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Current knowledge in enhancing moisture content for sandy soil through the application of pristine rice husks biochar and polyvinyl alcohol (PVA) - A review

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Abstract Biochar and super-absorbent polymers such as polyvinyl alcohol (PVA) possess numerous unique properties that are increasingly used in soil amendment applications. Subsequently, a combined application of rice husks biochar and PVA or utilization of biochar/PVA composites could be a promising direction to enhance moisture content of soils in arid regions or sandy soil to promote plant growth. However, independent data from individual studies to explicitly expose the potential benefits and challenges of utilizing biochar and PVA singularly or in combination in soil amendment initiative is limited. Therefore, a review of recent articles was done to enhance our understanding of the essence of the processes involved; provide insight about future research directions; and contribute to the development of theoretical framework for soil amendment using both biochar and PVA. In this case, properties of rice husks biochar and PVA; effects of pyrolysis temperature on hydrological and chemical properties of rice husks biochar; and their deficits and advantages are discussed. Applications of PVA in singular or combined forms in various fields; and preparation of biochar-PVA composites are also highlighted. Based on this work, coupling biochar with PVA would be super singular use of biochar and PVA in improving water content of soil in arid environment.

Keywords: *Biochar; Pyrolysis temperature; Soil amelioration; Polyvinyl alcohol; Hydrophilicity; Arid lands.*

1. Introduction

One of the major contributors to the failure of plants and biocrusts' sustainable growth in the arid lands is the persistent deficiency of moisture particularly in sandy soils. Wide adoption of soil amendment technologies using biochar and super-absorbent polymers could be a promising approach that can help to improve moisture content of the soil, among other hydrological, chemical and physical parameters that are necessary for the growth of plants. Application of biochar can also be beneficial to the environment as this carbonaceous material has the ability to sequester carbon dioxide, and reduce emission of nitrogen oxide and methane into the atmosphere. Although many studies have registered significant positive results for soil amendment using biochar for agronomic and environmental benefits, this technology has not been widely adopted or scaled-up. This is attributed to evidence gap between research and technology application; unavailability of affordable biochar products on the market; lack of quality standards for biochar; absence of best-use biochar application programs; and low awareness by prospective end-user of biochar (Guo et al., 2016). Although numerous studies have also demonstrated significant positive results for soil amendment using biochar, some few studies have found slightly different results. For instance, biochar from other biomass (such as herbaceous feedstock) did not show significant effect on soil water retention, aggregate stability, and hydraulic conductivity in some studies (Jeffery et al., 2015; Ma et al., 2016; Wiersma et al., 2020). This implies that type of feedstock and pyrolysis conditions matter in producing biochar for soil amendment.

Apart from biochar, various chemical substances have been studied and applied to soil in an effort to improve sandy soil properties to promote growth of vegetation. Among many chemicals under study, cheap super-absorbent polymers such as polyacrylamide (PAM), urea–formaldehyde resin, polyvinyl acetate (PVAc), polyvinyl alcohol (PVA), polyacrylate and polyurethane (Ben-Hur, 2006; Inbar et al., 2015) have demonstrated high efficacy for sandy soil amelioration. Specifically, PVA has been used for erosion control studies and improving structural stability of the soil for several decades. In general, both biochar and PVA have become of great interest to many scientists owing to their high-water retention abilities which are induced by their possession of hydrophilic properties. However, singular use of each of the aforementioned agents in sandy soil amendment exhibit tremendous shortfalls, a situation which has led to the study of alternative approaches that can exhibit comparable or better results at a low cost and without negatively affecting the environment. The efficiency of these agents can be improved by modifying or coupling them using other substances. Coupling of biochar with PVA can offer complementary properties in the soil for better growth of biocrusts and vegetation in the arid environments through increased water retention capacity of the soil. Although many studies have registered positive results for soil amendment, and there has been extensive study on the advantages and mechanisms for water retention by biochar and PVA, to authors' knowledge, no work has been done to compile and analyze the independent data from individual studies. Based on the previous studies, this paper therefore presents a comprehensive review of research work on the utilization of biochar and PVA in soil amendment with focus on moisture content enhancement. The paper discusses biochar and PVA characteristics, and their proposed mechanisms attributed to the enhancement of water and PVA retention in soil. This work will act as a flagship for development and exposition of biochar/PVA soil amending technology to promote growth of plants in sandy soil and other arid soils.

2. Soil amendment

2.1. General attributes and fate of biochar for soil amendment

It has been widely accepted in the scientific arena that biochar from various feedstock is an ideal soil additive for various purposes, particularly agronomic purposes although its application for promoting growth of vegetation in arid environment has not been emphasized. However, due to lack of solid and coherent monitoring programs as well as insufficiency of economic resources for capital investment for soil amendment activities, many developing countries cannot achieve tangible improvements of their agronomic systems through application of biochar. Recent studies have attributed the existence of biochar's soil amendment ability to biochar's high surface area, high cation exchange capacity, possession of negative charges and functional groups, and resistance to degradation (Munera-Echeverri et al., 2018; Sizmur et al., 2015; Zhang et al., 2018). On the advantages of biochar application, several studies have confirmed that biochar has great ability to improve water retention and water-holding capacity of the soil (Glaser et al., 2002; Liang et al., 2006; Laghari et al., 2016), particularly for the coarse-textured soils (Edeh et al., 2020; Razzaghi et al., 2020). Biochar application has been shown to improve soil properties by decreasing soil bulk density, and increasing total pore volume which eventually enhances water retention of the soil (Abel et al., 2013; Berihum et al., 2017; Herath et al., 2013; Obia et al., 2016; Zhang et al., 2016). Further to that, Hale et al., (2012) have also proven that biochar increases soil pH, cation exchange capacity, soil aggregation and porosity. Likewise, the use of biochar is widely recommended because it retains nutrients in the soil (Laghari, et al., 2016). Biochar improves soil environment for growth of microbes which subsequently can improve soil fertility through decomposition of organic matter, though this can lead to emission of greenhouse gases into the atmosphere. Biochar can also increase microbial activity (Lehmann et al., 2011); increase gene abundance of N_2-fixing microbes in the soil (Ducey et al., 2013); enhance microbial diversity (Singh et al., 2022); and improve microbial reproductive rate (Jin, 2010).

