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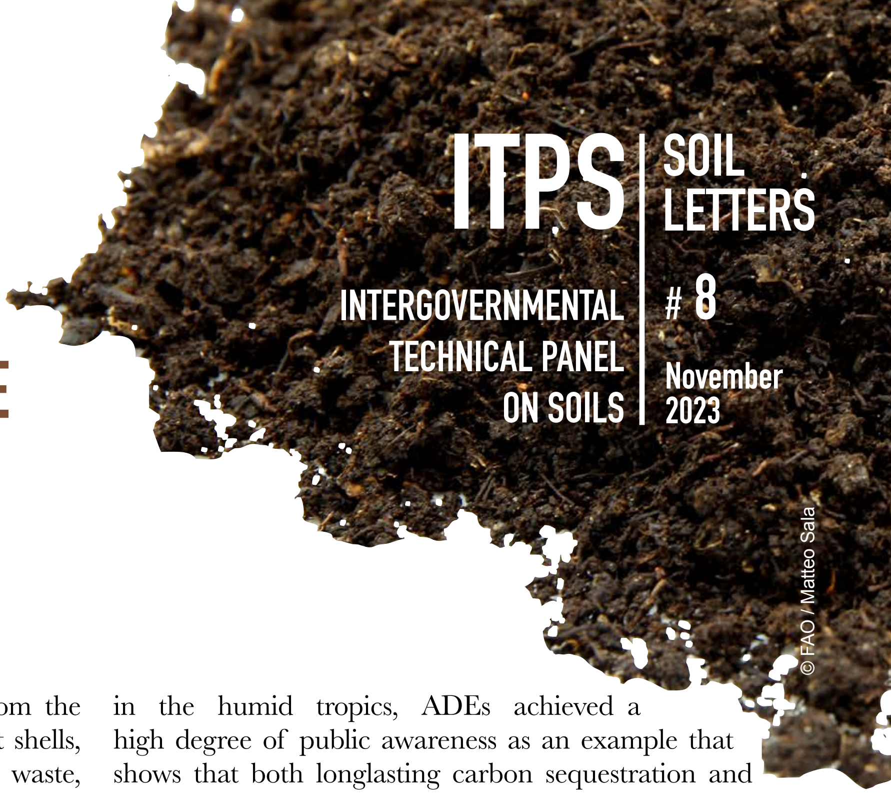
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BIOCHAR IN SUSTAINABLE SOIL MANAGEMENT: POTENTIAL AND CONSTRAINTS

Biochar is a material rich in carbon that results from the pyrolysis of any biosolid material such as wood, fruit shells, residues of plants, manure, industrial and municipal waste, sewage sludge, farming, and fermentation residuals (Duku, Gu and Hagan, 2011; Wang *et al.*, 2018a). Biochar remains in the soils for thousands of years (Aslam *et al.*, 2014), and it is therefore considered more resistant to decomposition than organic matter, acting as an important long-term carbon sink.

The potential use of biochar in modern agriculture draws inspiration from the ancient indigenous knowledge preserved in Amazonian Dark Earths (ADEs), a type of highly fertile soil containing large quantities of archaeological artefacts and charcoal, commonly with high levels of calcium and phosphorus, first described in the Amazon rainforest (Clement *et al.*, 2015; Myers *et al.*, 2003; Sombroek, 1966). Since sustainable soil fertility management is a major constraint in the humid tropics, ADEs achieved a high degree of public awareness as an example that shows that both longlasting carbon sequestration and soil fertility improvements are possible, which has boosted the interest in traditional practices translated in the form of biochar. In 2006, the *International biochar initiative* formed to promote the development of sustainable biochar systems. Since then, the amount of research, conferences, workshops and symposia on this theme has increased immensely worldwide. A bibliometric analysis on biochar research in Brazil from 2003 to 2021 has been presented in a paper by Arias *et al.* (2023).

