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A Comprehensive Review on the Production and Application of Sludge Biochar for Water and Soil Remediation

Diksha Pandey[1*], Nikhil Savio[2], Rajeev Kumar Srivastava[3]
[1,2]*Research Scholar, Department of Environmental Science, GB Pant University of Agriculture and Technology, Pantnagar, India*
[3]*Professor and Head, Department of Environmental Science, GB Pant University of Agriculture and Technology, Pantnagar, India*

***Abstract*: Biochar has a lot of potential as a wastewater treatment and soil remediation agent. This review highlights recent studies on the development and applications of sludge biochar. The disposal and reutilization of sludge wastes, which is necessary in wastewater treatment operations, is both environmentally benign and cost-effective. Thermochemical treatment of activated sludge to produce biochar is a potential waste management solution. The structure, chemistry, and catalytic capabilities of the resultant biochar are all influenced by the thermochemical process used to produce sludge. In addition, sludge biochar uses for water and soil remediation are highlighted. Based on the findings, it can be inferred that sewage sludge biochar technology is a novel, cost-effective, and environmentally acceptable method for pollution remediation.**

***Keywords*: Biochar, Heavy metal, Pyrolysis, Sludge.**

1. Introduction

Biochar is a carbon-rich solid substance produced by pyrolyzing biomass at low temperatures (around 700°C) under oxygen-depleted environment [1]-[3]. Biochars have gotten a lot of interest in recent years due to their huge potential for carbon sequestration, agronomic, and environmental applications [4], [5]. Because of its large specific surface area and unique surface chemistry biochar is sometimes referred to as a "super-sorbent." It may be utilized to immobilize hazardous heavy metal ions and adsorb persistent contaminants, making it a promising candidate for soil and wastewater cleanup [5]-[7]. Biochar can be made from a variety of organic feedstocks, such as wood, crop residues, animal manure, sewage sludge, and other organic waste. It can be produced using a variety of methods under oxygen-limited conditions, such as traditional charcoal production, slow, fast, microwave pyrolysis, gasification, hydrothermal carbonization, and flash carbonization [8]-[10].

The semi-solid or residual solids created as a byproduct during the treatment of municipal or industrial wastewaters are known as sewage sludge [11]. The presence of various pollutants and heavy metals in sewage sludge limits its application in agriculture. [12] Sewage sludge is a challenging waste to manage, not only because of the massive quantities produced, but also because of the high concentration of heavy metals and microorganisms. Apart from the traditional techniques of sewage sludge disposal, thermal processing of this waste has recently sparked interest. Despite the availability of alternate thermal treatment methods, such as microwave thermal treatment [13], [14] under anoxic conditions, the use of sewage sludge is only limited by the presence of pathogenic bacteria, which can be eliminated by pyrolysis thermal treatment of this waste [15]. Pyrolysis not only kills harmful bacteria, but also produces biochar, which stimulates nutrient cycling (K, P, Ca, Mg, etc.) and carbon release, making it suitable for use as a soil amendment [16]. This approach has a number of advantages, including reducing global warming and eliminating environmental concerns related to solid waste management. [17] Most researchers have been interested in sewage sludge biochar (SSBC) for its usefulness in improving water quality, waste water treatment, and heavy metal remediation for the past decade.

2. Biochar Production by Sewage Sludge

The production of biochar from sewage sludge is proven to be a long-term solution for managing sewage sludge, which is normally considered a waste [18]. The pyrolytic conversion of sewage sludge into biochar in an oxygen-free atmosphere is a promising technology that has environmental benefits when used for agricultural purposes [19]. Earlier, the use of sewage sludge biochar made from sewage and wastewater sludge as a low-cost adsorbent to treat wastewater for pollutants such organic dyes, heavy metals and pharmaceutical-based pollutants was investigated. [20], [21].It is a carbonization procedure followed by physical and chemical activation to produce sewage sludge biochar[22]. To avoid the loss of organic material found in sewage sludge at high temperatures, breakdown of sewage sludge is carried out in limited oxygen or in the presence of nitrogen [23]. Sun-drying and oven-drying

*Corresponding author: diskshp99@gmail.com

are two ways for removing moisture from sewage sludge. Sun-drying involves exposing the wet sludge to direct sunshine, while oven drying involves placing the sludge in a hot air oven at 100^0C for 24 to 48 hours [24].