It is advantageous to use biochar over its feedstock as biochar can stay in the soil for many years without decomposing. Depending on the environment, biochar has been reported to have the potential to stay in the soil in the recalcitrant form for a period of 1,000-1,500 years as observed in Amazonian dark earth (Glaser et al., 2002), wet tropical forest soils (Hammond et al., 2007), Costa Rica (Titiz & Sanford, 2007), and ocean sediments (Forbes et al., 2006). This happens because biochar's carbon is resistant to microbial attack (Kamara et al., 2014; Zou & Yang, 2019). Biochar pores serve as the habitat for some microorganisms such as bacteria apart from being useful for retaining water and dissolved nutrients for microbial metabolism and growth of plants. Greater surface area of the biochar also leads to more opportunity for microbial colonization. Its black colour traps more heat which may speed up microbial growth and enzyme activity; consequently, biochar-amended soils favour growth of gram-negative bacteria (Gul et al., 2015).

Biochar has high stability in soil, a property which has been attributed to aromatic structure of biochar, and presence of amorphous structures, and turbostic crystallites (Purakayastha et al., 2015). Further to that, sorptive characteristics exhibited by biochar have been reported to be responsible for biochar's resistance to loss of other minerals and organic compounds through degradation, leaching, and chemical oxidation in the soil (Shrestha et al., 2010) which in turn helps in maintaining the quality of biochar. Although biochar is known to be recalcitrant, to some extent, it is also subject to degradation through biotic forces via microbial incorporation or oxidative respiration of carbon as well as abiotic forces via chemical oxidation, photo-oxidation and solubility (Major et al., 2010). Besides loss of biochar's quality through degradation, Hilscher et al. (2006) add that biochar can be lost through erosion especially in steeper land.

As noted, numerous authors have described the properties of biochar made from various feedstock including rice husks; however, summarization of these properties and importance of biochar in soil amendment has not been given special attention. This makes it difficult for other readers to appreciate the usefulness of biochar as a soil conditioner. Therefore, herein a specific summary of the biochar properties or attributes with respect to water retention enhancement is given based on research studies done in the past ten years (Table 1).

Table 1: General properties for biochar

Biochar property	References
High surface area at high pyrolysis temperatures	Munera-Echeverri et al. 2018; Sizmur et al., 2015; Yuan et al., 2019; Zhang et al., 2018;
High porosity once pyrolyzed at high temperature	Li et al., 2017; Wang, Zhou et al., 2015
Has various enriched functional groups depending on pyrolysis conditions	Armynah et al, 2018; Munera-Echeverri et al., 2018; Sizmur et al., 2015; Win et al., 2018; Zhang et al., 2018; Shi et al. 2019
Is resistant to microbial degradation	Kamara et al., 2014; Zou & Yang, 2019
Exhibit hydrophilic properties at relatively high pyrolysis temperatures	Tang et al., 2013; Yuan et al., 2019
Has negative charges whose quantity varies with pyrolysis temperature	Alling et al., 2014; Munera-Echeverri et al., 2018; Tan et al., 2020

2.2. Attributes of rice husks biochar and its prospects for soil amendment

Among the many agri-residues derived biochar, rice husks biochar has great potential for soil amendment utilization owing to the wide availability of its feedstock; its relatively low production costs; and its favorable physical and chemical surface characteristics (large specific surface area, porous structure, enriched functional groups, and mineral components) (Tan et al., 2015). Therefore, with high global rice production of about 700 million tons, and 20% of this mass coming from rice husks (Steurer & Ardissone, 2015; Singh 2018), there is high prospect of widely amending soil with this biochar. Annual global production of rice husks was indicated to be at about 148.4 and 156 million tons in 2014 and 2018, respectively; and rice husks production for Africa, America, Asia and Oceania have been well reported by Asadi et al. (2021). With increasing demand worldwide for rice due to an increase in human population, more rice is expected to be grown for consumption; hence, more husks are expected to be generated. Biochar yield from pyrolysis of rice husks is about 33-38% (Günal et al., 2019; Vieira et al., 2017), subsequently a substantial amount of biochar can be obtained for large-scale soil amendment program. Rice husks biochar would be superior to other biochar such as animal manure-derived biochar and municipal waste-derived biochar as this other biochar have high probability of contaminating soil due to their high risks of possessing toxic heavy metals and organic pollutants such as PAHs (Kuppusamy et al., 2016).

2.3. Effect of pyrolysis temperature on properties of rice husks biochar versus hydrological properties of soil

Numerous studies and reviews have shown a link between pyrolysis conditions and properties of biochar which give enough background information on how biochar properties can be modified or improved. However, there has been little exposition on the linkage between pyrolysis conditions and hydrological properties of soil. Pyrolysis temperature is one of the key factors affecting the structural and physico-chemical properties of biochar (Zhao et al., 2017), which subsequently can influence the hydrophilicity of biochar. For instance, rice husks biochar produced at different temperatures has been found to contain various functional groups and chemical bonds such as O-H, C=O, C-O, C=C and C-H (Armynah et al., 2018; Claoston et al., 2014; Shi et al., 2019; Win et al., 2018; Zhang et al., 2018).

Biochar from various feedstock produced at higher temperatures (500^{o}C) have been reported to have a greater potential of improving water-holding capacity of soils compared to the biochar produced at lower temperatures (300 and 400^{o}C) (Laghari et al. , 2016). This is because biochar produced at high temperatures has greater surface area, microporosity or nanopores, and hydrophilicity than biochar produced at low temperatures (Tang et al., 2013; Yang et al., 2018; Yuan et al., 2019). Biochar produced at <400^{o}C adsorbs less water compared to biochar produced at higher temperatures, a phenomenon that has also been attributed to clogging of small pores by organic compounds including aliphatic functional groups and aromatic compounds (Marshall et al.,2019; Rajapaksha et al., 2016). Another study has shown that high pyrolysis temperature increases surface area, carbonized fractions; and decreases functional group content of the biochar (Tomczyk et al., 2020).