Due to the effects of better soil properties and long carbon sequestration, biochar as a soil amendment has been proposed as a strategy for mitigating climate change, along with improving soil quality and productivity. The burning of crop


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residues is becoming a serious issue in most countries, since it results in the release of black carbon in the form of suspended particulate matter that can pollute nearby urban areas. Hence, the conversion of organic waste to produce biochar using the pyrolysis process is also one of the viable options that can enhance natural rates of carbon sequestration in the soil, reduce farm waste and improving soil quality.

There are several methods of applying biochar to the soil. These methods include band placement, uniform topsoil mixing, top dressing, and the use of planting holes. Biochar can also be applied directly or through mixing it with crop residue, compost, manure and seed. The choice of biochar application method will depend largely on the availability of labour and farming system (Duku, Gu and Hagan, 2011). In some places where crops are established, surface application (top dressing) of biochar can be employed. Banding is another much-used technique that involves biochar addition below the soil's surface to a depth of 10 to 20 cm in an established crop. The banding approach improves the contact between the biochar, soil and plant, while avoiding the creation of dust (De Gryze *et al.*, 2010).

EFFECTS ON SOIL FERTILITY

The application of biochar has both direct and indirect effects on soil fertility. The direct effects include an enhanced nutrient availability (potassium [K], phosphorus [P], calcium [Ca], magnesium [Mg] and sulphur [S]), while indirect effects are through the improved physical, chemical, and biological properties of the soil (Cheng *et al.*, 2012; Beusch, 2021, Singh *et al.,* 2022). The main reported effects on chemical and biological parameters are increases in soil pH (Sohi *et al.*, 2010; Syuhada *et al.*, 2016; Verheijen *et al.*, 2010; Dong *et al.*, 2018), cation exchange capacity (Das *et al.*, 2021), mineral nitrogen (N) availability, dissolved organic carbon, and microbial diversity (bacterial and fungal) (Sing *et al.*, 2022; Tian Hu *et al.*, 2023). Some of the effects on the soil's physical properties are increases in water holding capacity and porosity (Ahmad Bhat *et al.*, 2022; Hien *et al.*, 2021; Major *et al.*, 2009; Rattanakam *et al.*, 2017; Sing *et al.*, 2022). All these positive results have been related to the improved yield of various crops in different soil types and regions (Gopal *et al.*, 2020; Xu *et al.*, 2015; Zhang *et al.*, 2015).

Biochar properties are affected by several technological parameters – mainly pyrolysis temperature and kind of feedstock – whose differentiation can lead to products with a wide range of pH values, specific surface area, pore volume, cation exchange capacity (CEC), volatile matter, ash, and carbon content (Pituya, Thavivongse and Saowanee, 2017; Tomczyk, Sokolowska and Boguta, 2020). The pyrolysis temperature and soil pH both play an important role in the biochar's ability to hold nutrients (Gronwald *et al.*, 2015; Ghodszad *et al.*, 2022). Most researchers focused on the production of inorganic forms of N as NO_3^- and NH_4^+ (Aghoghovwia, Hardie and Rozanov, 2020; Fatima *et al.*, 2021), and phosphorus (Wang *et al.*, 2021; Rashmi *et al.*, 2020). The high negative charges and surface area lead to high cation adsorption, higher than any other organic matter, in which cations act as bridges that encourage soil aggregation. Consequently, when biochar is applied to clayey soils, aeration and water infiltration are improved (Laird, 2008; Lehmann, 2007).

Biochar has a good potential to neutralize soil acidity, which enhances the availability of P and molybdenum (Mo) and decreases the availability of iron (Fe), aluminium (Al), zinc (Zn), and boron (B) (Van Zwieten *et al.*, 2007). It results in higher yields when applied to acidic soils, but the effect is not evident in alkaline soils (Van Zwieten *et al.*, 2010). It has also been suggested that biochar application in P-deficient soil results in higher grain yields and improves the response to N and NP fertilizer treatments (Ding *et al.*, 2016). While there are many references indicating that biochar significantly improves soil quality parameters when applied at higher rates to highly eroded, coarse-textured tropical soils, almost no significant effects have been detected in other soils, such as Mediterranean calcareous soils (Nogues *et al.*, 2023).