Depending on the desired end product, pyrolysis can be divided into three categories. Thermal degradation of sewage sludge for the production of solid adsorbent (biochar), pyrolysis of sewage sludge for the production of syngas and bio-oil, and thermo-gravimetric analysis of sewage sludge for the identification of reaction kinetics [25]. Pyrolysis temperature, dwell duration, heating rate, ambient gases, pressure, and raw material properties are the most important factors in influencing the quality of the pyrolysis result. The quality of the expected final result influences the process parameter [20]. The temperature of the pyrolysis process can range from 350 to 10000C, depending on the residence period. The optimal temperature for pyrolysis depends on the raw material, but it's normally approximately 850°C for 2-3 hours. When sewage sludge is pyrolyzed, carbon-rich solid char (biochar), bio-oil, syngas, and water vapours are produced. The thermal decomposition of sewage sludge begins with dehydration, which releases water at an average temperature of 200°C, followed by deterioration (primary, secondary and complete). Initially, the dried sewage sludge is subjected to primary degradation at temperatures ranging from 200 to 350^0C, releasing CO_2, CH_4, and H_2 to generate alcohols and hydrocarbons. The intermediate fractions formed after primary degradation are further degraded at $350\text{-}550^0$C to produce alcohols and hydrocarbons during secondary degradation. After secondary degradation of sewage sludge at an average temperature of $550\text{-}900^0$C, complete breakdown of the intermediate fractions occurs, resulting in biochar with CO_2, CH_4, and H_2 emissions. During the pyrolysis of sludge, approximately all of the biodegradable organic matter is volatilized at temperatures ranging from 150 to 400 degrees Celsius, followed by the volatilization of non-biodegradable organic matter at temperatures ranging from 400 to 550^0C [25]. The quality of biochar produced from sewage sludge pyrolysis varies depending on process factors, pyrolysis type (slow and fast), sewage sludge quality, pressure, adsorbent size, and heating rate and technique (by electrical heating, by muffle furnace and by microwaves). With respect to the generation of bio-oil, syngas, and biochar, the distribution of products obtained after pyrolysis (rapid pyrolysis) was investigated using a pyrolysis centrifuge reactor at an average temperature of roughly $475\text{-}625^0$C [26]. It was revealed that as the pyrolysis temperature rises, the yield of syngas rises but the output of biochar decreases [27]. It was found that the pyrolysis product distribution for dehydrated sewage sludge at two distinct temperatures using various heating rates, namely slow pyrolysis at 8 C/min and fast pyrolysis at 100 0C/min [24].

Sewage sludge biochar is produced from the carbonised thermochemical conversion of biomass in an oxygen-limited environment and is quite porous, allowing for increased adsorption of toxic heavy metals [29]. Heavy metals, which are extremely toxic to plants, animals, and humans, limit the use of sewage sludge in agriculture [30]. Though SSBC has the potential to prevent heavy metal migration, the process of combining the metals may threaten the environment. These alternatives pose a significant risk of pollution of the soil, air, and water [31]. Biochar was generated from three different treated sewage sludge biomasses in three pyrolytic temperatures, 300^0C, 500^0C, and 700^0C, under continuous N_2 supply [32]. The initial metal concentration of the manufactured samples, as well as the potential for metal leaching, were studied. The findings revealed that, despite their lack of physicochemical characterisation, biochar samples were successful as adsorptive materials in the studies. The influence of pyrolysis temperature, residence duration, and biomass chemical impregnation on the yield of biochar synthesis was investigated using sewage sludge pyrolysis. At a temperature of 300^0C, the maximum yield was attained. The surface area of biochar rose when the pyrolysis temperature was increased, and it was maximum by impregnating biochar with K_2CO_3. To explore the possible release of heavy metals, leaching tests were performed on raw sewage sludge and biochar samples. Pyrolysis reduced heavy metal release in non-impregnated biochars, demonstrating that employing sludge-derived biochars as soil supplements has no ecological footprint [33].