Other researchers have also found that ash content, surface area, porosity and aromatic C content increase at high pyrolysis temperatures while biochar yield, ratios of O/C, H/C and alkyl carbon content decrease (Li et al., 2017; Wang, Zhou et al., 2015). The sharp increase in surface area and micropore volume has also been attributed to decomposition of lignin and quick release of H_2 and CH_4 (Zhao et al., 2017) and releasing of volatile metals such as potassium from the biomass during pyrolysis (Ronsse et al., 2013; Suman and Gautam 2017). On the other hand, biochar produced at low temperatures has low porosity, low specific surface area, high content of tar that fills or blocks the residual pores (Batista et al., 2018; Herath et al., 2013; Marshall et al., 2019), and more retention of labile and oxygenated carbon which then results in production of more alkaline biochar (Ronsse et al., 2013). All these properties have great potential of influencing the hydrophilicity of biochar which in turn affect hydrological properties of the soil. Table 2 shows the linkage between pyrolysis temperatures and biochar properties, and subsequent effects on hydrological properties of the soil.

Table 2: Linkage between pyrolysis temperatures, biochar properties and hydrological properties of amended soil

Pyrolysis temperature	Physical and chemical properties for biochar	Hydrological properties for biochar	Inferred hydrological properties of sandy soil
Relatively high pyrolysis temperature	Increased surface area, microporosity or nanopores, variety of functional groups, and carbonised fractions; moderate functional groups content; more water and organic matter volatilisation, creating larger pores	Remarkably high hydrophilicity (high water sorption and water retention capacity	Improved water-holding and retention capacity of the soil
Extremely high pyrolysis temperature	Decreased surface area, microporosity or nanopores, variety of functional groups, and carbonised fractions; and decreased functional group content	Low water sorption and water retention capacity	Less water-holding and retention capacity of the soil
Low pyrolysis temperature	Less surface area, microporosity or nanopores, and carbonised fractions; increased tars content; and increased functional group content	Remarkably low hydrophilicity (lower water sorption and water retention capacity	Less water-holding and water retention capacity of the soil

2.4. Attributes of polyvinyl alcohol for soil amendment

As already mentioned, super-absorbent polymers are good for soil amendment. The potential benefits of applying these polymers to soil are affected by their complex properties (molecular weight, load type, charge density) and soil properties (texture, organic matter content, clay mineralogy, soil solution composition, and concentration) (Yakupoglu et al., 2019). PVA is a polymer with high prospects in soil amendment, particularly in hot areas. This would be due to its ability to degrade at high temperatures (above 150^{o}C) (Chiellini et al., 2003; Peng & Kong, 2007), a property that can increase lifetime of PVA. PVA also has other special properties that make it recommendable for usage for soil amelioration. Thus, PVA is cost-effective; highly water soluble; able to absorb water; environmental friendly; and has high water retention capacity (Gaaz et al., 2015; Liu et al., 2017; Yin et al., 2016; Zang et al., 2015). Further to that, PVA displays film, elastic and viscous membrane-forming characteristics on the soil surface, hydrophilicity (Moayedi et al., 2011; Liu et al., 2017), good mechanical and thermal properties, and resistance to oxygen permeation (Abdullah & Dong, 2019). Several studies have demonstrated that PVA is effective in reducing infiltration rate, runoff, and soil loss (Ben-Hur, 2006; Inbar et al., 2015; Yonter, 2010). In view of the aforementioned properties, PVA utilization for soil amendment would have more advantages than disadvantages as depicted in Table 3.

Table 3: Advantages and disadvantages of amending soil with PVA

Advantage	Disadvantage
It is environmental friendly	It does not have nutrient value for the plant
It has the great ability to stabilize soil particles	It is prone to leaching during rainy season
It can enhance water retention and water-holding capacity of the soil	It is prone to biodegradation in the soil
It reduces infiltration rate	
It is relatively cheap; hence it can be used by a wide range of communities	
It is required in relatively small quantities (is economical)	

PVA has several properties that make it be a suitable soil conditioner particularly for the arid areas such as deserts. Table 4 summarizes properties for PVA to enable readers to easily get the required information on the PVA properties for soil amendment.

Table 4: Properties for polyvinyl alcohol applicable for soil amendment

Properties	References
PVA chain has OH functional groups for hydrophilic properties	Satokawa & Shikata, 2008; Sonker et al., 2017; Wu 2019
It is highly soluble in water	De Campos et al., 2011; Liu et al., 2017; Yin et al., 2016
It is biodegradable for environment friendliness	Abdullah & Dong, 2019; Chiellini et al., 2003; De Campos et al., 2011; Kim and Yoon, 2010
It exhibits hydrophilicity	Liu al., 2017; Moayedi et al., 2011;
Its structure can be displayed in a fully hydrolysed or partially hydrolysed form, displaying hydrophilic and hydrophobic functional groups	De Merlis and Schoneker, 2003; De Campos et al., 2011; Halima, 2016
The biodegradability of PVA is influenced by the degree of polymerization	Deng et al., 2019; Kawai and Hu, 2009
Has high thermal stability; thus, it has high melting point (230^{o}C) under full hydrolysis condition; and has high boiling point (228^{o}C) under partial hydrolysis condition	Aslam et al., 2018

2.5. Deficits and prospects of PVA utilization in soil amendment: Biodegradability

Consistent advocacy for PVA utilization can lead to wide adoption of the polymer for soil amendment. However, if only PVA is applied to the soil, the technology would be rendered less effective as PVA is more biodegradable compared to biochar. Several microbes including *Brevibacterium incertum, Alcaligenes faecalis and Pseudomonas vesicularis* have been known to degrade PVA (Chiellini et al., 2003). Most PVA degrading microorganisms are *Pseudomonas* or *Sphingomonas* (Kawai and Hu, 2009). PVA can also be degraded by thermophilic bacteria *Geobacillus tepidamans*, *Brevibacillus brevis* and *Brevibacillus limnophilus* (Kim and Yoon, 2010) hence, effectiveness of soil amendment using PVA alone in hot arid areas can be reduced in the presence of these microbes. These employ different mechanisms such as use of enzymes to degrade PVA. To consume PVA, microbes first reduce its molecular weight by cleaving its main chain using PVA oxidase (Abdullah and Dong, 2019; Corti et al., 2002). Fungi *Phanerochaete chrysoporium* are also one type of microbes that promote degradation of PVA through use of enzymes. They do this by forming carbonyl groups and double bonds using enzyme lignin peroxidase (Mejia et al., 1999). Although PVA in general is prone to bio-degradation, PVA 1788 is an exceptional type in the sense that its segments and molecular chains cannot be easily assimilated by PVA-degrading fungi such as *Eutypella* sp. owing to its high molecular weight, great chain entanglement, and strong intermolecular force (Deng et al., 2019). Another positive side is that most PVA-degrading microorganisms such as *Pseudomonas* O-3 are not common in the environment (Doble & Kumar, 2005). Moreover, a recent study has established that PVA has relatively low degradation rates in some environments such as soil (Abdullah & Dong, 2019); a phenomenon that increases PVA's ability to stay long in the soil. This implies that PVA still has high prospects in soil amendment activities.

