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Green Synthesis of Biochar for Heavy Metal Adsorption from Industrial Effluents

Mofizul Hussain

Assistant Professor, Department of Chemistry, Bilasipara College, Bilasipara, Dhubri, Assam, 783348

Abstract

Industrial effluents contain heavy-metals that have long-term environmental and human-health problems because of its toxicity, mobility, and non-biodegradability or toxicity of metals like lead (Pb), cadmium (Cd), and nickel (Ni). This paper examines green synthesis of biochar using agricultural waste derived as rice husk, sugarcane bagasse, and groundnut shell as a low-cost and steady adsorbent of heavy-metals. Pyrolysis of biochar was slowed by moderate temperature with the use of steam as activation, which prioritized minimal use of chemicals and low energy requirements. Proximate analysis, FTIR, and BET and SEM-EDS characterizations were done to determine the presence of functional groups, porous microstructures, and mineral constituents that are conducive to adsorption. The batch experiments revealed high removal efficiencies especially that of Pb^{2+}, as sugarcane bagasse biochar had the best adsorption capacity because it had high surface area and good development of pores. Kinetic data correlated with pseudo-second order models and the isotherm was the Langmuir, so the behavior was monolayer chemisorption. The biochars were also efficient in the real industrial effluents and they also exhibited high regeneration potential in the multi-cycle. The general implications of the findings are compliance with the possibility of industrial wastewater treatment using agricultural-waste-derived biochar as an eco-friendly material and a driver of future applications of circular-economy strategies in motivation of pollution control.

Keywords: Biochar; Green synthesis; Agricultural waste; Heavy metal adsorption; Industrial effluents.

1. Introduction

The growth of industrial activities in recent decades increased the number of toxic heavy metals released into water bodies to previously unprecedented levels and undermines ecological and population health significantly. Lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), and arsenic (As) are heavy metals that are non-biodegradable and accumulate over time in the soils, sediments, and living organisms and lead to long-term contamination and biomagnification at different trophic levels (Gupta et al., 2012). Carcinogenic, nephrotoxic, and neurotoxic effects have been linked to prolonged exposure to such metals, which belongs to the list of environmental priorities in removing them in industrial effluents (Jaishankar et al., 2014). The dynamic and quick industrialization of developing economies makes the problem of treatment of effluents that contain metal all the more urgent, requiring age-time and ability to treat such effluents in a sustainable and cost-efficient manner (Renu et al., 2017).

The use of conventional wastewater treatment methods which are chemical precipitation, ion exchange, membrane filtration and electrochemical methods has been extensively used in the management of heavy-metal contamination. Nonetheless, these systems are usually associated with high operation costs, sludge

formation, second generation pollution as well as low efficiency when low concentrations of metals are involved (Fu and Wang, 2011). As a result, attention to the investigation of inexpensive and eco-friendly alternatives that could be used to solve the problem of heavy-metal removal and provide vehicles with new opportunities without burdening the environment with an extra load has increased around the world. In that regard, biochar has been noted as an exciting adsorbent with porous architecture, elevated surface capabilities, tuneable physicochemical characteristics, and capacity to adsorb a plethora of contaminants (Tan et al., 2015).

Biochar is considered as the product of pyrolysis or hydrothermal carbonization of biomass in the presence of limited oxygen, due to which it is beneficial in both ways: waste valorization and pollutant recovery. Agricultural residues have traditionally been utilized in the creation of biochar as biochar is attractive as a sustainability tool because of this reason. Rice husk, coconut shell, sugarcane bagasse, ground nut shell, and sawdust are some of the commonly used wastes in agriculture, and they are conveniently located, renewable, cheap and many are not used fully or openly burnt, assisting in air pollution and greenhouse gases (Lehmann and Joseph, 2015). By reforming these waste streams into useful adsorbents, it will be easier to implement a circular-economy, where waste is converted into useful products that will aid in environmental protection and recovery of resources (Mohan et al., 2014).

Furthermore, the notion of green synthesis implies low-energy synthesis, low amounts of chemicals used, and the use of natural activation agents like steam treatment or controlled pyrolysis. These methods lead not only to a decrease in the price of production, but also to the maintenance of the environmentally compatibility of the obtained biochar in all its life cycle (Hale et al., 2016). The natural functional groups and mineral composition of biochar obtained by the use of agricultural waste can lead to an increase in the ability to retain heavy metals due to the involvement of ion exchange, complexation, surface precipitation, and electro-static interactions (Inyang et al., 2016). A combination of these mechanisms results in the high metal-removal efficiencies with even the more complicated industrial effluent matrices.

Green-synthesized biochar can offer an alternative and scalable treatment of industrial wastewater in the light of rising regulatory demands and the need to treat wastewater at low costs. This research project is concerned with the production of biochar using the agricultural residues in a sustainable manner and assessing its capacity to adsorb the heavy metal content in industrial effluent. Focusing on the synthesis paths that are eco-friendly, this study is aimed at the general objective of environmental healing, waste recycling, and eco-friendly industrialization.

