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Revolutionizing waste management: transforming sewage sludge into eco-friendly biochar for sustainable soil enrichment

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Urban sewage treatment plants have contributed more sewage due to the movement of people to earn money towards cities in recent years. Biochar from high-temperature sewage sludge has lower nitrogen but higher phosphorus, potassium, and less water-soluble nitrogen. It helps soil by slowly giving out nutrients. When pyrolysis temperatures rise, nitrogen decreases while phosphorus and potassium increase. Likewise, it is made at higher temperatures and shows less water-soluble nitrogen but more water-soluble phosphorus and potassium. Biochar production slows when temperatures elevate, and the best results show at 700 °C - higher alkalinity, better pore structure, lower dissolved salts, and better nutrients, but nitrogen levels are still low. The trace nutrient levels in biochar are less than in sewage sludge, but heavy metals increase with pyrolysis. Yet, it has lower leaching toxicity than sewage sludge and acts as a more stable soil enhancer, significantly improving the soil's nutrients.

Keywords: Sewage, solid waste, biochar, anaerobic digestion, pyrolysis

Abbreviations: MSW-Municipal solid waste; GDP- Gross domestic product; AC-Activated carbon; IC-Inorganic contaminant; OC-Organic contaminant; SS-Sewage sludge

INTRODUCTION

Sewage, the primary solid waste produced by urban sewage treatment plants, has steadily risen over the past few decades, along with global GDP and urbanization. The absence of oxygen during the pyrolysis of biomass results in biochar, a carbon-rich solid [1]. Biochar feedstock could be sourced from various biomasses, including all types of agriculture, garden waste, biodegradable and municipal solid waste. Biochar has primarily been treated as an adsorbent for both organic and inorganic waste and as a catalyst for soil conditioning/amendment [2]. Applying sewage sludge to farmland has great potential because it boosts soil fertility and increases organic carbon storage [3]. Landfilling, incineration, and spreading it on fields are the most typical ways to get rid of sewage sludge. Toxic leachate and soil scarcity have hampered landfill and land application options, while incineration's high operating costs and hazardous gas emissions have caped the practice [4]. One promising alternative is pyrolysis, which not only destroys the microbes and different organisms and parasites in sewage sludge but also generates valuable bioenergy through the thermochemical accumulation of bio-degradable waste in the absence of oxygen (bio-oil and biogas) [4, 5]. Biochar, the solid residue that's left over, has great potential to boost soil quality by supplying nutrients and microbial biomass [6]. Adding biochar from sewage sludge to agricultural soil can increase crop yields by boosting soil aeration, cation exchange capacity, and nutrient supplementation [7]. The pyrolysis of wastewater and agri waste yielded biochar that exhibited improved characteristics, including heightened stability, a moderate pH level, a substantial concentration of accessible phosphorus, and reduced metal toxicity. India's raw sewage generation was calculated to be 7.34 kg/capita/year, or about 144 kg/million liter of sewage per day on a dry basis. Complete sewage treatment would produce 4.01 million tons of dry sludge [8].

Table 1 presents a selection of data collected by researchers about the -pyrolysis of wastewater and agri waste [4, 9, 10]. The production of biochar with improved stability was achieved by co-pyrolyzing bamboo sawdust. Furthermore, adding rice husk during co-pyrolysis resulted in higher metal stability within the biochar, particularly when the process was performed at 700 °C. The observation made by a researcher indicates an increase in the carbon (C) concentration of biochar when sewage sludge is subjected to co-pyrolysis with biodegradable additives such as reed straw, brewers' leftover grain, and sawdust. In contrast, the obtained biochar