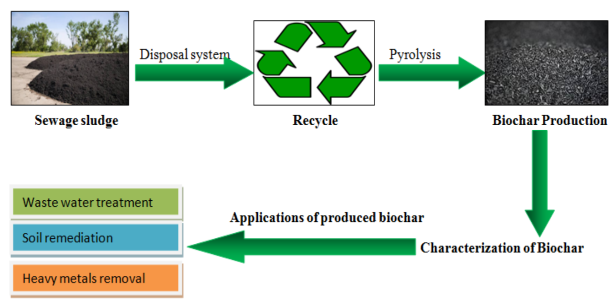

Fig. 1. Flow chart for Sludge Biochar production and Applications

3. Applications of Sewage Sludge Biochar

A. SSBC for waste water treatment

Due to its unique features, such as high SSA and extensive SFG, biochars are efficient adsorbents for the removal of a variety of pollutants. As a result, biochars have grown in importance as a means of removing pollutants from the industrial and agricultural sectors while also enhancing environmental quality [34]. Wastewater is a result of domestic, industrial, commercial, or agricultural activity and is a global issue. Biochars have a lot of potential as a wastewater treatment material. This section mostly discusses the use of sludge biochar in the treatment of industrial and agricultural wastewater.

B. SSBC for industrial wastewater treatment

Sewage sludge biochar has also been shown to remove color from lipid solutions more effectively than commercial activated carbon [31]. The surface chemistry and pore structure of sewage sludge biochar influence the adsorption of cationic and anionic dyes on it. The bonding interactions between negatively charged functional groups and dyes were primarily responsible for cationic dye adsorption [35]. Methylene blue is efficiently removed from various ecosystems by the high mesoporous volume of activated sewage sludge biochar by NaOH. The degree of mesoporosity and the surface chemistry influence adsorption. [36]. Electrostatic interaction is the main mechanism for dye adsorption onto sewage sludge biochar, in which carboxyl, phosphate, and anionic functional groups act as binding sites for cationic dyes, and positively charged amine groups were suggested for anionic dyes. [37]. It was revealed that biochar made from sewage sludge was effective as an adsorptive material, with pollutant removal ranging from 67 to 99 % in table water and 35 to 97 % in wastewater. The study's findings suggest that sewage sludge biochar has the potential to be an effective, low-cost adsorbent, as well as a practical and ecologically friendly solution to the complex issue of sludge management. [32]. Biochar, which was generated using a simple one-pot pyrolysis of sewage sludge, was found to be an effective persulphate activator for pollutant degradation, [38]. During the pyrolysis of raw sludge, metals in the sludge precursor were discovered to have a crucial role in active site development.

C. SSBC for agricultural wastewater treatment

Due to various SSBC's affinity for agrochemicals such as nitrate and phosphate, it minimizes pollution of groundwater and streams, resolving important issues such as eutrophication and nitrate contamination, which would otherwise stymie agricultural activity. As a result, forest clearing pressure will be relieved, and forest biodiversity will be conserved. Pesticide absorption from polluted soils is also reduced [39]. Researcher looked at how SSBC affected rice output and heavy metal bioaccumulation in acidic soil [40]. Municipal sewage sludge from Chinese treatment plants was employed [5]. The heavy metals and nutrients in the SSBC were next characterized, and the agronomic features of the treated soil in the pot experiment were investigated. The results showed that SSBC could accumulate heavy metals such as Cd, Cu, Cr, Pb, and Zn, which improved soil fertility, plant development, and remediation of polluted soil. The prevalence of agrochemical contaminants such as Polycyclic aromatic hydrocarbons and hazardous metals (As, Cd, Cu, Pb, and Zn) in agricultural soil was noted [41]. SSBC comes across harmful substances like dioxins, heavy metals, and Polycyclic Aromatic Hydrocarbons in raw sewage in urban agricultural regions.

