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Review

Potentials of urban waste derived biochar in minimizing heavy metal bioavailability: A techno-economic review

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SUMMARY

Contamination of heavy metals (HMs) in agroecosystem presented an additional dimension of complexity along with the adverse consequences of climate change for the scientific fraternity. The increasing population and urbanization on the other hand are regarded as the main sources of urban waste (UW). Holistic utilization of UW-derived biochar (BC) has shown potential to be utilized as a source of soil supplement in the agriculture sector, fulfilling several sustainable development goals (SDGs). An attempt has been made to evaluate the techno-economical prospect, efficacy of UW-BC in remediation HMs from SDGs and circular bio-economy prospective. Current review has highlighted that biochar, when amended alone/in combination, enhances HMs remediation potential. Economic analysis of UW-BC reinforces its viability as a sustainable solution for waste management. Consequently, the application of UW-BC has the potential to contribute significantly to the achievement of multiple SDGs, warranting further research and increased investment in this field.

INTRODUCTION

Heavy metals (HMs) endure in the environment because they are resistant to natural decomposition and undergo slow transformation processes. As a result, they accumulate at different levels of the food chain. Their harmful effects on agricultural ecosystems are well documented, affecting humans as well as animals. Thus, HMs pose a significant threat to life on earth.[1–3] Constant leaching of bedrock materials (during irrigation), rapid industrialization, irrational use of sewage sludge, dumping of manure from the farmyard, usage of chemical fertilizers along with unscientific treatment process have led to rising HMs load in arable soil.[2–4] According to an observation made by Liu et al.[3] 20.0 million ha of global land mass is being contaminated with cadmium (Cd), arsenic (As), mercury (Hg), lead (Pb), and chromium (Cr). Reports suggest that each year >600.0 km^3 and ~300.0 km^3 wastewater are being generated globally from industrial and municipal sources, respectively.[5–7] Speaking of economic burden of HMs contamination, it is estimated to cross 10.0 billion USD annually.[8] At present, to minimize the toxicity of HMs in soil-water-crop interfaces numerous approaches have been tried and tested. Alternation in irrigation regime,[9] seed priming,[10,11] nanotechnology[3,12] based interventions, crop rotation, and other soil and agronomic means[13] have their known merits and limitations.

Biochar can be best defined as a carbon rich product of thermochemical treatment of biomass waste of diverse origin in oxygen deprived or limited conditions.[14,15] Biochar has managed to get serious attention of diverse group of investigators in creating its efficacy in minimizing various contaminants. The method constraints are mainly liable for influencing the yield of biochar. Among the variables nature of biomass, holding time, temperature, rate of heating, pressure, etc. are prominent.[16] Due to having low-cost to produce, eco-friendly nature with huge surface area, significant variation in pore size, bearing diverse functional groups, enables biochar as suitable choice for soil amendment for minimizing HMs.[17–20] Apart from, the technical aspects, findings indicate that (1) economic facet of biochar (as a mean for soil supplement and C- sequestration) also projected to gain a sharp rise from 1.6 (year 2020) to 3.3 billion USD by 2025, and (2) holding of 9.6% market share of biochar for wastewater treatment purposes.[5,21,22]. Review articles are available, that discuss (1) the technical aspects[23,24] and (2) the broad spectrum of pollution mitigation using biochar derived from urban or municipal waste.[5,25–27] However, they lack a focused exploration of single-issue perspectives, particularly concerning circular bio-economics (CBE) and sustainable development goals (SDGs). The exploration of both technicalities coupled with CBE aspect will encourage the future researchers to orient their research to meet the requirements of (1) agro-environmental challenges, (2) market prospective, and (3) SDGs in a holistic manner.

To this end, this comprehensive review article has been conceptualized. It addresses the efficacy of urban waste derived biochar aiming at minimalizing HMs load in soil-water-crop interfaces with focus on (1) technical aspect, (2) circular bio-economic prospective oriented around the SDGs.

CHARACTERIZATION OF BIOCHAR

Physical and chemical properties of urban waste derived biochar

Urban waste frequently contains a significant amount of organic carbon (50%–70%) in developing nations, which presents an opportunity to convert hazardous waste into biochar, which is an ecofriendly resource.[28] The primary constituents of municipal solid waste (MSW) are food waste (21.59%), paper and cardboard (23.05%), wood (6.19%), yard trimmings (12.11%), and textiles (5.83%), all of which contain a significant amount of organic carbon.[23] Sewage sludge generated from sewage treatment plant (STP) is a potential source of biochar preparation, as biological sludge of STP contains high amount of organic matter.[29] Urban green waste biochar, which is produced from urban landscaping and urban gardening, can have higher surface area and porosity with increase in pyrolysis temperature that provide more adsorption capacity[30] (Li et al., 2024). The diverse composition and source of urban waste leads to even more noticeable variations in the characteristics of biochar, although they undergoes similar pyrolysis process.[31] Stable elemental composition of urban green waste derived biochar prepared by Li et al. (2024) can reduce the complexity of biochar applications in soil.[31] Kwon et al.[32] suggested the requirement of further research for cost effective application of biochar, as such type of waste requires costly treatment process before being utilized in pyrolysis process.