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exhibited a decline in pH, amount of ash, electrical conductivity, H/C proportion, and O/C proportion [9]. Significant attention has been dedicated to examining the behavior of phosphorus (P) and different heavy metals in sewage slurry and biomass co-pyrolysis. In several research papers and reviews, researchers discovered that transforming non-apatite inorganic phosphorus into apatite phosphorus can potentially be accomplished through co-pyrolysis. This process involves adequate mixing of elements such as magnesium (Mg), chlorine (Cl), potassium (K), calcium (Ca), that are present in cotton stems with phosphorus [10, 11]. Based on the findings of certain researchers, it has been observed that introducing bamboo shavings to sewage sludge reduces the hazard of heavy metals present in the resultant biochar. This reduction can be attributed to the conversion of the active states of these heavy metals into a potentially active form and a reliable condition [12]. However, it should be noted that not all biomass wastes can be attributed to the sewage treatment method. Utilizing wastewater and different types of agri waste, which yield biochar synthesis, would result in a notable escalation in transportation expenses. Organic materials, macro and phytonutrients, essential minerals, pathogenic organisms, and micro-pollutants comprise the biomass residue known as sewage slurry, a byproduct of water treatment [13, 14]. Using physical, chemical, and biological processes, constructed wetlands (CWs) can purify polluted water [15]. Recently, there has been an observable increase in the application of artificial wetlands as a commonly accepted approach for treating effluent derived from treatment plants. The reason for this is the possibility of treated water from treatment plants not adhering to set environmental quality standards for surface water. To achieve the intended degree of treatment efficacy, properly disposing of the wetland plants regularly generated during water purification was crucial. Therefore, co-pyrolysis combined with a wastewater filtration system can be viable for concurrently disposing of wetland plants and sewage slurry. The current body of research lacks exploration of the potential application of wetland plants and sewage wastewater for the manufacturing of biochar, as well as the behavior of phosphorus and different heavy metals during the pyrolysis process.

This research deals with co-pyrolyzed sewage slurry and a common wetland plant (*Phragmites australis*) at various temperatures and mixing ratios. The goals were: (1) to learn more about composite biochar, (2) to learn how phosphorus is transformed during co-pyrolysis, and (3) to learn more about the heavy metal's speciation in the resulting biochars. Most studies have concentrated on the thermochemical features of pyrolysis [19, 20] and the heating-and-cooling cycle's role in phosphorus recovery [21, 22]. Phosphorus migration and transformation have been the subject of relatively few studies [23].

Table 1. Biochar characteristics of different materials at elevated temperatures.

Biochar characteristics of bamboo [16]								
Temperature	Yield	Retention rate	Percentage					
			C (w/w)	H	N	O	H/C	O/C
350	52.1	-	68.4	4.5	0.33	26.7	0.07	0.39
450	34.3	-	70.9	0.33	0.25	24.91	0.06	0.35
550	31.1	-	73.4	0.63	0.25	22.38	0.05	0.3
Biochar characteristics of agri biochar [17]								
Temperature	Yield	Retention rate	Percentage					
			C (w/w)	H	N	O	H/C	O/C
300	48.5	--	62.1	4.51	0.88	24.2	0.86	0.29
400	38.5	--	4.04	4.04	0.95	16.4	0.66	0.17
500	34.4	--	2.84	2.89	0.84	12.4	0.45	0.13
Biochar characteristics of sewage sludge (SS) [18]								
Temperature	Moisture	Retention rate	Percentage					
			C (w/w)	H	N	O	H/C	O/C
350	2.6	--	45	4.2	4.9	7.3	--	--
400	0	--	42.1	3.2	4.6	5.3	--	--
550	--	--	40.5	2	5.7	0.7	--	--