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Indeed, the efficiency and viability of biochar application depend both on the type of biochar and the soils where it is applied. Siltecho *et al.* (2021) reported that *Pterocarpus macrocarpus* wood biochar showed important adsorption properties with a high specific surface area, CEC, and nutrient adsorption on unfertile sandy soils in marginal area in the northeast of Thailand. Regarding the origin of biochar biological material, Silva *et al.* (2016) report different increases of the grain dry matter of common bean after biochar application, depending on whether using rice husk, sawdust, or sorghum silage (increasing order) as the source. Contrasting results were also obtained when looking at the long-time effects of biochar application. Application of chemical fertilizers in combination with biochar increased the soil pH, organic carbon, available nutrient content, and improved soil biological activity (Saha *et al.,* 2019). The co-application of biochar and chemical fertilizers after five years in China were shown to improve soil physical properties and increased macronutrient availability and uptake by various crops over five years (Gu *et al.*, 2022). However, the beneficial effects of a single application of biochar were also shown over a period of eight years in Finland, where, despite the increased nutrient content of plants, no significant improvement was observed in crop biomass yield over the years. The enhanced plant available water and reduced bulk density previously reported during the initial years were diminished in the long term, likely due to the dilution of biochar concentration in the topsoil (Kalu *et al.*, 2021).

ROLE OF BIOCHAR IN IMPROVING FERTILIZER USE EFFICIENCY

An improvement in the water holding capacity and the increase in cation and anion exchange capacities in biochar-amended soils are reasons both for the higher retention of nutrients and decreased leaching of applied fertilizers out of the soil–plant ecosystem (Sohi *et al.*, 2010). The effect of applied biochar is also shown to alleviate abiotic stresses in saline–sodic soils and positively affects maize and wheat productivity (El-Sharkawy *et al.*, 2022). Biochar produced from manure, greenhouse waste and grasses are more effective for nutrient supplementation than wood-based biochar, with the opposite being true in terms of their carbon sequestration potential (Ippolito *et al.*, 2020).

EFFECT OF BIOCHAR ON SOIL PHYSICAL PROPERTIES

The surface area and porosity of the biochar enhance the soil's ability to hold water (being held inside the pores and between biochar colloids). Therefore, irrigation frequency might be reduced in some cases due to the increased available water especially in dry and semi-dry areas. Biochar may also enhance water infiltration into the soil and consequently, the water runoff may be reduced. Therefore, biochar could be considered an option for water conservation and the prevention of water erosion (Itsukushima *et al.*, 2016; Abrol *et al.*, 2016).

The effect of biochar on soil porosity is variable according to soil types. It increases the percentage of large soil pores in clay soil while increasing micropores in sandy soil (Major *et al.*, 2009). Consequently, soil aggregation is improved, which seems to correlate to the amount of biochar amendment applied to the soil. A recent study in Italy on biochar produced from forest biological mass seem to confirm these findings (Baiamonte *et al.*, 2021).

EFFECT OF BIOCHAR ON SOIL BIODIVERSITY

Biochar modifies biological properties as the microbial community structure, microbial biomass and activity, macrofauna activity, or nitrogen cycling enzymes. Due to its high specific surface area, biochar pores could act as shelters protecting soil microbial mass, enhancing microbial mass growth, especially in dry conditions (Sohi *et al.*, 2010). The creation of extra spaces for the growth of microbes would provide oxygen, and hence increase their biodiversity and density in the soil (Reddy, 2014).

The microbial biomass living in the inner biochar structure are active in the production of polysaccharide compounds capable of improving soil aggregates, and therefore, enhance soil condition and health (Aslam, Khalid and Aon, 2014). However, as biochar itself is resistant to microbial decomposition, in the cases when it does not affect the pore volume or other soil physical and chemical properties, no major changes in microbial communities or biomasses are to be expected (Soinne *et al.*, 2020).