Surface area and porosity of biochar

Pyrolysis is a process in which biomass is dehydrated, causing the loss of water and the release of volatile components from the carbon matrix. The pore structure of biochar is influenced by these parameters, which also contribute to the formation of basic pores.[33] The surface area and porosity of biochar are crucial factors that determine the quantity and quality of active sites within biochar. These active sites play a key role in enhancing biochar properties such as cation exchange capacity (CEC), water holding capacity, and adsorption capacity.[34] Analyzing the distribution of pore sizes can determine the heterogeneity of the pore structure of biochar. Macropores often facilitate the dispersion of substances, mesopores serve as conduits for the movement of mass, and micropores offer room for containment. It was also observed that due to structural ordering and collapse of the microporous structure, the surface area of biochar reduces significantly as the pyrolysis temperatures go beyond 900°C.[35] The porosity and interconnectivity of the pores are essential factors that affect the water retention capacity of biochar.[36] Biochar, known for its significant internal porosity and irregular shapes, improves water retention in coarse soils by increasing the amount of water present and disrupting the arrangement of soil particles.[37]

Increasing the pyrolysis temperature has been shown to change both the surface area and porosity of biochar.[35] Moreover, elevating the pyrolysis temperatures leads to the decomposition of aliphatic alkyl and ester groups, therefore exposing the underlying aromatic lignin core. This procedure has the potential to result in an augmented surface area.[38] At higher temperature, the volatilization of substances in biochar,[39] development of mesopores along with micropores[40] and increase of aromaticity and stability while reducing functional groups that are less stable[41] leads to increased surface area and pore structures in biochar. Bahrami et al. (2020)[42] found that thermal treatment of substances like bovine bones with temperatures ranging from 500°C to 1100°C created hydroxyapatite adsorbents. The treatment removed organic components and enhanced the adsorbent's porosity and surface area, especially at 500°C.

The porous structure of biochar and enhanced surface area improves its capacity to absorb pollutants from both water and soil, including HMs, organic compounds, and nutrients. Qu et al.[41] found that biochars that possess a large specific surface area and microporosity have demonstrated excellent adsorption capabilities for pollutants such as Cr(VI) and naphthalene. The water retention capacity of biochar in soils is influenced by its pore structure. Biochars possess bigger and more linked pores to enhance soil water retention, hence providing advantages for agricultural purposes.[43] Research has demonstrated that the use of biochar improves the ability of soil to retain water, hence aiding in the preservation of soil moisture levels.[44] The pore structure of biochar enables it to retain and gradually release nutrients, hence enhancing soil fertility. Plant-available water and nutrients may be stored well in biochar due to the existence of micropores and mesopores, making it a beneficial soil amendment.[45] The porous structure of biochar provides a habitat for soil microorganisms, enhancing microbial activity and diversity. This can lead to improved soil health and increased plant growth. The pore spaces offer suitable niche for beneficial microbes that play a vital role in nutrient cycling.[46] Biochar application enhances the aeration and water retention capacity of soil, which can be beneficial for agronomic productivity.[47]

Lu and Zong[47] analyzed the properties of pores in biochars obtained from various sources using nitrogen adsorption (NAD) and mercury intrusion porosimetry (MIP) techniques. The research identified significant variations in pore properties depending on the kind of feedstock material that may be attributed to changes in the cellular structure, shape, and size distribution of herbaceous plants, coniferous forests, and broad-leaf forests. Biochar often has a surface area ranging from 8 to 132 m^2/g and a total pore volume ranging from 0.016 to 0.083 cm^3/g.[48] However, by carefully choosing the precursor and ensuring ideal pyrolysis conditions, those qualities could experience a substantial enhancement. For instance, researchers have successfully obtained surface areas of up to 490.8 m^2/g[49] and total pore volumes of

0.25 cm^3/g[50]. Through the utilization of efficient post-treatments such as KOH activation, it is possible to significantly increase the surface area and total pore volume of biochar, resulting in impressive values of up to 3263 m^2/g and 1.772 cm^3/g, respectively.[51]

Pyrolysis temperature

The chemical characteristics of biochar are affected by the presence of aromatic carbon and condensed aromatic structures, which are determined by the pyrolysis temperature.[52] Chen et al.[48] observed that at temperatures below 500°C, biomass undergoes an initial transformation into a "3D network of benzene rings" that contains a high concentration of functional groups. At temperatures ranging from 500°C to 700°C, it undergoes a conversion into a "2D structure of fused rings" that exhibits a high level of porosity. At temperatures above 700°C, the material may undergo a transition to a "graphite microcrystalline structure," resulting in a decrease in both porosity and functional groups.