2.6. Coupling of PVA with other substances for various applications

PVA either in its singular form or coupled form has been used in various fields for various purposes. It is generally widely used in industries for adhesives, paper-coating, textiles, wood and furniture, tannery, paints, and biodegradable polymer products (De Campos et al., 2011). PVA is used as warp sizing in the textile industry, and as an ophthalmic lubricant in the pharmaceutical industry (Chia-Chang et al., 2014; Huang et al. 2015). Although studies have shown advantages of using PVA for soil amendment, and that PVA has already been known to improve soil properties for over fifty years now, its utilization has not been scaled-up. The reasons for this phenomenon are not well documented. For decades, the application of PVA for soil amendment mostly focused on stabilizing sand particles in the desert other than enhancement of moisture retention or water-holding capacity. Our analysis shows that PVA has been mostly used as a singular soil conditioner to promote plant growth unlike in other applications where it has been coupled with other substances. Even though PVA has been used in studies to improve plant growth, the role of PVA in promoting plant growth and metabolism is not discussed explicitly. In a number of those studies, PVA was used as a soil conditioner under simulated rainfall conditions where it was discovered to reduce the soil sediments in runoff (Stefanson, 1973; Wood & Oster, 1985; Yonter, 2010). Recent publication has also indicated that PVA like other polymers such as polyacrylamide (PAM) is widely used in agricultural practices to enhance soil aggregates stability (Yakupoglu et al., 2019).

PVA has been coupled or modified with other substances such as biochar, starch and nanoparticles to improve their efficiencies and resistance against degradable forces. These composites have mostly been investigated or used in engineering fields for various applications other than in agricultural field or biological or environmental fields for crop improvement or forest restoration purposes. Thus, studies have been conducted on the effects of composites of PVA and biochar on electrical conductivity, thermal and mechanical properties in electrical applications (Nan et al., 2015), pressure sensor applications (Nan et al., 2017). Reports further show that biochar nanoparticles have been coated with PVA to stabilize nanoparticles for use in subsurface applications in brine environment (Griffith & Daigle, 2017). Another study has proven that nano-composite films from PVA and bamboo biochar can be fabricated for material packaging and biomedical engineering (Mousa & Dong, 2018). Table 5 shows recent studies on the utilization of PVA alone as well as PVA composites in various fields.

Table 5: Some recent studies and applications of polyvinyl alcohol in different fields

PVA formations	Applications/studies on PVA utilization	
PVA alone	Textile and pharmaceutical industries	Chia-Chang et al., 2014; Huang et al., 2015
	Improving growth of cyanobacteria in the soil	Park et al., 2014; Park et al., 2017
	Enhancing soil moisture retention, hence increase seed germination	Rasslany, 2014
	Enhancing water use efficiency and seed yield for peanut	Aly et al., 2016
	Improving the growth of plants and microbes of sandy land	Zang et al., 2015
	Increase rooting capacity of shoots in pear clones (*Pyrus communis* L)	Sun et al., 2009
	Reducing run-off and soil sediments in run-off	Stefanson, 1973; Wood & Oster, 1985; Yonter, 2010
Coupling PVA with biochar	Used in packaging material; and biomedical engineering.	Mousa & Dong, 2018
	Pressure sensor applications	Nan et al., 2017
	Electrical conductivity; thermal and mechanical properties in electrical applications	Nan et al., 2016
	Electromagnetic properties of the composites under both direct and alternating regimes	Bartoli et al., 2022
Biochar nanoparticles coating with PVA	Nanoparticles stabilisation for use in subsurface applications in brine environment	Griffith & Daigle, 2017
Coupling PVA with starch/glycerol/halloysite nanotube	Forming biodegradable and water-resistant nanocomposite films for sustainable food packaging	Abdullah & Dong, 2019

2.7. Recent studies on use of pristine rice husks biochar and polyvinyl alcohol for soil amendment

Studies have been conducted on pristine rice husks biochar and PVA, focusing on different aspects. Although there are already more reviews on the utilization of rice husks biochar and PVA for soil amendment and other applications, there is also need to have specific review on rice husks biochar and PVA more with focus on water retention enhancement ability for large-scale soil amendment in arid places such as deserts. A number of reviews have focused on other areas other than enhancement of moisture content of the soil. For instance, Asadi et al. (2021) have extensively made a review focusing on rice husks biochar production and characterization; chemical properties of biochar (pH, elemental composition, chemical functional groups); physical properties (surface area, physical structure); rice husk biochar as soil amendment agent (improvement of soil chemical properties and nutrient balance, effect of rice husk biochar on soil pH, effect of rice husk biochar on soil organic carbon and nutrient content, effect of rice husk biochar on cation exchange capacity, and improvement of soil physical properties); biochar as plant growth promoter; use of biochar in reducing toxicity to plants; use of biochar in reducing nutrient leaching; and use of biochar in reducing greenhouse gas emission. Milla et al. (2013) have characterized biochar, and determined the effect of biochar application in the soil; effect of biochar on plant physiology, plant growth, and chlorophyll content. Biochar properties affect the soil properties which in turn may affect the growth of plants. For instance, Masulili et al. (2010) found that application of rice husks biochar decreased soil bulk density, soil strength, exchangeable Al, and soluble Fe and increased porosity, available soil water content, C-organic, soil pH, available P, CEC, exchangeable K, and Ca which subsequently promoted the growth of rice. In general, more studies have been conducted on utilization of rice husk biochar than on PVA for soil amendment. Tables 6 shows some published work on utilization of pristine rice husk biochar, respectively for soil amendment in the past ten years.