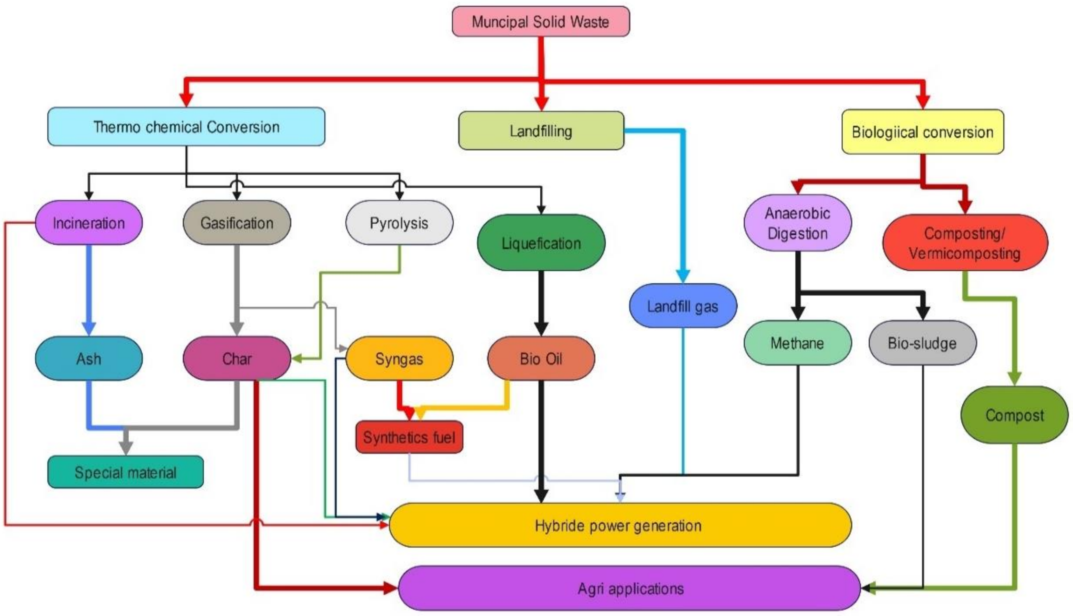

Figure 1. MSW method of waste to energy

POTENTIAL FOR RECOVERING ENERGY FROM SEWAGE SLUDGE.

Potential factors for energy regaining by the incineration and anaerobic digestion of municipal sewage sludge are provided. It has been calculated that between 500 and 1070 kWh/ton of dry sludge can be recovered through sewage sludge incineration. Anaerobic digestion of the wastewater slurry was found to have a potential energy generation range of 300-609 kWh/ton of dry sludge. A study conducted in Greece supports these results [24]. Their research shows that the energy produced by incineration is around 1399–1698 kWh/ton total amount of dry sludge matter, while the energy produced by anaerobic digestion is approximately 1398–1449 kWh/ton. Anaerobic digestion in the present study yielded biogas with CH_4 concentrations of 58-65% in ASP effluent sludge, 55-67% in SBR effluent sludge, 50-60% in UASB effluent sludge, 55-73% in MBBR effluent sludge, and 36-53% in WSP effluent sludge, as shown in Figures 1 and 2.

SEWAGE SLUDGE

Various types of sludge are generated at distinct phases of wastewater treatment plants.

1. *Primary sludge*: The byproduct generated during the initial treatment phase of wastewater, whereby solid materials such as heavy particles, grease, and oils are separated from the raw sewage through filtering, removal of dust and lumps, backing, precipitation, and deposit. This sludge typically contains a solids content ranging from 1.9% to 9.8%, with the remaining composition being predominantly water, accounting for more than 89.9% of its total volume [25].

2. *Secondary sludge*: The byproduct of biological treatment, in which microorganisms decompose the organic matter in wastewater (activated sludge) [26]. Depending on the specific natural treatment method, the solids concentration can be anywhere from 0.79% to 3.29%, with water making up the rest, C (49-55 %), oxygen (24-25%), nitrogen (9.8-15.1 %), hydrogen (5.8-10 %), phosphorus (1.9-2.9 %), and sulfur (0.5-1.5 %) make up the organic component of activated sludge [27].

When nutrients must be removed from the effluent before it is released into the ecological system or all kinds of water sources, tertiary sludge (nitrogen and phosphorous) is produced in the final stage of sewage treatment [28].

To lessen the biodegradable loading for the successive treatment method, sewage treatment plants often use a chemical process that includes dosing with the appropriate coagulant upstream of the elementary deposit. This results in the accumulation of chemical sludge. Phosphorus is often precipitated from treated wastewater at some wastewater treatment plants by adding compounds like alumina or iron salts. This methodology is also reflected in a chemically treated method. Separating the slurry, which is generated as chemical sludge, is impossible because it is frequently combined with secondary sludge [29, 30]. Future waste management issues include sewage sludge disposal and reuse [25]. Global sludge production is at an all-time high and is estimated to keep moving in the upcoming years [26]. Significant sewage waste is generated yearly in European countries, more than 10 million tons (dry/dewatered quantity). Sludge production is highest in Germany, the UK, and other European countries. Compared to Spain and Italy, they produce more than five lakh-ton dry matter annually. An additional 75% of Europe's sewage sludge is thought to originate from just five countries. Sewage waste is a growing environmental concern due to issues surrounding its accumulation, utilization, and disposal [31, 32].

