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Utilisation of biochar and superabsorbent polymers for soil amendment

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Abstract

The application of superabsorbent polymers (SAPs) and/or biochars to stressed lands offer solutions to several critical ecological, energy and economic challenges posed by degraded lands due to human activities. These substances are like, 'artificial humus' as they are hydrophilic and contain carboxylic groups (SAPs) which enable them to bind cations and water, and sequester carbon from air to reverse global warming (biochars). Several research studies using these substances point to their ability to increase the plant-available water in the soil which enables the plants to survive longer with water shortage, increase soil fertility and agricultural yields, improve soil structure, aeration and water penetration, reduce use of synthetic fertilisers and pesticides, reduce nitrous oxide and methane emission from soil, reduce nitrate and farm chemicals leaching into watersheds, convert green and brown wastes into valuable resources, and reduce the evapotranspiration rate of the plants. SAPs and biochars induce a significantly higher growth rate in plants; they bind heavy metals and mitigate their action on plants as well as mitigate the effects of salinity. This paper reviews what is known about these claims and considers the wider environmental implications of the adoption of these processess. The intention is not just to summarise the current knowledge but also to identify gaps that require further research.

Keywords: *stressed lands, biochars, superabsorbent polymers, soil amendment*

Introduction

Desertification, flooding, erosion and pollution are just some of the ways to stress drylands. This results in the loss of biological or economic productivity and complexity in croplands, pastures, and woodlands. It is due mainly to climate variability and unsustainable human activities. The most commonly cited forms of unsustainable land use are overcultivation, overgrazing, pollution, deforestation, and poor irrigation practices[1]. In addition, another change in land use is alarming: the conversion of arable to grazing land and pollution due to oil spillage. This land stress is becoming a major threat to peace and sustainability in the world[2]. Of the 3.5 billion ha of stressed lands worldwide, 2.4 billion ha are located in the tropical regions[3]. These ecosystems are so fragile that once the vegetation cover is destroyed, recovery is extremely difficult. Environmental studies have revealed widespread contamination and degradation of lands by different chemicals used in industry during manufacturing processes, and during oil spillage[1]. These chemicals include organic compounds, heavy metals and other pigments such as dyes in the textile industry. At least 20 metals are classified as toxic and half of these are emitted into the environment in quantities that pose risks to human health and the ecosystem[4].

The restoration of soil quality through improvements is especially difficult in Sub-Saharan Africa (SSA), because of the harsh climate, fragile soils, and resource-poor farmers. Effective strategy requires the adoption of a holistic approach based on sound scientific principles of managing the soil and water resources in accord with social, economic, and political realities of the region[3].

The main problems of land degradation are erosion[5] and soil deterioration[6], flooding, pollution, and finally vegetation loss[7]. These changes are followed by secondary developments; crusting of the soil surface[8], an increase in the clay content of the soil[9] and a severe loss of carbon in the soil[10,11].

The fastest way to stop and reverse desertification is to plant trees[12,13]. The best way to achieve this in cooperation with local farmers is through agroforestry, so that farmers can achieve better harvests[12,13]. Precipitation in these regions is, to a certain extent, independent of the degree of land stress[14]. It is safe to assume that most of these lands would be suitable for agroforestry and afforestation using methods that will be outlined below. We now review research findings that have offered sustainable solutions to several critical current ecological, energy and economic challenges posed by stressed lands. Our intention is not just to summarise the current knowledge of the subject, but also to identify the gaps that require further research.

Biochars

Biochar is the charcoal applied to the soil along with other amendments to enhance the fertility of the soils. Biochar is not a nutrient nor a food for soil microbes, but acts like a catalyst for the soil. Biochar in the soil is like a coral reef in the sea. All other soil nutrients are required to be replenished regularly by the conventional sustainable practices of the farmer[15].

Biochar is a new word selected to describe fine-grained charcoal made from biological material (biomass), high in organic carbon. This excludes fossil fuel products, geological carbon and industrial synthetics (plastics)[16,17]. Biochar is a key ingredient in a new carbon-negative strategy that offers solutions to several critical current ecological, energy and economic challenges.

Biochar is the by-product obtained when biomass is burned or heated with a minimum or absence of oxygen. In normal combustion, biomass is oxidised into alkali ash, plus steam, CO_2, other gases and vapours. When air is excluded, oxygen for combustion is stripped from the biomass, which is thus reduced to carbon–carbon bonds of charcoal[18].