Table 6: Some recent studies on pristine rice husks biochar and its utilization for soil amendment

Purpose of the study/Topical area	References
To determine effect of rice husk biochar on soil properties of two Alfisols (sand and sandy loam soils)	Gamage et al., 2016
To determine effect of rice biochar and coal fly ash on physical properties of expansive clayey soil	Lu et al., 2014
Investigating the influence of rice husk biochar on the properties of acid sulfate soils and rice growth	Masulili et al., 2010
Determining agronomic properties and characterisation of rice husk biochar and wood biochars and their effect on the growth of water spinach	Milla et al., 2013
Determination of effects of rice husk biochar on carbon release and nutrient availability in three cultivation age of greenhouse soils	Tsai & Chang, 2020
Influence of rice husk biochar and amendments on salt contents and hydraulic properties of soil and rice yield in salt-affected fields	Phuong et al., 2020
Effects of rice husk biochar application on the properties of alkaline soil and lentil growth	Abrishamkesh et al., 2015
Effects of rice husk biochar on selected soil properties and nitrate leaching in loamy and clay soil	Ghorbani et al., 2019
Determining effects of rice husk biochar application to paddy soil and its effects on soil physical properties, plant growth, and methane emission	Pratiwi & Shinogi, 2016
Determining effect of rice husk biochar as an amendment on a marginal soil in Guyana	Persaud et al., 2018

Like on utilization of biochar, several other studies have also been made on the utilization of PVA for soil amendment for different purposes. However, our analysis shows that there has been little focus on studies related to application of PVA for enhancing moisture content of soil compared to those done on PVA utilization for other purposes. Tables 7 below shows some published work on utilization of PVA for soil amendment over the past decade.

Table 7: Some recent studies on PVA utilization for soil amendment

Purpose of the study/Topical area	References
Efficiency of the PVA hydrogels as soil conditioner determined by monitoring the *Capsicum* sp growth	Patachia et al., 2011
Determining the effect of encapsulating or coating urea prills on controlling the release of nutrients from urea fertilizer into soil	Zafar et al., 2021
Investigation of the effects of PVA application as a soil conditioner on soil particle stability against erosion by runoff and by splash	Yonter, 2010
Effectiveness of PVA application in reducing infiltration rate, and runoff in soil	Ben-Hur, 2006
Analyzing potential benefits of polymers such as PVA in soil erosion control for agronomic plans	Yakupoglu et al., 2019

2.8. Biochar Production and Biochar/PVA composite preparation

Addition of chemical modifiers to pristine biochar before or after pyrolysis to form biochar composites can be another way of improving the characteristics of biochar for soil amendment. There are three main methods for preparing biochar composites namely, pre-pyrolysis, post-pyrolysis, and co-pyrolysis of co-fermented biomass (Moyo et al., 2020). The method used has an impact on the quality of biochar produced as such different chemical bonds are generated within the composite. Biochar composites have been prepared for various purposes and in different ways. Often times, rice husks are oven-dried and then pyrolyzed in chamber over a wide range of time ranging from few minutes to hours. This pyrolysis time includes time for raising the temperature at a particular rate (for instance 10°C/min) from ambient temperature (for instance 30°C) to target temperature (for instance 300°C), then holding at the target temperature for minutes or hours (residence time).

Heating rates are critical in the production of suitable biochar for particular soil type. Slower heating rates and lower processing temperatures enhance the production of biochar unlike higher heating rates which promote production of bio-oil, the pyrolysis product that is not suitable for soil amendment. Using this set-up, rice husks biochar has been produced at various target temperatures such as 300°C, 350°C, 400°C, 450°C, 500°C, 550°C and 600°C. The pristine biochar or biochar-modifier samples can then be milled with a mortar and pestle to pass through a specific sieve such as 0.25mm-sized sieve (60-size mesh) for water retention tests, while samples for functional groups and crystalline analyses are milled further to pass through 200-size mesh. For soil amendment activities, the biochar needs to be milled to particles sizes similar to average sizes for soil particles for proper blending with soil constituents. The schematic presentation of process for the rice husks biochar powder production for analysis is presented in the Figure 1.

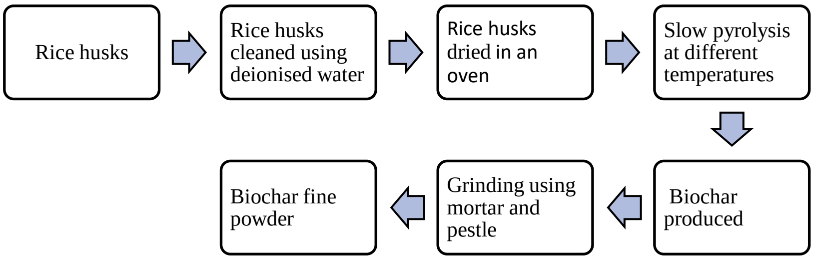

Figure 1: The schematic presentation of process for the rice husk biochar powder production

In case of preparing biochar-PVA composite, post-pyrolysis method is feasible, and a small amount of PVA is required to blend with biochar depending on the purpose of the study. Thus, PVA powder can be thoroughly mixed with biochar mechanically in a crucible before mixing with deionized water to saturation level, and then blend the contents. After that, the crucible with its contents needs to be placed in the oven to dry the biochar-PVA slurry before milling the composite to form a powder for other tests such as water retention tests for biochar, Fourier Transform Infra-Red (FTIR) tests and X-Ray Diffraction tests. The biochar/PVA, biochar and PVA or biochar-PVA can be mixed with soil in a container, and then have water retention, water holding capacity, and dynamic moisture contents tests for the mixtures be determined. It has been observed that biochar-PVA composites are prepared in various ways depending on the purpose. For instance, to determine their electrical conductivity, thermal and mechanical properties in electrical applications, Nan et al., (2016), prepared biochar-PVA composites in this way: biochar which was loaded at three different levels, thus, 2wt%, 6wt%, and 10wt% was mixed manually with PVA (10% solution) until there was an even black colour distribution. The mixtures were degassed and evaporated at room temperature to form films before drying them in an oven.