The storage of sewage waste at ground level might pose ecological hazards due to its ability to undergo fermentation and the existence of many harmful compounds, both bio- and non-biodegradable matter. These substances include microbes and hazardous metals [32, 33]. Leaching production and CO_2 emission are directly affected by sewage sludge landfilling. Large amounts of waste necessitate environmentally responsible management of sewage sludge, and its management and disposal are among the trickiest issues facing wastewater treatment facilities, so any solution must be well-received [34, 35]. Developing countries face several challenges in efficiently managing waste, primarily due to insufficient regulations, the absence of a systematic approach for choosing appropriate slurry management systems, and the substantial financial burden associated with upgrading outdated sewage treatment facilities [36]. Sewage sludge is classified as a hazardous waste in numerous nations owing to its substantial organic content, presence of chemical contaminants (including heavy metals, pesticides, and toxic organic compounds), abundance of solid waste, and potential for harboring pathogenic bacteria, viruses, and other disease-causing agents [37]. Even though some sludge is reused in the treatment process to improve efficiency, a significant amount of wastewater slurry still needs to be resolved and properly managed. Compaction, stabilization, conditioning, dewatering, hygienization, and drying are all components of sewage sludge treatment. However, not all these steps must be taken in every sewage treatment plant [38]. Implementing sludge treatment techniques has resulted in increased infrastructure development and associated expenditures for supplemental treatment.

Additionally, the imposition of strict requirements about wastewater treatment before discharge has contributed to an escalation in the expenses associated with sludge disposal. Environmental concerns, such as unpleasant odours or the escalation of waste volume, can be mitigated using appropriate sludge treatment and disposal techniques. Moreover, the energy harnessed from these procedures can be effectively utilized in other beneficial applications. The proper remedy, controlled disposal, and appropriate management of sludge are widely recognized as crucial due to the significant environmental consequences that can arise from improper sludge disposal. These consequences encompass risks to public health and the potential contamination of ecological and aquatic life sources. Conventional techniques of sewage sludge management have become obsolete due to the coexistence of infective agents, medicinal compounds, all types of hazardous metal and biodegradable pollutants, and limited space availability. As environmental regulations become more stringent, old methods of sludge disposal are being phased out in favor of more modern approaches. The European Union has mandated the replacement of traditional sludge storage techniques with more environmentally friendly waste stabilization and recycling methods. The removal of the solids and the subsequent reduction in odour concerns caused by sludges are two examples of how resource recovery contributes to all three of sustainability's pillars (economy, environment, society). Thanks to the recent implementation of various state-of-the-art technologies, sludge recycling rates have increased, and the number of toxic substances in this biodegradable waste has decreased. Choosing a sewage sludge managing mode or technique that has the least negative impact on the environment in the short and long term is essential. By applying these cutting-edge processes, potentially dangerous wastes can be processed and used in agricultural settings, different industrial sectors, and thermal and electrical energy production [39].

REUSING AND REPROCESSING WASTEWATER SLUDGE

The goals of current sludge treatment technologies are to lessen the mass and volume of the waste, kill any harmful microorganisms present, eliminate any unpleasant odors, and reduce the number of volatile solids present so that they can be safely disposed of.

PYROLYSIS

The final sewage sludge management method significantly impacts the number and variety of technological processes required for sludge treatment. The physical and chemical properties of sludge are altered during treatment, which can affect the final product's quality and viability [36]. Some of the most common methods for getting rid of sewage sludge are:

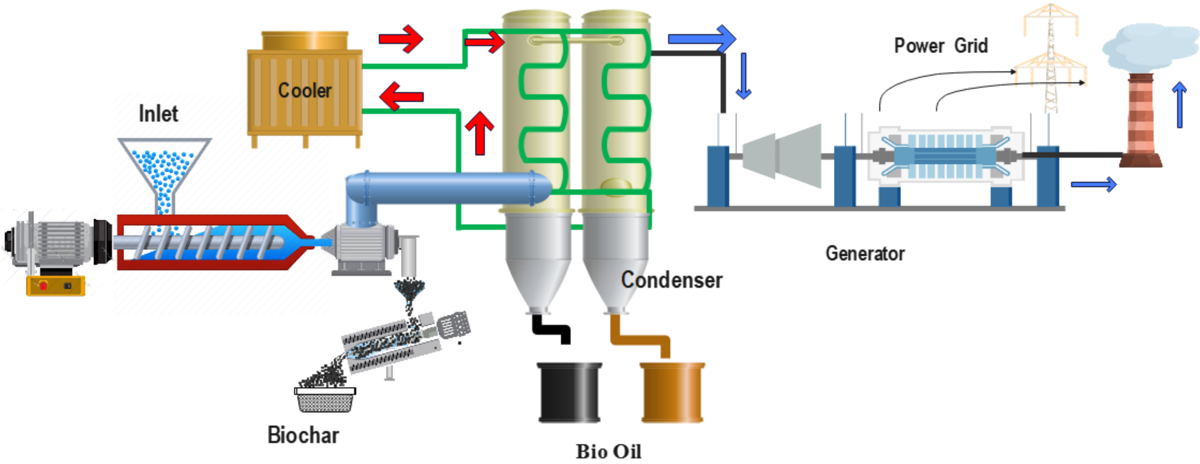

Figure 2. Process of biochar generation and other practical utilization

- Organic recycling has garnered significant interest due to the possible utilization of sewage sludge as a fertilizer. Various approaches have been explored, including applying this sewage waste in agriculture, which helps rebuild degraded soils, composting slurry for fertilizer manufacture, and mechanical and biological treatment methods.
- Several thermal processing methods, including all types of energy generation and co-incineration in concrete factories and the energy generation sector, can utilize sludge for energy and material recycling. These processes facilitate the conversion of sludge into fuel and other valuable minerals.

Due to the stabilization and reduction of the hazardous metal movement and the accessibility of biodegradable pollutants and pathogenic agents, sewage sludge treatment technologies have intensified and diversified over the past decade. Because optimal sludge treatment modifies sludge properties and ultimately affects product quality, it can have wide-ranging effects on the environment, the economy, and society. A diverse range of treatment methods exists, encompassing anaerobic digestion, composting, alkaline material stabilization, chemical ingredient stabilization, thermal processing, Pyrolysis, combustion, and more. When formulating a strategy for recycling sewage sludge, it is imperative to consider both financial implications and environmental consequences [44, 45].

The method of thermal accumulation of biodegradable compounds in the absence of O_2, occurring within the range of temperature between 250 to 900 ºC, is commonly known as "pyrolysis." This could be a step toward allowing modern biomass pyrolysis techniques for global carbon capture, creating biofuels, Biochar, syngas, and other valuable products. An alternative to incineration that can mitigate these massive waste volumes is the production of Biochar from agricultural byproducts. Compared to alternative biomass feedstocks, Biochar performs better in its catalytic action, surface area, absorbency, and physicochemical strength. Char and bio-oil may be identified as solid and liquid byproducts, respectively, and CO_2, hydrogen, CO, and syngas can be classified as gaseous byproducts, explicitly falling under the category of C_1-C_2 hydrocarbons. Kilns and bubbling fluidized beds are a subset of reactor types that can produce Biochar, among other alternatives. The quantity of Biochar generated by the pyrolysis is contingent upon the specific characteristics and makeup of the biomass utilized. The yields, pore volumes, and surface areas of chars are primarily influenced by holding time concerning temperature. The products resulting from the pyrolysis process can be classified into three distinct groups: syngas, bio-oil, and solid residue. This will possess diverse applications within the energy and chemical sectors [39].

Combustible aliphatic volatile materials are prevented from escaping the structure during biochar production at low temperatures. Once heated, the volatile components of biochar can be used as fuel. Nevertheless, at elevated temperatures (such as those over 500 °C), the volatiles within the biochar undergo evaporation, resulting in the retention of solely the carbon framework.

ANAEROBIC DIGESTION

The anaerobic digestion process is often employed in certain types of sophisticated wastewater treatment facilities, which convert this sewage sludge into valuable materials such as biogas, methane hydrogen, or value-added products (as shown in Figure 2). Applying the technique decreases the levels of organic carbon and the C/N ratio in the sludge, hence impeding the proliferation of pathogenic fauna. Utilizing methane-rich biogas generated via fermentation holds potential as a fuel source for gas turbines, enabling energy recovery. This practice not only aids in revitalizing eroded soils but also assists farmers.

Table 2. Different soil parameters concerning sewage sludge/slurry (SS) [7]

Parameters	Gravel characteristics	SS
Sand (%)	76.4	–
Silt (%)	13.9	–
Clay (%)	5.7	–
pH	8.1	7.01
EC (dS m^{-1})	0.55	11.64
Organic carbon (%)	0.37	24
Nitrogen (%)	0.05	1.23
Carbon nitrogen ratio	6.92	19.01
Total phosphorus (%)	0.18	0.5
Total potassium (%)	0.02	0.93
NH4+ N (mg kg^{-1})	5.9	680.16
NO3− N (mg kg^{-1})	42.1	260
Metal content (mg kg^{-1})	Gravel characteristics	SS
Zn	31.2	530
Cu	20.9	329
Cd	--	12.01
Cr	2.5	270
Ni	2.7	121
Pb	27.4	250
Fe	3509	14021

* The dry weight determines the value of sewage sludge and soil.