Zhang et al.[53] performed an experiment and discovered that elemental ratios such as H/O, O/C, and (O + N)/C, as well as elements like hydrogen and oxygen, including functional groups, exhibited a negative trend with various pyrolysis temperatures during the synthesis of biochar. Biochar generated at lower temperatures possesses greater amounts of total nitrogen and organic carbon, while exhibiting a lower C/N ratio in comparison to biochar produced at higher temperatures[54]

Ghani et al.[55] discovered that when the temperature is below 500°C, lignin does not transform hydrophobic polycyclic aromatic hydrocarbons (PAHs). As a consequence, the hydrophilic characteristics of biochar are enhanced. However, as the temperature exceeds 650°C, biochar achieves thermal stability and undergoes a conversion that enhances its water resistance. Elevated temperatures lead to the production of biochar with higher alkalinity, which can effectively counteract the acidity of soil.[56] Higher pyrolysis temperature also enhances the carbon retention capacity of biochar and improves its stability, which is crucial for carbon sequestration.[57] The pyrolysis temperature has an impact on the composition of macro and micronutrients in biochar. Elevated temperatures enhance the nutrient content of biochar, but they can also cause the release of some elements such as nitrogen and sulfur through volatilization.[58] Increasing the pyrolysis temperatures of biochar enhance its mechanical properties, including hardness and modulus. This improvement makes biochar acceptable not just for environmental purposes but also for structural applications.[59] Slow pyrolysis favors the formation of high yield biochar due to low heating rate and longer residence time, whereas fast pyrolysis facilitates biofuel with high heating value.[60] Table S1 shows different stages of biochar heating during the pyrolysis process.

Surface functional group

The existence of surface functional groups on biochar, such as carboxyl, hydroxyl, and phenolic groups, is crucial in enhancing soil properties and promoting nutrient accessibility. Functional groups included in biochar enable its attachment to soil particles, organic matter, and nutrients, hence improving soil structure and fertility.[61] Table S2 summarizes the essential functional groups found in biochar, highlighting their significant features.

Biochar that is supplemented with a sufficient amount of oxygenated functional groups improves the soil's ability to retain nutrients by creating stable complexes. This preservation hinders the depletion of nutrients and improves their accessibility to plants.[62] Kamran et al.[63] found that biochar application increased the soil pH and higher functional groups of biochar inhibit soil particles from adsorbing phosphorus, thereby increasing its availability to the plants. The increase in soil pH promotes the dissociation of acidic functional groups on biochar, which then compete with phosphate for adsorption sites on soil surface. This mechanism reduced phosphate adsorption by soil and increased availability of Olsen-P for plant. The amount of nutrients and pH level of biochar typically rise as the pyrolysis temperature increases, with the exception of nitrogen. Biochar improves nitrogen retention in soil by minimizing leaching and gaseous loss, and promotes phosphorus availability by reducing its leaching.[64]

The presence of surface functional groups on biochar, including carboxyl, hydroxyl, phenolic, quinone, and amino groups, is crucial for effectively removing HMs from soil through various methods. Carboxyl groups increase the ability to exchange cations and create stable compounds with metals such as Pb, Cu, and Zn.[65] On the other hand, hydroxyl groups boost adsorption by forming hydrogen bonds and electrostatic interactions, which might cause the precipitation of metal hydroxides due to the pH increase caused by biochar.[66] Phenolic groups have a role in ion exchange activities, while quinone groups are involved in redox reactions, where they reduce metals such as Cr(VI) to forms that are less soluble.[67] Amino groups increase adsorption through electrostatic attraction, particularly in biochars that have been treated with nitrogen.[68] In addition, the application of H_2O_2 treatment can augment the quantity of oxygen-containing functional groups on biochar, so greatly improving its ability to adsorb metals such as Pb and Cu. The combination of these mechanisms makes biochar a highly promising amendment for stabilizing and immobilizing HMs in contaminated soils.[68]

The permeable characteristics and chemical groups of biochar assist in improving soil structure by promoting soil ventilation, water retention capacity, and the stability of soil aggregates. These improvements promote the cultivation of stronger and more resilient root systems in plants, hence enhancing their overall growth[69]

Elevating the temperature of biomass within the range of 350°C–650°C induces the disintegration and rearrangement of its chemical bonds. The procedure leads to the creation of many specific functional groups, such as carboxyl, lactone, lactol, quinine, chromene, anhydride, phenol, ether, pyrone, pyridine, pyridone, and pyrrole.[70]

The Fourier transform infrared spectroscopy (FTIR) spectra suggest that biochar is primarily composed of functional groups that are frequently observed in oxygenated hydrocarbons, which are a prominent feature of the carbohydrate structure of cellulose and hemicelluloses.[55] Pyrolysis may result in the disappearance of absorption bands that are distinctive to the original material and the emergence of unique bands that are characteristic of biochar samples (Figure 1; Tables S2 and S3).[60]

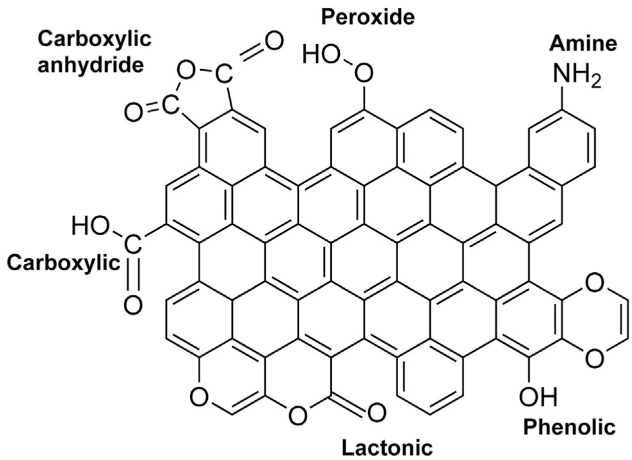

Figure 1. Basic functional group of biochar[71]