In another study, Bartoli et al. (2022) investigated electromagnetic properties of biochar/PVA composites. In this case, waste cotton fibers were pyrolyzed in a tubular furnace at a heating rate of up to 15 ◦C/min reaching 1000 ◦C and then the temperature was kept at 1000 ◦C for 30 minutes before cooling down to a room temperature in nitrogen atmosphere. This biochar was mechanically milled, dispersed into the PVA matrix, and then the composite materials were dried in a ventilated oven before conducting further tests such as FTIR tests. In another study, Terzioğlu & Parin (2020) used biochar to reinforce PVA/starch composites in the process they prepared PVA/starch/biochar composites. In this case, the PVA/corn starch/biochar mixture was stirred for 30 minutes to obtain homogeneous solution in a 600 ml beaker. Citric acid (25 wt % of total polymer) was added to the solution and stirred for 10 minutes at 50°C. The glutaraldehyde (500 µl) was added to the mixture then the contents were held at 100°C for 5 minutes. Finally, the mixture was dried at 50°C in a vacuum oven. In spite of the wide availability of rice husks for biochar production, and rice husks biochar being extensively studied for various purposes, we could not come across the biochar/PVA or biochar-PVA composites for soil amendment. Figure 2 demonstrates the set-up of post-pyrolysis method that may be employed to prepare biochar-PVA composite.

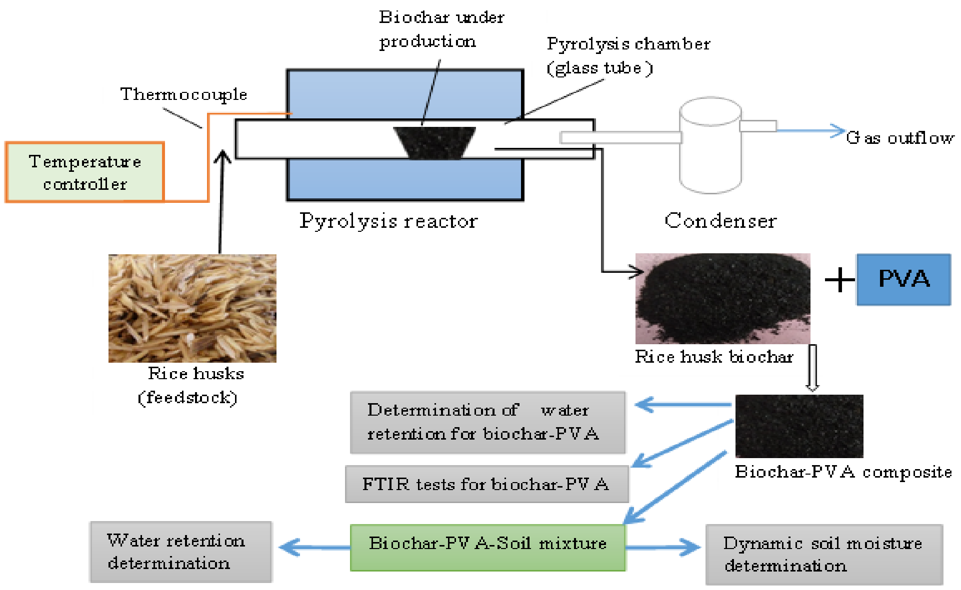

Figure 2: Schematic diagram showing biochar production by pyrolysis reactor and possible tests conducted during the study

2.9. Biochar-sand mixing strategies

Several studies have been conducted on the role of PVA in stabilizing soil, and water retention for soil (Ben-Hur, 2006; Liu et al., 2017; Gaaz et al., 2015; Yin et al., 2016; Yonter, 2010; Zang et al., 2015). However, to the authors' knowledge, the information on the fate of PVA in soil amended with both biochar and PVA is currently scarce, implying that no or little research has been conducted on the same. Besides that, mechanisms responsible for PVA and water retention in the biochar-amended soil seem to have not been described in any of the previous reviews. Laghari et al. (2016) also concede that the specific mechanism by which biochar improves soil aggregate stability and soil water retention is poorly understood although biochar's porosity has been proposed to be the key contributing factor for enhancement of water retention in the soil. Biochar application at various rates has been reported to reduce the hydraulic conductivity of the sandy soil Laghari et al. (2016). Besides that, the biochar column or stratification across the soil profile can also have great impact on the water and PVA retention capacity of the soil. Two biochar application strategies were investigated in one study, thus, uniform top mixing and deep-banding (Basso et al., 2012). In their study, biochar was applied in two different ways, either at the top or in the bottom of plastic pipe containing soil, to simulate uniform topsoil mixing and deep-banding in rows applications, respectively as presented in the Figure 3. Water was then poured in each pipe and water leaching through a column of soil and biochar was collected and its mass determined for comparison of water retention capacity of each biochar application strategy. Gravimetric water content and effective cation exchange capacity (ECEC) were also determined for soil samples collected at three depths (depth 1 = 0–1.3 cm, depth 2 = 5.05–6.35 cm, and depth 3 = 13.94–15.24 cm) in each column at the time of sampling.

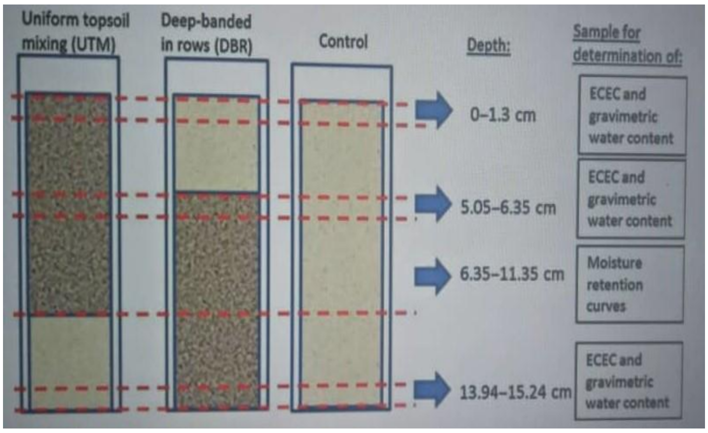

Figure 3: Graphical representation of the soil-biochar mixing strategies. Dark-textured colour represents biochar plus soil and light-textured color represents soil only (Basso et al., 2012)

2.10. Possible mechanisms responsible for water and PVA retention in the biochar-amended soil

This section attempts to explain the possible mechanisms that would occur in the top most layer of the sandy soil where biochar and PVA would be homogeneously blended with soil particles (uniform whole column mixing strategy) to promote growth of plants in the arid land. The perforated container represents the soil profile of sandy soil ameliorated with biochar and PVA where water and PVA must be retained through various mechanisms (Figure 4). According to the model soil profile, PVA and water molecules in soil can be bonded to each other; either PVA or water molecules can be bonded to biochar, and can be entrapped by biochar (adsorbed the surface or absorbed into micropores) or bonded to sand particles. PVA retention can be influenced by hydrophobic or hydrophilic structures, charges, and surface area of the biochar occurring depending on pyrolysis temperature. The model also shows that biochar particles fill the pores between sand particles. Therefore, biochar improves overall soil porosity and increases water and PVA retention capacity of soil via reducing the mobility of the water and PVA molecules.