Charcoal has been made for centuries by simple methods with little or no tools. Modern pyrolysis and gasification technology use controlled combustion in air-tight retorts to process tons of biomass into energy gases and liquids. Biochar enhances soil in numerous ways. Its use in soil is new, exciting and not yet fully understood. Biochar is not a fertiliser, nor a food source for plants or microbes. Understanding its action is a paradigm shift from chemical views to biological insight into fertility and the soil food web.

Benefits of biochar application to stressed lands

New research shows that biochar has several effects in the soil: it increases water infiltration and water holding capacity, improves soil structure, tilth and stability, adsorbs ammonium, phosphate and calcium ions, enhances nutrient retention capacity, promotes better root development, increases soil pH and buffering, increases cation exchange capacity and also anions, enhances fertility and nutrient retention and soil organic matter, increases soil biological activity and diversity, creating conditions described as a "microbial reef", reduces fertiliser runoff, especially nitrate and phosphorus, decreases by 50–80% nitrous oxide emissions from soil, reduces total fertiliser requirements, mitigates climate and environmental impact of cropland, reduces phosphorus runoff into surface water and reduces nitrogen leaching into groundwater.

Research consistently reveals that poor soils enriched with biochar grow bigger, stronger plants that yield higher crop quantity and quality. Even better, soils retain nutrients and sustain their productivity better than soils without biochar. Plants grow well in soils with up to 9% biochar, at less cost and increased yield, and sustain this greater production longer using less fertiliser[19,20].

In soil, biochar significantly increases fertiliser efficiency, thus reducing needs for chemicals, while enhancing crop yields.

A Mississippi corn farmer plowed 15 tons an acre of biochar into a sandy river bottom, and saw his corn yield more than double. After the first year, his fertiliser use declined. Australian research in New South Wales applied 4.5 tons/acre (20lb/100sq.ft) to carbon-depleted soils, and doubled soybean biomass and tripled wheat biomass[21].

Tomato transplant trials in 2008 at Virginia Tech with less than a cup of biochar in a gallon of soil mix found an average 48% increase in yield. Preliminary studies of biochar's performance in soils cultivating the oil palm in Nigeria undertaken by Ekebafe *et al.*[22], showed good improvement in the water holding capacity of the soil at 35% more with 40 t ha^{-1} dry biochar application than the control. The results of the soil–biochar analysis on the growth of the oil palm measured at biweekly intervals for two months showed that there was a significant ($P<0.05$) increase in the biometrics data compared to the control. Crop response is enhanced if the biochar is inoculated with beneficial micro-organisms which increase nutrient use efficiency and overall plant health[23].

Field observations reveal a reduced need to irrigate when biochar is applied. Biochar is distinctly different than conventional organic matter created by decay of plant and animal wastes. The stability of biochar in soil depends on the O/C ratio. A ratio of 2.0 is likely to mean a material that is robust over 1,000 years, but a ratio of 0.6 accords with a stability of 100 years[24].

Biochar applied to soil is more effective if inoculated with microbial cultures, compost, compost tea and mycorrhizae[23]. Plant photosynthesis fixes CO_2 out of the air, combined with water to make carbohydrates or sugar. When biochar is made, some carbon returns to the air by burning, but 20–50% of the carbon remains in the biochar. When biochar is put in soil, its carbon–carbon bonds do not break down, and remain in soil thousands of years—far longer than carbon in compost, plant residues or animal wastes, which oxidise into the air quickly. So, carbon fixed by photosynthesis is converted to inert forms and safely stored long-term. Thus, biochar in soil is a true carbon-negative strategy. Theoretically, biochar applied to arable land can store carbon equal to all 200 billion tons of human-generated CO_2 in the atmosphere today. But back in soil, char improves fertility by stimulating greater plant growth which then fixes more CO_2 from the atmosphere. Biomass is the world's fourth largest fuel source, after coal, oil and natural gas[25]. Most biomass is woody matter, green wastes, crop residues, food processing wastes (*e.g.* rice husks). Current biomass-to-energy technology is at best carbon neutral, and is not sustainable, because harvesting depletes nutrients, reducing soil fertility and productivity.

Making biochar by pyrolysis also produces energy. As hydrocarbons in plant matter break down, hydrogen, methane and other gases are released. They can be captured and burned. Renewable oils and gases produced can be used as fuels. The energy produced making biochar can be turned into electricity, process heat, or be reformed into ethanol and methanol, or an ultra-clean liquid diesel fuel. Thus, this strategy also produces renewable energy[26].