Influence of the feedstock quality

The characteristics of the input material significantly affect the attributes of biochar. Different feedstocks result in varying amounts of biochar stability and unique properties.[72] The presence of carbon, hydrogen, nitrogen, and oxygen (CHNO) in the elemental composition, together with the quantities of dissolved organic carbon (DOC) and water-soluble carbonates (WSCs), were significant factors in determining the stability of biochar. A direct relationship was seen between elevated concentrations of DOC and WSCs and a reduction in stability. Biochars produced from lignocellulosic materials including straw, wood, and grass had enhanced structural integrity after carbonization, whereas biochars formed from food waste included larger levels of readily decomposable carbon and exhibited lower stability. The pH, CEC, and ash concentration of biochars varied depending only on the kind of feedstock used. Biochars produced from kitchen garbage and green grass showed elevated levels of ash content and CEC. Higher organic matter concentration in feedstocks leads to the creation of biochars that are more resistant to decomposition, contain higher amounts of aromatic compounds, and have greater energy values.[73] Furthermore, the co-pyrolysis of lignocellulosic biomass results in a reduction of HM concentrations in biochar, an augmentation of carbon, hydrogen, and nitrogen composition, and an enhancement of thermal stability.[73]

The ash level of the feedstock affects both the formation of char and the reactivity during CO_2 gasification.[74] Biochars with a high concentration of ash in the feedstock tend to have reduced carbon levels and stability, which may impact their capacity to sequester carbon.[73] The ash content of biochar directly affects its thermal stability and specific surface area. Consequently, this may impact the efficacy of biochar in soil applications and its capacity to hold water and nutrients.[73] Using ash as an addition in the process of synthesizing biochar may increase the amount of biochar produced and enhance the recycling of nutrients. Nevertheless, it is important to show prudence when dealing with the possible escalation of some pollutants.[75]

An elevated concentration of volatile matter (VM) may enhance the availability of carbon, facilitating the proliferation of microbes and the circulation of nutrients. Nevertheless, it may also lead to the fixation of nitrogen in the soil.[76] The VM composition of biochar has a significant impact on its thermal stability. A greater proportion of VM is often associated with reduced stability and increased reactivity.[77] Volatile chemicals may enhance the synthesis of biochar and alter its surface properties during the pyrolysis process. This may lead to an augmentation in hydrophobicity and an enhancement in heat stability.[31] Moreover, biochars that have a high amount of VM often have larger specific surface areas and porosities, which makes them beneficial for applications in pollution remediation and soil health enhancement.[60]

The pH, specific surface area, and VM content of biochar are greatly affected by the pyrolysis temperature and the kind of feedstock used.[60] Furthermore, the features of the initial substance used and the precise circumstances in which pyrolysis occurs (including temperature and rate of heating) greatly impact the physical and chemical attributes of biochar. The usability of a substance for different purposes, such as soil remediation and carbon sequestration, is determined by these properties.[78] Moreover, biochars obtained from different sources have varying effectiveness in reducing the uptake of HMs in plants, with certain sources showing a significant decrease in HM concentrations in grains.[79] Therefore, the meticulous selection of feedstock is essential to tailor the characteristics of biochar to fulfill particular requirements, such as improving soil quality, reducing pollution, and storing carbon.

Remediation of contaminated soil

Urbanization and industrialization have led to significant soil contamination due to the presence of elevated concentrations of HM and metalloids, resulting in serious environmental and health risks. Traditional methods of rehabilitation are sometimes costly and might have adverse effects on the environment. Utilizing biochar obtained from urban garbage is a practical and effective method to combat soil pollution caused by metals. A thorough investigation carried out by Guo et al.[80] provides a comprehensive overview of the mechanisms involved in stabilizing HMs in soil using biochar. Biochar efficiently immobilizes HMs in soil via surface interactions, including electrostatic attraction, ion exchange, surface complexation, and (co-)precipitation processes. The carboxyl, hydroxyl, and phenolic groups found on the surface of biochar play a crucial role in effectively attaching cationic HM contaminants. Biochar application to soil raises the pH, hence promoting the hydrolytic degradation of HMs. Hydrolysis is a chemical process in which metals with a positive charge react with hydroxyl ions to form solid metal hydroxide complexes. This reaction reduces the concentration of metal ions that are able to dissolve in water. The existence of surface functional groups on biochar, such as -CO, -COOH, and -OH, increases its ability to trap HMs by surface adsorption and structural sequestration.[81] Biochar has a large specific surface area, CEC, and porosity, which enables it to efficiently trap HMs in soil, hence reducing their availability and movement.[82] Li et al.[83] observed that soil contaminated with combination of metals resulted in reduction of adsorption of metals to the biochar due to competitive adsorption. This results in excessive application of biochar to achieve required remediation from combination of HMs.