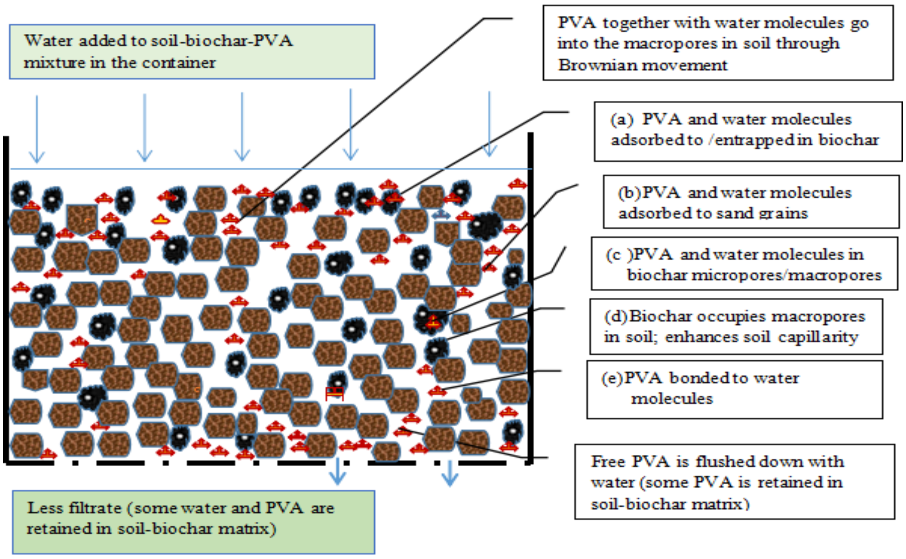

Figure 4 Graphical representation of whole column biochar-PVA-sand mixing strategy, and water and PVA retention mechanisms exhibited in amended soil

In general, less PVA retention is expected to occur in soils amended with biochar produced at low temperatures since such biochar has less porosity (Batista et al., 2018), and has high hydrophobicity (Nartey & Zhao, 2014) due to expected repellence against hydrophobic functional groups found in biochar produced at low temperatures. In contrast, other studies have revealed that there is strong affinity between PVA and SiO_2 particles at low pH, and a weak affinity at high pH (Labidi & Djebailli, 2008). Thus, this condition can lead to occurrence of high PVA retention in soil amended with biochar produced at low temperatures as this biochar would be acidic. Similarly, PVA is slightly acidic with reported pH values ranging from 5.0 to 7.0 (Saxena, 2004; Liu et al., 2017). Based on these two contrasting cases, it becomes difficult to clearly point out the parameter with greater influence on soil pH to enhance PVA adsorption on sand grains or biochar particles.

Presence of charges on PVA and biochar is another important factor. PVA is positively charged (Morgan, 2018), hence it can be attracted to negatively charged biochar surface (Munera-Echeverri et al., 2018). The quantity of these negative charges on the biochar surface decreases with an increase in pyrolysis temperatures (300-700°C) (Tan et al., 2020). Therefore, more PVA-biochar attraction is possible in soil amended with biochar produced at low temperatures. With an increase in ageing, biochar in soil environment can also have its negative charge and oxygen-containing compounds from oxidation increased (Cheng & Lehmann, 2009; Nagodavithane et al., 2013), which is advantageous to the retention of PVA in the soil. The surface of sand grains is naturally hydrophilic because sand comprises the tetrahedral silica and silicate which have hydroxyl functional groups (-Si–OH) (Haryanto et al., 2018; Zang et al., 2015), and this may contribute to adsorption of PVA and hygroscopic water. However, the surface of sand grains is not sufficient to have sustainable PVA retention in the soil as sand grains have low surface area compared to that for montmorillonite particles (Chiellini et al., 2000).

The functionality of PVA in improving hydrological properties of the soil is also governed by the presence of large number of OH groups on PVA main chain which attract water molecules (Sonker et al., 2017). This property can potentially contribute to the increase in water retention for biochar and soil blended with PVA. Besides that, it has been proven that the OH groups for water molecules are hydrated to bulk water, and then to PVA main chain through OH groups for PVA (Satokawa & Shikata, 2008). Additionally, studies have shown that PVA-H_2O macromolecules have the ability to bond to H bonds that occur between PVA and H_20, PVA and PVA, and H_2O and H_2O (Satokawa & Shikata, 2008; Wu, 2019). The hypothetical functionalities and properties of biochar and PVA affecting PVA and water retention in the soil are highlighted in Figure 5.

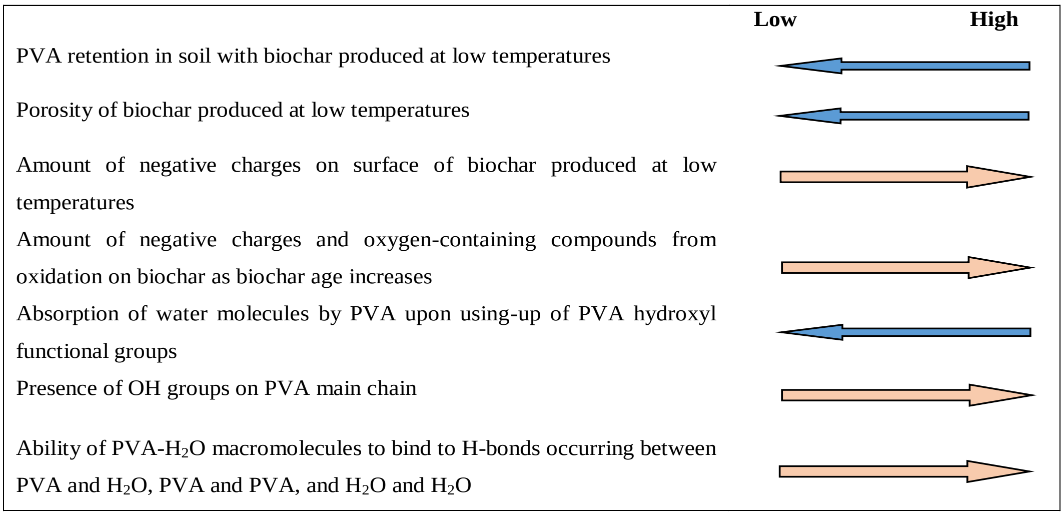

Figure 5: The hypothetical functionalities and properties of biochar and PVA affecting PVA and water retention