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ENVIRONMENTAL IMPACT OF BIOCHAR

The formation of functional groups and adsorption sites both on the surfaces and inner pores of the biochar increases the soil's CEC (Liang *et al*., 2006). Due to this effect, biochar has been used for sorption of organic and inorganic contaminants, since the bioavailability of heavy metals (lead [Pb] and cadmium [Cd]) can be reduced by immobilizing them in soil using biochar as an amendment which limits their movement through the soil (Hartley *et al*., 2009). This function of biochar is the result of the negatively charged groups on its surfaces, which seems to increase with time due to the oxidation processes in the soil (Cheng, Lehmann and Engelhard, 2009). Biochar along with phytoremediation strategies could provide a good combination for effectively stabilizing and decontaminating heavy metal-polluted sites. On the other hand, some researchers have warned against health risks due to exposure to polycyclic aromatic hydrocarbons (Wang *et al*., 2018b; Zhang, Zhang and Liao, 2021).

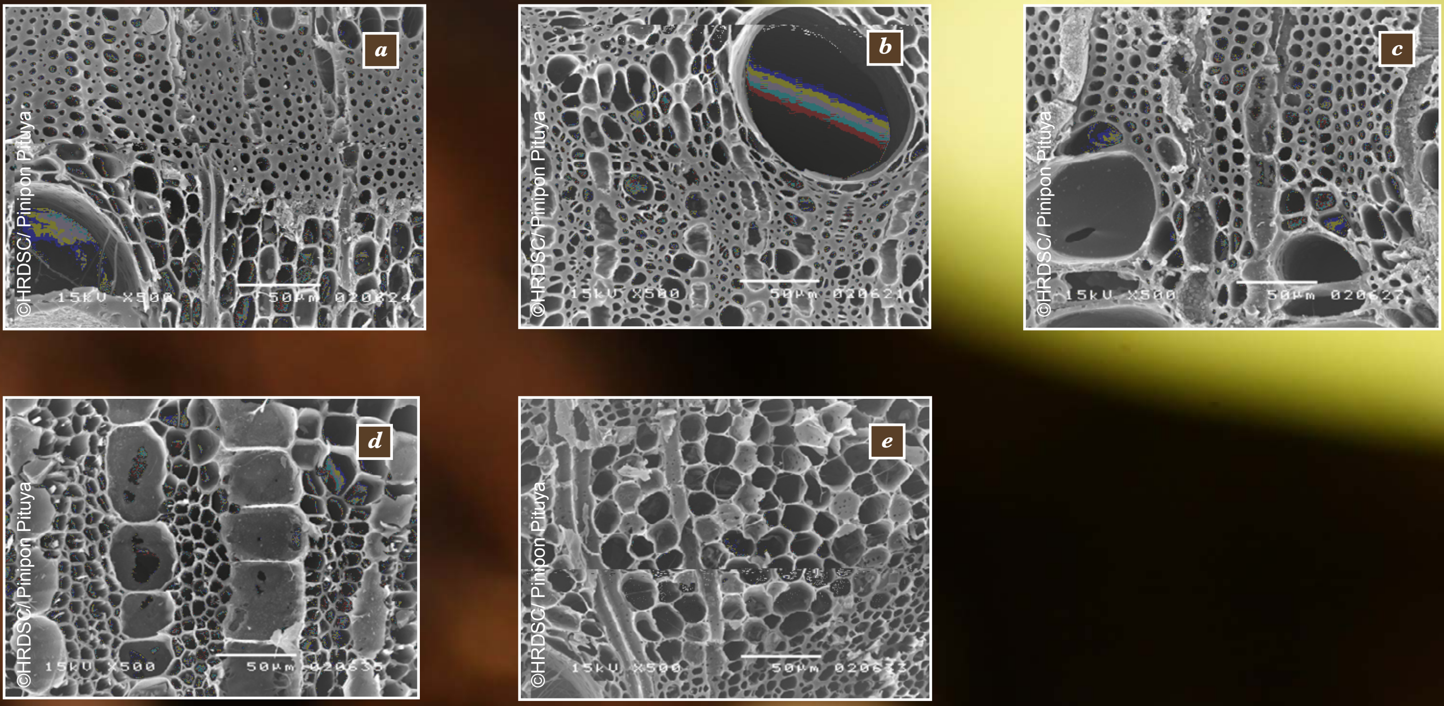
REDUCTION OF GREENHOUSE GAS EMISSIONS (GHG)