The combustibility of high-temperature biochar surpasses that of low-temperature biochar due to its absence of volatiles and pores. The fireproof nature of high-temperature biochar can be attributed to the robustness of the C-C covalent bonds. Biochar produced through pyrolysis at temperatures over 500 °C exhibits notable fire-resistant characteristics because of the creation of robust C-C covalent bonds and the absence of volatile substances. Figure 3 illustrates the mechanics of the pyrolysis reaction. Influences such as reaction temperature, residence time, and pressure distinguish two broad categories of pyrolysis: fast and slow.

RESULTS AND DISCUSSION

Biochar's sensitivity to temperature

An increase in pyrolysis temperature led to a decrease in the nitrogen content of the Biochar produced from sewage sand. According to the data presented in Table 3, it can be noted that when the pyrolysis process is performed at a temperature of 400 ºC, over 50% of the nitrogen content is depleted. Conversely, at a lower temperature of 300 ºC, 96.92% of the nitrogen remains intact inside the sewage slurry biochar. The volatilization of nitrogen in sewage slurry biochar when subjected to elevated temperatures has been previously hypothesized. Furthermore, the syngas exhibited detectable levels of nitrogen gas (N_2), ammonia (NH_3), and hydrogen cyanide (HCN), suggesting that a complete conversion of nitrogen in the sewage sludge to tar-nitrogen did not occur. Due to the extensive binding of N to various organic molecules, particularly in the form of protein-N, the extraction of N from sewage sludge poses a challenging task. Biochar's RR (retention rate), defined as the percentage by which its element content exceeds that of the sewage sludge sample, ranged from 0% to 100%. Since biochar had a lower RR, fewer elements had been removed. The RR was determined using

$$RR = \frac{C_{biochar,i}}{C_{feed,i}} Y_{biochar} \quad (1)$$

Equation (1), where $C_{biochar}$, ***i*** element content represents ***i*** in the biochar, C_{feed}, ***i*** showed how much element ***i*** is present in the sewage sludge, $Y_{biochar}$ represents biochar production results [41].

The sewage slurry sample and the biochar generated at 300 °C were acidic, but the biochar generated within the temperature range of 400-700 °C exhibited alkalinity. One plausible explanation is that pyrolysis induces the accumulation of organic acids and carbonates. Higher pyrolysis temperatures also increase the biochar's alkaline organic anion content [42].

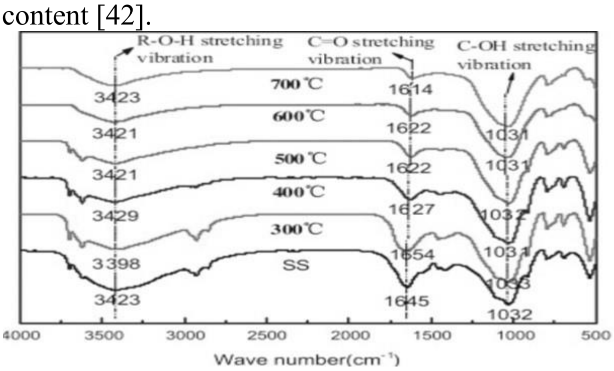

Figure 3. Thermally induced changes in the FTIR spectra of a sludge sample and biochar [30]

Table 3. Biochar made at different temperatures has varying nutrient content [30].

Temperature	RR (Retention Rate)	NPK and other heavy metal composition						
		Cu(mg L^{-1})	N(mg kg^{-1})	Pb(mg L^{-1})	P(mg kg−1)	Zn(mg L−1)	K(mg kg^{-1})	Ni(mg L^{-1})
300	83--96	5.23	61200	3.52	38800	12.04	7470	1.83
400	53.32--96.92	2.71	37900	3.81	42700	5.57	8990	2.31
500	24.44--94.71	2.2	18500	3. 75	44700	5.34	10100	1.94
600	18.62--92.2	2.25	14600	3.55	45100	5.67	13300	2.06
700	11.25--97.5	2.07	9100	3.38	49200	5.63	16600	2.15

Figure 3 shows that the FTIR spectra of the sewage slurry sample and biochar support the previous conclusion. The presence of carbonyl and hydroxyl peaks observed at. 1.6×10^{-7} cm^{-1} and 3.3×10^{-3} –3.4×10^{-3} cm^{-1} were weaker in the sewage slurry sample than in the biochar generated at the temperature of 700 °C [43].

