize and deposits in the ocean for millions of years. Carbon stored in the soil is negative, so it needs to be promoted to reduce the concentration of CO₂ gas in the atmosphere.

2.3. Microorganism
Biochar and microorganism have a complex interaction, however biochar provides a good growth medium for various microorganisms [22]. Lehman and Rondon [22] reported that biochar also provides a good growing medium for different soil microbes. [24] stated that the characteristics of biochar (porous, have a surface, and able to absorb inorganic nutrients) are suitable for microorganisms to grow and develop, especially actinomycetes bacteria arbuscular mycorrhizal fungi. The diversity and population of microorganism may potentially affected by biochar type. Based on multi level DNA, RNA and protein, the addition of biochar was increase the diversity of ammonia-oxidizing microorganisms which it contribute on nitrification process [25]. Nitrification is a vital process in N transformation, and it coupled with organic matter mineralization and denitrification process.

3. Biochar and Waste in Cocoa Cultivation
The nature and quality of biochar depend on the raw materials and the production method. For example, biochar derived from wood is more porous than livestock manure and other properties, such as water and nutrient holding capacity and soil aeration [2]. Materials containing high carbon and cellulose elements can be used as biochar.

Agricultural and forestry industrial systems generate large amounts of biomass waste. The biomass waste is composed of cellulose, EMI cellulose, and lignin, which have a high percentage of carbon and are good raw materials for biochar production [3] Biomass waste such as (i) waste of forestry industries, waste of logging and dead wood, (ii) waste of wood processing and sawmill, (iii) crop residues, (iv) household waste, and others.

3.1. Biochar from harvest waste
Cocoa crop waste can be in the form of cocoa pods, reaching 75% of the pod's weight. Cocoa productivity can reach 800-1,200 kg/ha/year. With 18 tons of cocoa pods/ha/year are produced, the waste generated is significant. Cocoa pods contain 17.27% cellulose, 52.02% lignin, and 19.56% hemicellulose [26]; thus have the potentials to be processed into activated charcoal. If as much as 30% of the pod waste of cocoa pods harvested is processed into charcoal, approximately 5.4 tons of charcoal is produced annually and can be used to improve soil fertility in cocoa plantations. With a dose of up to 4.9 kg/plant/year, it is adequate to enhance soil fertility.

3.2. Biochar from plants
Pruning on cocoa plants produces a significant amount of biomass. Pruning is done regularly and has several types: shape pruning, maintenance pruning, and rehabilitation pruning. Aside from cocoa trees, pruning is also necessary on shade trees, such as gliricidia, which produce large biomass. Biochar from gliricidia contains quite a high organic C, 12.68% higher than rice husk biochar (6.68%). According to Laird et al. [27], the c-organic faction is a stabilizer of soil aggregates and can maintain and improve the physical condition of the soil. It is estimated that the amount of pruning from cocoa and gliricidia plants can reach up to 8 tons/year, which will produce 2.4 tons/year of biochar. This amount is sufficient for the plant's need that is 2 kg/plant/year.

3.3. Biochar of wood weed
There are plenty of unwanted and bothersome plants in cacao plantations. For example, *Melastoma malabathricum* L and *Lantana Camara*, a woody plant and considered weed, is often found in cocoa plantations. Such plants are also potential materials in producing biochar. The weed biochar was
produced in thermal condition at 600 °C, and continue to sun dried and heat it at 100 °C for 24 hour. The higher quantity of weed biochar application able to increase seed germination of maize [28].

3.4. Cocoa plant
Cocoa is a tree plant that can reach 15 m in height, with pruning maintained so that its height does not exceed 4 m. Cocoa plants include C3 plants according to their need for sunlight. C3 plants are plants that carry out maximum photosynthesis at a sunlight intensity level of 60%. The higher the intensity of the sun against the lower will cause the production to decrease. Therefore this plant requires permanent shade plants to obtain the desired level of shade, which usually uses Glirisdia sp, with regular pruning to maintain the shade level.

The cacao plant originates from the Amazon plains in South America, which is a tropical forest with high rainfall. Cocoa plants require soil that has a high organic matter content, is not resistant to drought, requires an evenly distributed amount of rainfall of 2500-3000 mm per year. The availability of water greatly affects the productivity of cocoa plants. In some countries, to meet the water needs of the cocoa plant is done by irrigation, and the cost will be higher.

In cacao plantations, to increase the soil's ability to hold water, rorak-rorak is made. Rorak-rorak will collect water and store it for the needs of plants in the dry season. The rorak-rorak is also filled with organic matter or fallen cocoa leaves, so that it becomes compost.

4. Biochar and Improved Cocoa Production
The addition of biochar to cocoa plantations is still rare since crops estate require a long duration plantation. [29] applied biochar from pod cacao coupled with local microorganism in seedlings of cocoa. This treatment, 30 g biochar/polybag and 40 mL local microorganism/polybag had a significant effect on improvement cocoa seedling, consisting of accelerated the height of plant (69.16%), shoot dry weight (92.22%) and root dry weight (7.0%).

5. Conclusion
The soil fertility in cocoa plantations has declined due to leaching, erosion, or exploitation after each cultivation season. Untreated, the degraded land will become critical. One strategy to improve fertility is the application of organic materials, such as manure and compost. However, due to its inefficiency and adverse impact on the environment, an alternative solution is needed that is biochar. Biochar is derived from organic matters that are abundant in cocoa plantations. Biochar can hold CO2, store nutrients, so they don't wash away, causing fertilizers to be more efficient, store water in the soil, and enlarge soil pores so improving soil aeration, thereby increasing soil fertility. In cocoa plantations, the biomass produced can be converted into biochar, such as cocoa and shade trees resulted from pruning, and cocoa pods, which can reach up to 8-18 tons/year and is sufficient to improve the soil for cocoa cultivation hence increasing the cocoa productivity.

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