Biochar application to agricultural soils has been recommended as a strategy to reduce increasing atmospheric carbon dioxide (CO_2) concentrations and mitigate climate change (Lorenz and Lal, 2014). Several studies have reported that biochar application reduces the emissions of soil greenhouse gases (GHGs) (Zhang *et al.,* 2020), but the mechanisms responsible for the effects of biochar on soil GHGs emissions are still unclear. The biochar feedstock, pyrolysis conditions, C:N ratio and application rates influence nitrous oxide (N_2O) emission. However, the increase in soil methane (CH_4) and CO_2 emissions were also reported after biochar application (Mukherjee and Lal, 2013; Wang *et al.,* 2012).

CONCLUSION

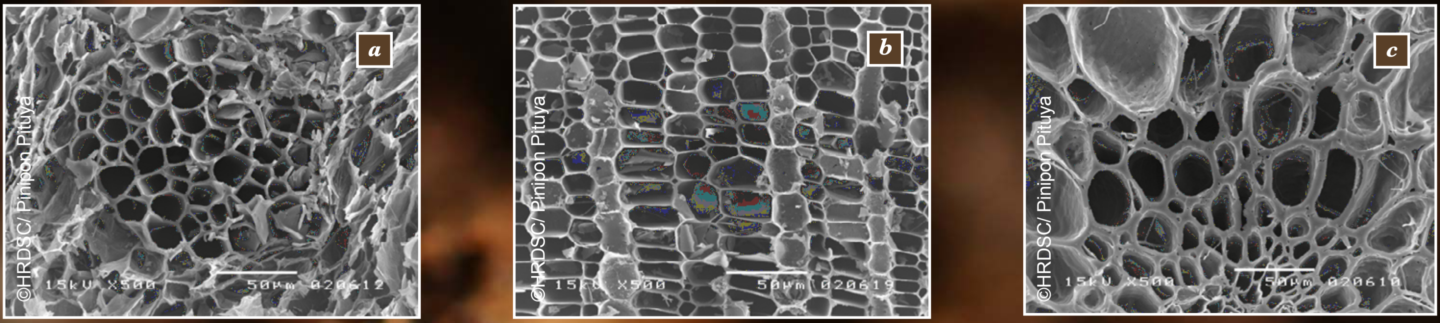
The efficacy of biochar in improving soil health, crop productivity, land reclamation and mitigation of climate change has been extensively studied over the last decade. This research has shown varied results, from clear improvements of soil health to almost no difference compared with the control, depending on the types of soil, crop, type of biochar and the environment. Moreover, information is still very limited from large scale field trials, probably because of the high costs of biochar in the market. Large-scale production of biochar from all kinds of organic wastes may help in reducing the costs. The greatest potential may be in having very targeted applications to address specific environmental concerns. A proper regulatory mechanism is required to avoid any possible risks of soil contamination due to potential contaminants present in biochar, and on the global GHGs emissions when producing it, which should be considered when using it as a carbon sequestration strategy.

Figure 1. Scanning electron microscope of biochars from wood materials:
(a) Peltophorum pterocarpum, (b) Eucalyptus, (c) Pinus, (d) Anacardium occidentale
(e) Cassia siamea (Lam.)



Source : Pinipon Pituya (Huaysai Royal Development Study Center, Petchaburi Province, 76120, Thailand), personal contact.

Figure 2. Scanning electron microscope of biochars from organic wastes:
(a) durian peel (b) cassava rhizome (c) corn cob



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