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Arsenic (As)

Utilizing biochar is a very efficient method to tackle soil pollution caused by As. Multiple research studies have analyzed the mechanics and effectiveness of biochar, especially when used in conjunction with iron or other compounds, to inhibit the migration of As in contaminated soils. Iron-modified biochar (FeBC) effectively immobilizes As in paddy soils, independent of the current redox conditions. This is accomplished by the process of converting iron oxides that are bonded to As, resulting in the creation of long-lasting complexes.[84] Wu et al.[85] revealed that several kinds of FeBC, including biochar-FeOS, biochar-$FeCl_3$, and biochar-Fe, are successful in decreasing the level of bioavailable As in soils by transforming it into more stable forms. The use of biochar and nano zero-valent iron (nZVI/BC) results in a significant reduction in the quantity of readily available As in soil, hence resulting to a substantial drop in the quantities of As that may be absorbed by living organisms.[86] Utilizing biochar in the co-contaminant stabilization approach has shown to be effective in stabilizing both As and Cd in soil. This is accomplished by transforming unstable As into more enduring forms and diminishing its capacity to be absorbed by living organisms.[87] Biochar, particularly when fortified with iron or other minerals, is an exceptionally effective amendment for extracting As from soils. The process involves the transformation of volatile As into more stable forms, resulting in reduced mobility and uptake by living organisms, hence lowering environmental risks. Table S4 displays several forms of alterations in the use of biochar in soil polluted with As.

Chromium (Cr)

Biochar application has great potential in addressing Cr pollution in soil as a remediation method. Multiple studies have examined the effectiveness and mechanisms of biochar, particularly when used in combination with other chemicals, in immobilizing Cr and decreasing its toxicity. Biochar employs many techniques to address Cr contamination, such as adsorption, reduction, electron shuttling, and photocatalysis. Biochar may be subjected to many methods, including physical, chemical, hybrid, and biological processes, to enhance its properties and efficacy in remediation.[88]

Mandal et al.[89] reported that the modification of biochar by the addition of chitosan and zerovalent iron (ZVI) enhances the reduction of Cr(VI). The biochar generated from chicken dung, which had been treated to modify its surface, was seen to cause a substantial reduction of up to 55% in the levels of Cr(VI) in soil. The decrease in reduction may be attributed to the existence of many oxygen-containing functional groups on the biochar's surface.

The peanut shell-derived biochar, when treated with cetyltrimethylammonium bromide (CTAB), exhibited a much superior ability to remove Cr(VI) in comparison to the untreated biochar. The designed biochar had a removal effectiveness of 79.35%, while the pristine biochar exhibited a removal efficiency of just 37.47%. The synthesized biochar significantly decreased the presence and mobility of Cr(VI) in soil, as shown by Murad et al.[90] The addition of biochar to nanoscale zero-valent iron (nZVI@BC) improves its endurance, mobility, and efficacy in immobilizing Cr(VI) when compared to unmodified nZVI. Su et al.[91] shown that this results in a significant decrease in the detrimental impact of Cr and the release of iron into soils. In a research done by Wang et al.,[92] it was shown that Fe-biochar, with its modifiable redox activity, may be a very efficient means of stabilizing Cr and As in soil. Fe-biochar effectively reduced the release of Cr(VI) by up to 99.7% during a 90-day trial, and it demonstrated long-term stability under simulated environmental conditions.

The concurrent application of biochar and elemental sulfur (ES) or compost has a significant beneficial influence on plant development, alleviates the detrimental effects of Cr toxicity, and reduces the concentrations of both Cr(VI) and Cr(III) in soil and plant tissues.[93] Biochar, especially when fortified with compounds like iron or combined with sulfur and compost, is a powerful supplement for remedying soils polluted with Cr. It significantly reduces the uptake and translocation of toxic Cr(VI) in the soil, hence enhancing soil quality and minimizing environmental risks. The Table S4 provides a comprehensive list of several uses of biochar for the purpose of rehabilitation of Cr-contaminated soil.

Cadmium (Cd)

Biochar has been shown to be a helpful addition for the treatment of Cd pollution in soil. It operates via many methods, including adsorption, immobilization, and enhancement of soil characteristics, eventually decreasing the availability of Cd and facilitating plant development.

A research done by Li et al.[94] showed that the use of vinegar residue biochar may efficiently adsorb and stabilize Cd in soil. This procedure also results in an elevation of soil pH and an augmentation of organic matter content. As a result, acid-extractable Cd is transformed into more enduring forms. Spartina alterniflora-derived biochar is used to immobilize Cd in soil by forming complexes with silicon and aluminum. This process enhances the durability of biochar and decreases the amount of available Cd.[95] The simultaneous use of biochar and vermicompost reduces the amount of Cd and enhances the biochemical properties of soil, even when exposed to acid rain stress.[96] Calcium-based magnetic biochar decreases the presence of Cd via raising soil pH and CEC, while also improving microbial diversity. Consequently, this approach proves to be a very effective technique for mitigating the simultaneous presence of Cd and As pollution.[87] Wheat straw that has been treated with sulfur biochar efficiently immobilizes Cd in soil by producing stable molecules, such as cadmium sulfide (CdS), resulting in a significant decrease in the bioavailability of Cd.[97] Table S4 displays several biochar variants used in the process of remediating soil polluted with Cd.