Pyrolysis uses wastes, and about half the original carbon and most of the minerals are returned to the soil where the biochar supports sustainable, biological fertility.
This energy production does not require the planting of forest or farm crops but instead uses crop residues and biomass wastes to produce hydrogen, electricity, bio-oils, ethanol, and biochar.

Superabsorbent polymers or hydrogels

Polymer hydrogels are loosely cross-linked, three-dimensional networks of flexible polymer chains that carry dissociated, ionic functional groups. They are basically the materials that can absorb fluids of greater than 15 times their own dried weight, either under load or without load, fluids such as water, electrolyte solution, synthetic urine, brines, biological fluids such as urine, sweat, and blood. They are polymers which are characterised by hydrophilicity containing carboxylic acid, carboxamide, hydroxyl, amine, imide groups and so on, insoluble in water, and cross-linked polyelectrolytes. Because of their ionic nature and interconnected structure, they absorb large quantities of water and other aqueous solutions without dissolving by solvation the water molecules via hydrogen bonds, increasing the entropy of the network to make the SAPs swell enormously. The factors that supply the absorbing power to polymers are osmotic pressure, based on movable counter-ions, and the affinity between the polymer electrolyte and water. The factor that suppresses absorbing power, in contrast, is found in the elasticity of the gel resulting from its network structure[27].

Benefits of superabsorbent polymers

Although the classical application of SAPs is the prolongation of plant survival under water stress, new data show that they also have an influence in soils which have water contents close to field capacity. The advantages of the amendment of soils with SAPs can be summarised as follows:

1. They increase the plant available water in soils[28];
2. They induce faster growth of plants, even under optimal watering conditions; and
3. They prolong the survival of plants under water stress[29].

Thus the ecological range of the plants is widened considerably. Thus with the aid of SAPs, it is possible to convert degraded land into a fertile field.

SAPs for soil remediation

For the plant–soil relationship, the following are important: heavy metals, salinity and fertilisers. One way to decrease the bioavailability of heavy metals for plants is to increase the binding sites for heavy metal ions in the soil, *e.g.*, with amendments using humic substances or zeolites[30,31] or expanded clay and porous ceramics[32]. In the case of addition of organic substances to soil, it is very important to work with water insoluble materials which are not rapidly degraded by microorganisms. It was found that the addition of hay to a soil contaminated with heavy metals increased the solubility of Cu, Cd, and Zn, whereas for Pb such an effect was not observed. The amendment of the soil using peat had the opposite effect. Owing to the high density of metal chelating groups in the gel, SAPs are well suited to bind heavy metals and to decrease their plant availability[33-38].

The combination of a SAP together with EDTA has already proved to be successful in the phytoremediation of heavy metal polluted soils[39,40]. The salinity of soil is a big problem worldwide for agriculture and forestry, 372 million ha land have a high level of salinity (FAO-Statistics, Terrastat). Being an osmotic entity, it is obvious that the swelling behaviour of SAPs will be changed by the presence of solutes in the solvent. This is especially true for saline soils[41-43]. In spite of these limitations in water retention, the water-holding capacity of SAPs in saline soils is still considerably higher than in control soils with no SAP amendment[42-47].

To elucidate the reasons for better survival of the poplars growing on the mine waste heap with the highest SAP concentration, more detailed plant physiological investigations were carried out. The following important differences between the plants growing on the SAP amended mine heap and the original mine heap were found[48]:

1. The SAP amended mine heap substrate had a 40% higher water content.
2. The soil solution of the mine waste heap amended with SAP had a 30% lower NaCl and a 50% higher Ca^{2+} concentration compared to that of the untreated mine heap.
3. The concentration of NaCl in the tissues of the *P. euphratica* plants was 50% lower in those growing on the SAP amended mine heaps compared to the control plants.

These results suggest that hydrogel incorporation into the soil reduced apoplasmic ion transport into the inner root. This contributed to the restriction of subsequent root-to-shoot salt transport, enhancing the salt exclusion capacity of *P. euphratica*[48].