2.11. Anticipated costs of the biochar and biochar-PVA based soil amendment technologies

Utilization of biochar or biochar-PVA based technologies like other soil amendment technologies have a number of associated costs which generally are not discussed in the research papers related to soil amendment. These costs mainly emanate from procurement of materials and labour force. Major costs would come from acquisition of pyrolysis reactors and their accessories, biochar production, purchasing and transportation of rice husks and biochar, and payment of labour force for biochar production and soil amendment activity. For instance, the agronomic economic evaluation of biochar application has shown that both fast and slow pyrolysis are unprofitable as the cost-benefit ratio is less than 1, and that the overall profitability of the pyrolysis process is minimized by its high production costs (Kuppusamy et al., 2016). Pyrolysis reactors are of different types and sizes, hence they attract different prices. The commonly used reactors include the well-swept fixed-bed, bench-scale fixed-beds, auger, vertical tubular, and the fluidized-bed reactors (Mohan et al., 2014). Although the modern pyrolysis plants have greatest returns in terms of efficiencies and greenhouse gas abatement potential, they have high initial costs and are expensive to operate compared to the traditional earthen bricks and steel kilns (Pratt & Moran, 2010).

Prevention or minimization of pollution and optimization of biochar production are other costs that need to be factored in. This can be achieved by improving machinery efficiency and waste disposal methods redesigning. Unfortunately, efforts to improve the process efficiency and optimization of biochar production by controlling operating conditions have not yet been undertaken extensively due to competing priorities from energy production (Kuppusamy et al. 2016). For instance, maximizing biochar production would be at the expense of bio-oil and syngas production (Jeffery et al., 2015), the pyrolysis end-products which currently have gained much attention of researchers. In view of these aforementioned expenses, extensive lifecycle assessment concerning the source of biochar or cost of feedstock purchase and production, land-use implications and energy input as well as the entire pyrolysis process need to be considered before making decisions on biochar production for large-scale applications. The good part of this technology however is that rice husks are relatively cheap and are widely available as feedstock for biochar production. Besides that, not much skilled labour is required to operate pyrolysis machinery and run soil amendment programs. Figure 6 gives a summary of the costs that can be incurred in the soil amendment technology through utilization of biochar and PVA.

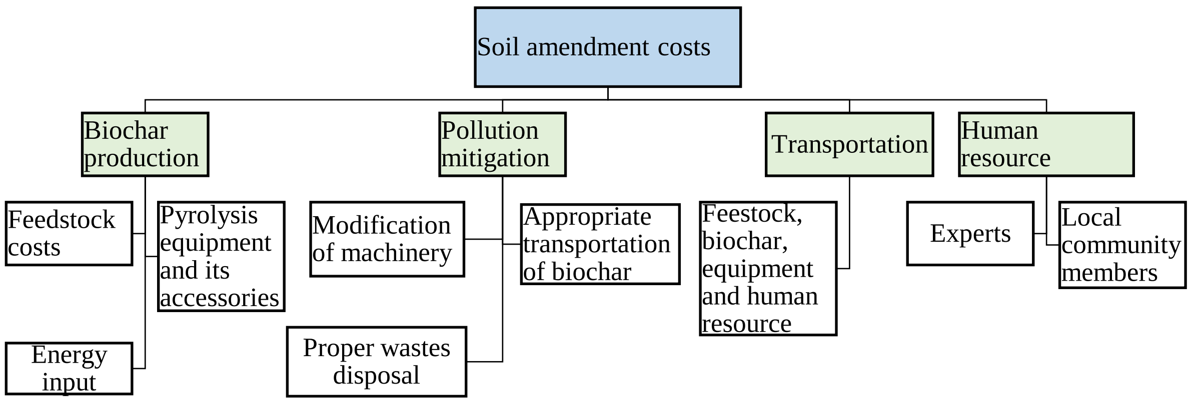

Figure 6: Expected costs for utilization of soil amendment technology using biochar at large scale

3. Conclusion

This paper has shown that biochar and polyvinyl alcohol have been recommended for soil amendment for many decades to enhance growth of plants; unfortunately, this technology has not been scaled-up yet. This problem has been attributed to existence of knowledge gap on the ability of biochar and PVA to amend soil; best-use application programs; and operational costs among other reasons. Biochar and PVA have unique properties that make them suitable conditioners for enhancing moisture content capacity of the soil. Pyrolysis temperature is one of the key parameters affecting the hydrophilicity of biochar via modification of chemical and physical properties of biochar which in turn may influence the hydrological properties of the soil. Biochar/PVA soil amendment technologies separately have been shown to have advantages. However, they also have great deficiencies with regard to enhancement of hydrological properties of sandy soils. Considering these weaknesses and persistent water shortage in arid areas, soil amendments through combined application of rice husks biochar and PVA or use of biochar-PVA composites could be alternative cost-effective approaches for enhancing water retention capacity of the soil; subsequently, improving growth of biocrusts and vegetation. This work has also demonstrated that whole column mixing strategy may be useful in enhancing water and PVA retention in biochar-PVA amended sand soil. It will be of importance to conduct field studies to elucidate the workability of combined use of biochar and PVA as a soil amendment technology for arid areas.

Author's contributions

Gift Gladson Moyo: Conceptualization, Writing - original draft, Writing - review & editing. **Zhiquan Hu:** Writing - original draft, Writing - review & editing.

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Declaration of conflict of interests

The authors declare that they have no conflict of interest with regards to this work. Even the funders did not interfere or influence in any other way with this work.

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