EVALUATION OF POTENTIAL THREATS TO THE ECOSYSTEM

Due to its inherent internal structure, biochar possesses agronomic utility and can serve as a soil conditioning agent. Biochar can boost several soil features, including biological and physical aspects. These improvements include the augmentation of soil nutrient levels and the enhancement of water retention capacity. Consequently, biochar mitigates supplement leaching and facilitates plant nutrient accessibility, increasing crop output. Protecting the natural world requires carefully considering the dosage of sewage sludge for agricultural purposes. There are dangers to living things from incorporating a circular economy that uses sludge containing micropollutants. Soil quality in areas where sewage sludge and its byproducts have been used in agriculture can be impacted. Pharmaceuticals were also examined for their potential impact on microorganisms in the environment. Treatment of soil with sewage sludge can expose bacteria to antibiotics, which could increase the prevalence of antibiotic-resistant strains of bacteria. This is supported by research showing that antibiotics inhibit microbial growth in the short term. Despite prolonged drug exposure, bacterial activity and biomass eventually return to their pre-test levels. Sewage sludge contains a mixture of antibiotics and bacteria resistant to those antibiotics. Since antibiotic resistance is a growing problem, many worry that spreading sludge on farmland will help fuel its growth. Biochar's ability to retain fertilizing elements depends on the raw materials used and the temperature and length of the pyrolysis process (N, P, K). Biochar's impact on yields is moderately dose- and application-rate-dependent. Plant growth necessitates the presence of a diverse array of micro- and macronutrients, encompassing carbon, hydrogen, oxygen, nitrogen, potassium, magnesium, phosphorus, sulfur, boron, chlorine, copper, iron, manganese, molybdenum, zinc, cobalt, silicon, and salt [44].

SEWAGE SLUDGE BIOCHAR AND ITS POTENTIAL HAZARDS

It is advisable to conduct a comprehensive ecotoxicological assessment before implementing biosolids in soil, as treated sewage sludge may comprise hazardous organic compounds and heavy metals that could compromise the integrity of the soil and water. An adequate soil ecotoxicological evaluation, as outlined by ISO soil quality guidelines, considers the loam's ability to serve as an environment for organisms and their ability to immobilize contaminants, thereby preventing groundwater adulteration [39].

Chemical analysis alone cannot be relied upon to identify all potential hazards of applying biochar from sewage sludge to soil as a fertilizer. Due to its widespread application in agricultural settings, it is crucial to determine biochar's toxicity to various organisms and populations. Biochar's direct impact on lifeforms can result from its content of organic or inorganic pollutants, which can have beneficial and detrimental outcomes depending on the organism we are talking about, as shown in Figure 4. To achieve low toxicity levels, pyrolysis temperatures above 600 °C are advised; however, not all biochars are suitable for agricultural purposes. Because of its low nutrient content and high porosity, Biochar made through the rapid pyrolysis method is recommended for restoring degraded soil.

Large-scale agricultural uses are possible for biochar is made at lower temperatures (500 °C) and contains more nutrients [45]. Not every ground loam has shown dramatic improvement, and not every crop responds similarly to the biochar as an alteration to the soil is also worth noting.