SAPs interaction with fertilisers

Fertiliser salts may decrease the maximal swelling of SAPs by about 20–30%[49]. This inhibition of swelling, however, is dependent on the ions which are supplemented to the system. It was found, for example, that potassium ions may reverse swelling inhibition caused by calcium ions[50]. Another interaction between SAPs and fertilisers is the fact that some ions, especially ammonium, are retained by the gel[51,52]. A solution to the problem of gel swelling inhibited by fertilisers is the addition of slow release fertilisers to soils amended with gel[53-55]. Direct chemical combinations of slow release fertiliser and SAP have also been developed[56-60].

SAPs and irrigation

With irrigation, two aspects of SAPs may be important; one is the water retention in the upper soil layers, the other the improvement in the drought resistance of the plants. With irrigation, the problem is always that too much water may be applied and lost to the aquifer. In many types of commercial irrigation, the water lost to the aquifer leads to economic problems, especially in regions where water is expensive. This is true, for example, in many regions of the world for golf courses. The soil layer which really needs the water, the rooting zone of the grass, is rather thin and all the water which is not absorbed by this shallow layer disappears to the aquifer.

It has been shown recently that the amendment of SAPs to the soil significantly prevents the trickling down of irrigation water to seepage[61-64]. It has been shown that amendment of soils with SAPs not only significantly enhances the survival of the trees, but also leads to a much higher timber yield. With a two-fold increase in height and a two-fold increase in diameter, the hydrogel amended trees grew eight times faster than the surviving control trees.

Safety and biodegradation consideration

Hydrogel materials cannot return to their starting monomers, i.e., they are scientifically irreversible to toxic initiating materials. Here, like so many polymers, the starting toxic monomers are converted chemically to totally non-toxic products via a polymerisation reaction. Hydrogels are organic materials with well-known general structure. The conventional hydrogel materials are neutral and inert. They are moderately bio-degraded in the soil by the ionic and microbial media to convert finally to water, carbon dioxide and organic matter[65]. Therefore, hydrogels do not contaminate the soil and environment. They do not exhibit systemic toxicity (oral LD_{50} for rats ~5000 mg kg^{-1}). In addition, their safety in the soil has been approved by the Agriculture Ministry of France (APV No 8410030)[66]. Other research has shown little or no consistent adverse effect on soil microbial populations[67]. The environmental fate of hydrogels and their microbial degradation has been widely investigated; the researchers at the University of California, Los Angles (UCLA) found that no toxic species were retained in soil after several years of consuming hydrogel[68].

Research studies on the toxicity of SAPs on an acrylate base have revealed that these substances have a positive toxicological profile and can be considered environmentally safe[69-74]. The influence of polyacrylates on microbial communities of forest soils has been studied using the polyacrylate gel Firesorbm[75,76]. The investigators came to the conclusion that the polymer had no adverse effects on the microbial community of the forest floor[76]. A few studies have been published on the degradation of high molecular acrylates in biological systems. In the case of polymers which contain acrylamide, the first step is the extracellular biological hydrolysis of the amide into ammonia without any cleavage of the carbon chain[77]. This effect is obviously dependent on the soil microflora. In other cases, even in enrichment cultures, it was impossible to demonstrate microbial growth when cross-linked polyacrylamide was used as the sole nitrogen source[78]. Biodegradation of two superabsorbent polymers in soil, a cross-linked polyacrylate and a polyacrylate/polyacrylamide copolymer, by the white-rot fungus Phanerochaete chrysosporium has also been investigated[79]. The polymers were both solubilised and mineralised by the fungus. The results suggest that biodegradation of these polymers in soil works best under conditions that maximise solubilisation[80]. After 22 weeks, a rate of mineralisation of 9% of the initial radioactivity of 14C labelled acrylamide acrylic acid was observed in soil that was inoculated the white rot fungus *Pleurotus ostreatus*[80].

Conclusion

Biochar has unique properties that make it not only a valuable soil amendment to increase sustainably health and productivity, but also an appropriate tool for sequestering atmospheric carbon dioxide in soils for the long term in an attempt to mitigate global warming. The benefits of hydrogel amendment to soils substantially outweigh their costs. Hydrogel used for agricultural applications has shown encouraging results.

Human life is entirely dependent on food, food relies highly on agriculture, and agriculture is absolutely linked to water and the quality of the land. Taking into account the advantageous characteristics of biochar and hydrogel materials, their applications in the agricultural fields have increasingly been investigated in order to improve the ecological chemistry of stressed lands The urgency to address the problem of stressed lands creates an ever increasing demand for solutions that can be implemented now or in the near future. These solutions need to be actioned both locally by individuals and by more widely by governments in order to produce effects on a global scale.

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