D. SSBC for soil remediation

It has been observed that SSBC helps to maintain and boost crop productivity. Furthermore, it enhances the quality of nutrient-deficient soils such as acidic, dry, humid, and tropical soils. It maintains nutrient, mainly Nitrogen (N), in porous soil during rainy conditions due to its affinity for the nutrient. [39]. The pH of the soil drops as a result of its use in the agricultural field, while it complements nitrogen fixation, and crop yield improves as a result. The application of wastewater sludge and pyrogenic carbonaceous material increased soil cation exchange capacity (CEC) by up to 40% and soil pH by up to one pH unit [42], boosting nutrient availability and carbon sequestration, and making crops drought resistant. Furthermore, it improves earthworms and soil microbial biomass such as arbuscular mycorrhizal fungi [43]. The influence of slowly pyrolyzed papermill sludge on soil characteristics and plant growth by amending it with it on two agricultural soils. The pH, CEC, Total C, and exchangeable Ca, N content all increased significantly as a result of the experiment. In soil modified using papermill waste, yields of radish, soybeans, and wheat were all increased. Furthermore, earthworms preferred soil modified with pyrolyzed papermill waste [44]. Agronomic features of SSBC as well as the bioavailability of heavy metals in cherry tomato cultivation. pH adjustment and CEC increased soil fertility [42]. Adding SSBC to the soil increased the total nitrogen, organic carbon, available potassium, and phosphorus content of the soil [45]. It was found that incorporating sewage sludge into the soil increased the nutritional content [46]. In another study it was investigated the impact of different characteristics of SSBC on nitrogen availability and corn development in temperate soil [47]. In another study it was observed that adding SSBC to an urban soil and then growing turf grass in pots increased total soil nitrogen by 1.5 times, organic carbon (1.5 times), organic carbon (1.9 times), black carbon (4.5 times), available phosphorus (5.6 times) and potassium (0.4 times), respectively. Because of the improved plant mineral nutrition, turfgrass dry matter increased proportionally with increasing amounts of applied biochar. When compared to plants cultivated in the reference soil [46]. In a study it was observed faster Allium sativum growth and better dry matter yields in the SSBC-amended soil. According to the paper, the C:N ratio of SSBC ranged from 6.4 to 9.2, which was significantly lower than that of biochars made from biomass such as straw, confirming SSBC's significance as a nitrogen source. As a result, the amount of organic carbon accessible for microbial activities was higher, requiring more nitrogen; thus, a higher dose of SSBC promotes development [48]. In a one-year field experiment incorporating corn-radish rotation, compared the effects of sewage sludge-derived biochar and its precursor on the buildup of metals (Cd, Cu, Pb, and Zn) in soil and their uptake by plants. When compared to sewage sludge, biochar considerably increased radish yield ($p <0.05$; not corn yield) and dramatically reduced metal accumulation in both plants ($p >0.05$) As the amount of sewage sludge or its biochar applied grew from 7.5 t ha-1 to 30 t ha^{-1}, the overall concentration of Cd, Cu, Pb, and Zn in soil gradually increased [49].

4. Conclusions and Future Directions

This review primarily focuses on a list of relevant literature to highlight the implications of sewage sludge biochar for land and water treatment. Biochar is a renewable resource that has the potential to reduce a variety of environmental challenges, including wastewater contamination. Now SSBC manufacturing technologies focus on sludge pre-treatment, thermal conversion, and post-treatment. This review also outlines the SSBC's wastewater treatment applications, which include industrial and agricultural wastewater and the mechanisms driving the pollutant adsorption by biochar are explored. The primary conclusions of this review are that SSBC production methodology was the important factor impacting the yield of SSBC generated and Pyrolysis temperature was the most important factor affecting the yield of SSBC produced.

Biochar has been shown to be effective at removing pollutants from industrial wastewater and agricultural water. Its suitability for onsite use necessitates additional examination. Despite the fact that numerous studies have been conducted on the manufacture and use of SSBC in wastewater treatment, there are still information gaps that must be filled. Additional research is needed to develop a novel biochar modification technology that is both low-cost and high-efficiency, as well as to extend the practical application of biochar in wastewater treatment.

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