Lead (Pb)

The MgO-coated corncob biochar (MCB) was investigated by Shen et al.[98] The immobilization of Pb in contaminated soil was significantly enhanced by the conversion of the exchangeable form of Pb into more stable compounds. The outcome of this was a decrease of 50.71% in the amount of Pb that was leached, as determined by the toxicity characteristic leaching procedure (TCLP) test. The use of a mixture of biochar and nano-hydroxyapatite (nHAP/BC) has been shown to effectively absorb and immobilize Pb, hence reducing the bioavailability of Pb via dissolution-precipitation and cation exchange processes.[99] Zhao et al.[100] found that incorporating rice straw biochar into soil efficiently immobilizes Pb, hence reducing its availability and potential for leaching. Furthermore, it enhances soil fertility and regulates pH levels. The use of biochar-supported nano-hydroxyapatite (nHAP@BC) successfully immobilizes Pb in soil, leading to a reduction in the accessibility of Pb and a promotion in plant development by reducing the accumulation of Pb in plant tissues.[50] Biochars that are high in phosphorus have the potential to fix Pb in soils, leading to a decrease in the availability of Pb and an increase in the activity of soil enzymes. Phosphorus-rich biochars provide a sustainable substitute for conventional phosphate fertilizers, as shown by Netherway et al.[101] Table S4 summarizes the different types of urban waste-derived biochar used for Pb-contaminated soil remediation.

Mercury (Hg)

Altaf et al.[102] have shown that cost-effective biochar made from MSW is capable of effectively removing highly toxic elemental mercury (Hg0) that is released during coal burning. In addition, they have the ability to adsorb positively charged copper ions (Cu^{2+}) from water-based solutions and extract benzene from liquid waste found in landfills.[103]

Economic viability and market potential of urban waste-derived biogenic biochar

Fast urbanization, industrialization, and population growth have resulted in increasing growth of waste generation in the under developed and developing countries. The mismanagement of urban waste not only has a negative impact on the environment but also causes numerous health issues along with rises the socio-economic issues.[104] The advanced technologies like Waste to Energy (WtE) can be used to produce substantial heat energy and somehow decrease the environmental issues caused due to the urban waste to a certain extent[105] that brings to the release of greenhouse gas that is the root cause of global warming.[106]

The production of biogenic biochar can reduce the disposal of waste cost and generating revenues by selling the products in the market.[104] The economic technique like feedstock hybridization can be effectively used for the production of biodiesel by using animal waste and different waste gathered from crops together.[107] The feedstock hybridization technique is becoming the most cost effective and innovative technique for the production of biodiesel. The biogenic biochar that is a byproduct of urban waste alleviates the change of climate, environmental sustainability and a way to the development in the circular economy. The application and the production of biogenic biochar has been extensively increasing in the recent years in all over the world that has a great potential in the construction, agriculture as well as commercial uses.[108–110]

Urban waste biochar has a significant market potential with sustainable solution for both the agricultural industries and waste management and very much potential for improving the fertility of soil and growth of the plant.[111] European biogenic biochar foundation describes need of research and further investment on the production of biogenic biochar and its marketing potential as a viable solution renewable energy and waste management.

The expenditures and profits for treating one kilogram of moist biomass within developing as well as lower-income nations were estimated for the exact same functional unit to make the economic and environmental assessments as consistent as possible. The net profit is shown as follows.[112]

$$\text{Net profit} / \text{Loss} = R - C_{CT} - C_P(LK) - C_A \qquad \text{(Equation 1)}$$

where

R = revenue generated from producing maize in place of energy, fertilizer, etc.

CCT = collection and the treatment of wet waste biomass costs.

CP (LK) = labor (L) and capital (K) costs associated with each biochar production process.

CA = cost associated with transportation and application of biochar and waste composted.

Environmental analysis and economic analysis typically approach the impact of different timing.[113] The economic analysis assumed that the effects of the environment would materialize within a year, so revenues and discontinuing costs could generally be ignored. The exception to this was the costs of capital that were annualized using assumptions about the technical life cycle and the rate of discount.[112] According to a recent analysis of biochar cost restrictions, low income and high value crops grown in tropical regions are the two main determinants of the viability of a biochar scenario.[114] The practicality from an environmental and economic standpoint of using biowaste to make biochar and using it in agriculture. Both pyrolysis methods are expected to be more effective than compositing and to have a favorable effect on the environment.[115]

One of the biggest challenges to the growth of the modern bioenergy sector is the availability of biomass feedstock. These include the use of more land for food production, environmental issues, and an increase in greenhouse gases (GHG) emissions by directly or indirectly.[116–118] The calculation of feedstock's purchasing prices and its supply is the major challenges.[119] Social costs must also be factored into feedstock costs because the growth of the bioenergy industry in developing nations aims to promote rural development.[120] Considering its potential as a building material, the practical viability of employing biochar in composites made of cement would depend on a number of criteria, such as the type of feedstock available locally, the size of production, and the already used alternative waste management approach.[115]

According to a recent report analysis by Precedence Research, the worldwide biochar market is expected to be valued USD 220.27 billion in 2022 and USD 633.31 billion by 2032. In 2022, the Asia-Pacific region accounted for 70.7% of global revenue. At a CAGR of 12.1% throughout the projected period, the worldwide biochar market is anticipated to increase from USD 164.5 million in 2021 to USD 365.0 million by 2028.[121] North America has emerged as the second-largest market for such biochar globally as a result of the rising demand for organic foods and the high meat consumption in the area.