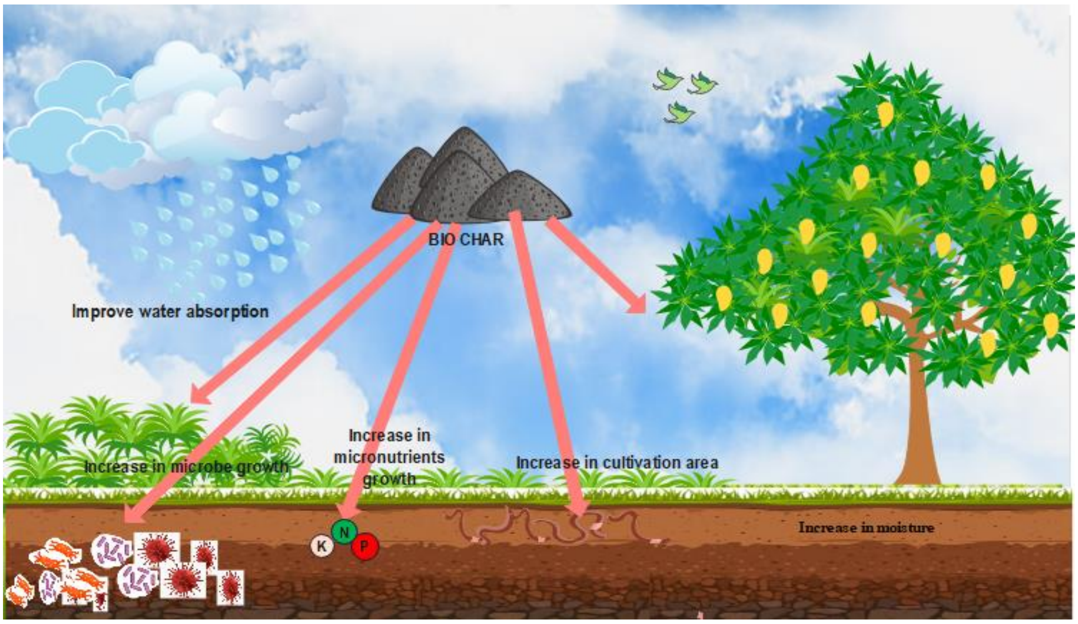

Figure 4. Effect of biochar on soil and agriculture

Biochar has a high capacity for sorption, which means it can absorb nutrients while decreasing their bioavailability and deactivating agrochemicals like pesticides and herbicides. Some plant modifications, such as shifts in root characteristics, may be determined by adding biochar, for instance, in agricultural fields with crops and weeds (depth, length, shape). In general, the phytotoxicity of biochar predominates and will alter depending on the treatment cycle and doses; this is because some plant groups are susceptible to specific chemical elements (P/B/Cu/Na/Zn/Mn/Cl). More importantly, biological tests provide the best evidence for the presence or absence of a toxic effect on organisms by allowing the investigation of interactions between various contaminants [46].

FUTURE PROSPECTS

Due to increasing global populations, a global imperative exists to explore more effective strategies for recycling and repurposing organic waste. Researchers are actively working to alleviate the escalating environmental consequences associated with the proliferation of global organic waste. One potential method for recycling the nutrients included in organic waste is incorporating them into the soil as a form of amendment. The mitigation or complete removal of harmful constituents in organic waste can be achieved through appropriate treatment measures before utilization. Several approaches can be employed to accomplish this objective, including composting, anaerobic digestion, or heat treatment. These procedures facilitate the decomposition of organic waste, converting said waste into valuable resources such as compost that is rich in nutrients or biogas, which can generate electricity.

Furthermore, implementing stringent legislation and disseminating educational initiatives to promote proper waste management techniques can effectively reduce the environmental repercussions of organic waste. The environmental impact of waste volumes is a matter of concern. Nevertheless, it is worth noting that organic waste has the potential to be recycled and utilized as a source of crop fertilization, provided that appropriate conditions are met. To achieve a final product that minimizes its environmental footprint and avoids excessive production expenses, it is imperative to ascertain the most efficient approach for managing organic waste, considering economic and ecological factors. Furthermore, the utilization of organic waste in the future can serve several purposes, including the rehabilitation and recovery of soils that have been contaminated. Using organic waste as a soil amendment has positively affected soil structure and fertility. Additionally, the transformation of organic waste into biogas offers potential benefits such as the reduction of greenhouse gas emissions and the decrease in reliance on fossil fuels. From a waste management perspective, it is crucial to evaluate the effectiveness of various methods for managing organic waste and to ascertain their possible impacts on the environment, soil quality, plant life, and other relevant factors. Comparative studies on organic waste use might illuminate alternative viewpoints about the long-term ramifications and interplay between biodegradable waste and chemicals employed as soil enhancers.

CONCLUSIONS

The study demonstrated that the nitrogen content of wastewater biochar decreases while phosphorus and potassium levels increase with rising pyrolysis temperatures. Sewage sludge biochar produced at peak temperatures effectively reduces water-soluble nitrogen while enhancing water-soluble phosphorus and potassium content, with the optimal synthesis occurring at 700 °C. At this temperature, biochar exhibited higher alkalinity, improved pore structure, reduced dissolved salts, and enhanced nutrient composition, excluding nitrogen. While the pyrolysis process increased heavy metal concentrations in the biochar, its leaching toxicity remained lower than that of sewage sludge, making biochar a more reliable soil amendment. Future research could explore alternative biomass sources, investigate co-pyrolysis with diverse additives, and optimize biochar properties for use in extreme environmental conditions. These efforts could further enhance biochar's applicability in sustainable waste management and soil enrichment. Alternative sources of biomass and optimization strategies may be considered in future studies so that biochar is applicable in extreme environmental conditions.

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