Europe is another key region for this sector. Because of Europe's abundant supply of forestry waste, the industry is expanding. In 2020, over 17,000 tons of this char were produced in Europe, and 15 more fresh factories had been established and put into operation. Germany now has the greatest market share in Europe. Due to the existence of several enterprises in both established and developing nations, the international market is fragmented. Presently, BSE Inc (US), 3R Enviro Tech Group (India), Airex Energy Incorporation (Canada), American Biochar Company, Farm2Energy (India), Green Man Char (Australia), Terra Humana Ltd (Poland), and Oregon Biochar Solutions (US) are the market leaders.

The largest compound annual growth rate (CAGR) of 13.2% is anticipated for the Asia Pacific biochar market, which in 2021 accounted for 69.2% of global biochar market share.[122] The market for biochar is anticipated to reach a value of USD 1.5 billion in 2022 and grow at a CAGR of 14% from 2022 to 2030. By 2030, it is anticipated that the worldwide biochar market will be worth USD 4.2 billion. The region with the fastest growth is predicted to be North America.[121]

Due to collaboration in between SUEZ Group and Airex Energy, the commercialization of the conversion of biomass waste into biochar has been occurred in June 2021. Airex Energy joined the BDO Zone Strategic Alliance as a technology group partner in June 2022. This organization is made up of some of the leading bioenergy companies that aid in the growth of bio-based projects in Biofuel Development Opportunity (BDO) Zones.[121] The broad availability, usefulness, and easier manufacturing of biochar from organic waste and biomass have increased interest in it in recent years. As a result, production methods are always being modified to increase production quality and efficiency.

Using a systems approach based on the triple value framework, the aforementioned figure demonstrates how to simulate the generation and disposal of wastes along the business value chain. It does this by explicitly mapping the interdependencies among three types of dynamic systems: communities, industry, and the environment.[123] Resources are recycled or disposed of after being removed from the environment and placed through production processes to provide value for markets. The life cycle of a product is depicted in the aforementioned figure and includes the following stages: extraction of raw materials from terrestrial sources; transportation; processing; manufacturing; packaging; distribution and product support through various channels in the market; consumer use of the product; and final disposal or recycling of excess waste. These wastes can include greenhouse gases and toxic contaminants. They are produced in solid, liquid, and gaseous form.

Role of biochar application in the SDGs

The utilization of biochar obtained from urban waste plays a crucial role in attaining numerous SDGs by promoting soil health, waste management, water and air quality, clean energy production, and climate change mitigation. This comprehensive strategy not only tackles environmental concerns but also fosters sustainable urban growth and resilience. Figure 2 explains the linkage between different SDG with the application of urban waste derived biochar.

Biochar plays a vital role in fostering sustainable development and urban resilience by strengthening soil health, managing waste, improving water retention, providing clean energy, and mitigating climate change. In order to support decent work and economic progress, biogenic biochar made from urban garbage must be commercially viable and have a large market. MSW can be converted into biochar for wastewater treatment due to its high surface area and porosity, with various functional groups aiding in pollutant adsorption and catalysis.[28] The process of turning municipal garbage into energy and selling it as biomass will help to maintain clean cities for human habitation. The significance of biomass trading in utilizing vegetable waste, reduces pollution, and fulfills energy requirements that lead to energy sustainability in urban areas.[124] The strategic opportunities such as biochar standardization, bioengineering higher-value products, and closing the circular economy to maximize biochar benefits and profitability across various industry sectors and it emphasizes the conversion of city waste into bioenergy for economic value and environmental sustainability, advocating for improved marketing strategies.[125] The considerable potential of biogenic biochar produced from urban trash in resolving issues related to urban sustainability is highlighted in recent research on sustainable cities and communities. Research shows that biochar, which is created by pyrolyzing organic waste from urban areas, provides a variety of benefits for improving environmental health and urban resilience. Biogenic biochar produced from urban garbage can improve sustainable business communities' contributions to social fairness and the sustainability of the entire city.[126] The ability of biochar to sequester carbon offers a sustainable way to lower greenhouse gas emissions. The multidisciplinary contributions to the development of sustainable urban design demands the necessity for faster knowledge production based on socioeconomic data, climate classifications, and geographic features, especially in the tropics.[127]

Future research direction

(1) Long term impact (using field trail) of UW-BC supplement and its interaction with HMs.
(2) Role of modification(s) using greener approaches in UW-BC for effectivity enhancement in HMs remediation from soil-water-crop system.
(3) Site specific HMs remediation using UW-BC in crops designated urban, innovative urban large scale agriculture system.
(4) Rhizospheric physicochemical-biological aspect of interactions (among microbes, UW-BC, and HMs) should be clarified in detail for better understanding the phenomenon of HMs, nutrient transport mechanism in food chain.
(5) The marketable production of biochar-based nanomaterials is still in its infancy and needs interference of production technologies should be encouraged.
(6) Holistic production system of UW-BC should be encouraged under smart-city plan with focus in CBE.

Conclusion

The comprehensive review of urban waste-derived biochar demonstrates its significant potential in mitigating the bioavailability of HMs in soil, water, and crop interfaces. The technical features of biochar, such as its characterization, surface area, porosity, and functional groups, demonstrate its effectiveness in adsorbing and immobilizing HMs like As, Cr, Cd, Pb, and Hg.

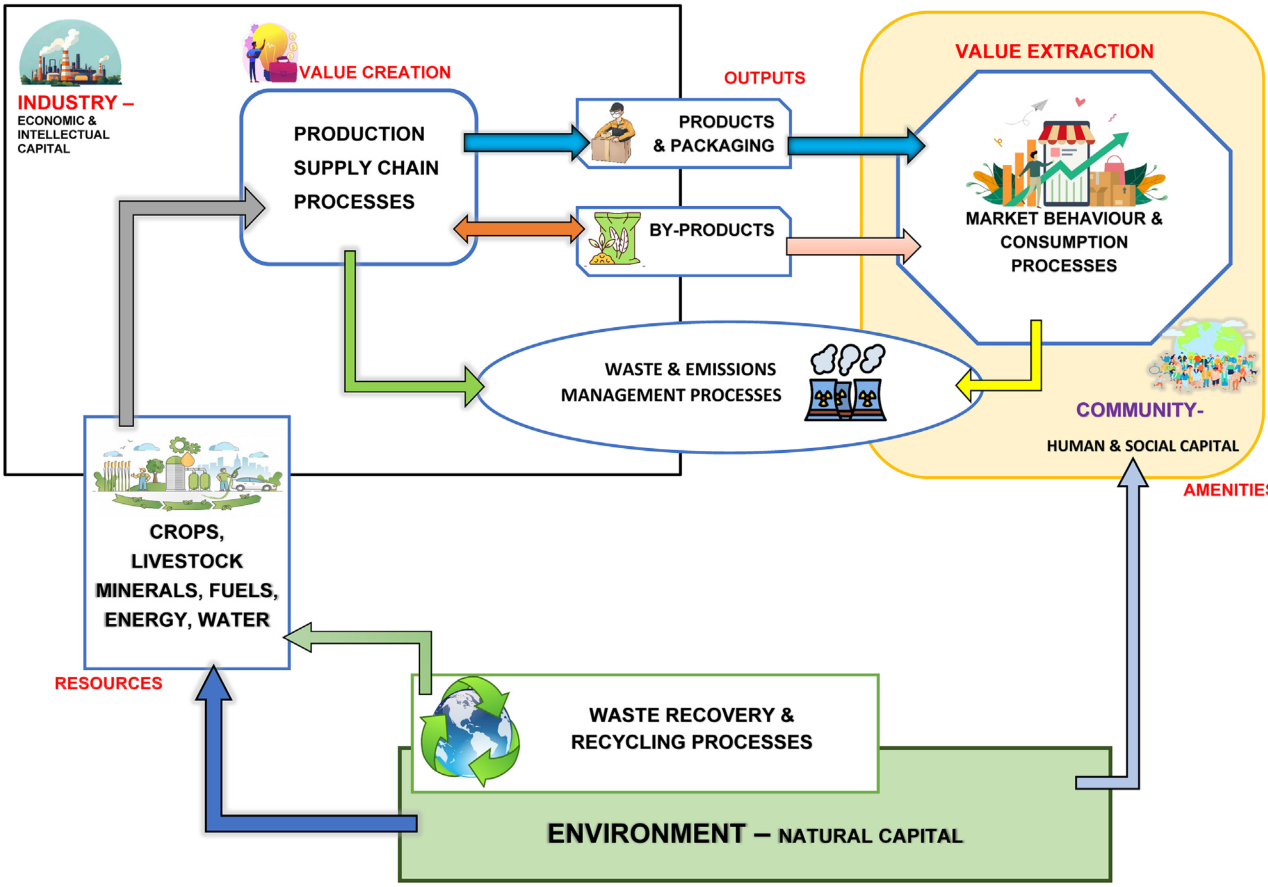

Figure 2. Circular bio-economic flow of urban waste derived biochar

The review highlights the adaptability of biochar, especially when combined with substances such as iron, sulfur, and nanomaterials, which improve its ability to address environmental issues.

From an economic standpoint, the production and application of biochar provide a feasible alternative for waste management and soil amendment that adheres to circular bio-economic principles. The biochar market is expected to increase due to the rising demand for sustainable farming practices and waste management solutions, which in turn enhances its economic feasibility. Incorporating biochar production into waste management systems not only tackles environmental issues but also creates economic worth, hence promoting sustainable development.

Biochar plays a crucial role in attaining SDGs by enhancing soil health, managing waste, improving water and air quality, producing sustainable energy, and mitigating climate change. The diverse advantages of using biochar emphasize its significance in promoting sustainable urban growth and resilience.

Overall, urban waste-derived biochar emerges as a highly promising remedy for the removal of HMs, providing significant advantages in terms of both the environment and the economy. It is imperative to do further study and invest in biochar technology and its uses in order to fully exploit its potential and contribute to global sustainability initiatives.

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AUTHOR CONTRIBUTIONS

D.M. and B.K.P., conceptualization, design, and writing; R.B., analysis and writing; S.C.S., S.C., A.H., and J.K.B., representation and review; all authors approved the submission.

DECLARATION OF INTERESTS

The authors declare that Prof. Jayanta Kumar Biswas is a guest editor for the special issue, "Biochar for Sustainable Environmental Management," but was not involved in the editorial handling of this article

SUPPLEMENTAL INFORMATION

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