2. Literature Review

Industrial effluents have led to heavy-metal pollution that has become a consistent concern in the environmental domain, trying to prevent the problem nature and low-cost remediation approaches are highly investigated. Traditional methods of treatment like chemical precipitation, ion exchange, coagulation-flocculation and membrane filtration have been successful to some extent but have drawbacks including high costs of operation, the generation of sludge, and diminished efficiency in lower traces of metals (Fu & Wang, 2011). Biochar has become one of such sustainable alternatives, with its physicochemical versatility, outstanding adsorption efficiency, and the capacity to be generated using the great waste biomass of agriculture (Lehmann and Joseph, 2015). The literature review hereafter discusses some of the major topics related to the agricultural-waste-derived biochar, the green synthesis processes, the adsorption process and the scientifically proven use in the heavy-metal removal of industrial effluents.

2.1 Production and Properties of Biochar

Biochar is a porous substance that is rich in carbon by product of pyrolysis or hydrothermal carbonizing of biomass in low oxygen environment. Temperature, heating rate and residence time are some of the production parameters that affect the surface area, pore structure, functional group and mineral composition of the resulting biochar (Mohan et al., 2014). Pyrolysis at low temperatures (300-400ºC) preserves more oxygen groups of functional groups (-OH, -COOH and -C=O) capable of binding metals through complexation reactions (Al-Wabel et al., 2013). On the other hand, high-temperature pyrolysis (500-700degC) increases the surface area and aromaticity as well which makes biochar applicable in adsorption due to pore-filling and electrostatic processes (Keiluweit et al., 2010). Agricultural waste biochars are usually endowed with natural mineral materials like silica-potassium and magnesium which also aid metal immobilization by their reaction on the surface (Chen et al., 2011).

2.2 Agricultural Waste as a Sustainable Feedstock

Agricultural residues are considered to be one of the largest and rapidly replenished biomass sources in the world. Some of these wastes include rice husk, rice straw, coconut shell, sugarcane bagasse, corn stover, and groundnut shell, and in their current state they are usually burned or mishandled producing greenhouse gases and air pollutants (Tan et al., 2015). These residues are biodegradable materials, converting them to biochar is a considerate option in terms of the principles of the circular economy, as it has the dual benefit of reducing the waste management issue and offering cheap resources to clean the environment (Ronsse et al., 2013). An example is rice husk biochar that is highly silica content and that has been shown to possess high affinity to adsorb lead and cadmium (Ahmad et al., 2014). Similarly, coconut-shell-obtained biochar is highly stable and microporous, which is why it can be used to adsorb chromium and nickel ions in effluents (Kizito et al., 2015). Sugarcane bagasse biochar has demonstrated excellent efficiency in multi-metal adsorption because it is highly porous and has functional groups of a variety (Melo et al., 2016). These results indicate that there is a possibility of agricultural biomass to be used as a sustainable, inexpensive feedstock to make biochar.

2.3 Green Synthesis Approaches

The term green synthesis focuses on low-emission, energy-efficient and non-toxic techniques of making biochar. Chemical activation in the conventional strong acids and bases, though increasing the surface area, presents environmental hazards of waste of chemicals and corrosive residual products (Deng et al., 2019). Green methods do not use such treatment by chemicals, but instead, they use mild forms of activation like steam, CO_2 or water using hydrothermal activation (only water) (Libra et al., 2011). It has been reported that steam activation leads to a beneficial improvement in the pore structure without any contamination (Heidari et al., 2019). Hydrothermal carbonization, which can be done at temperatures of 180- 250ºC, is specifically applicable to wet biomasses like food waste and sugarcane bagasse, and it provides a low-energy pathway towards the formation of hydrochar with desirable adsorption characteristics (Sevilla and Fuertes, 2009). These green synthesis protocols reduce environmental imprints and produce biochars that would be used in the cleanup of heavy-metals.

2.4. Mechanism of Heavy-Metal Adsorption

Biochar reacts with heavy metals by use of various physicochemical reactions. Ion exchange is one of the most predominant processes wherein inorganic cations present on the biochar surface (e. g. Ca^{2+}, Mg^{2+}, K^{+}) are substituted by metal ion present in solution (Inyang et al., 2016). The functional groups that can be involved in surface complexation include -OH, -COOH, and -C=O that create stable coordination complex with the metal ions (Ahmad et al., 2014). Electrostatic attraction is involved when the biochar

surface is in the form of a negative charge, especially at a higher pH value than the point of zero charge of the material (Chen et al., 2017). The mechanisms of precipitation take place when biochar minerals that include carbonates, phosphates or silicates are reacts with metals to form insoluble reactions, as is seen in lead adsorption studies with chromium (Beesley et al., 2011). These processes tend to work in synergy and increase the general removal capacity with regards to the type of metal, pH, ionic strength and biochar characteristics.

2.5 Biochar as Heavy-Metal Remover: Experimental Results

Such studies have documented the usefulness of biochar made of agricultural wastes in purifying industrial and synthetic effluents. Under ideal conditions, rice husk biochar has been able to remove Pb^{2+} and Cd^{2+} at perfection of over 90% (Ahmad et al., 2014). Coconut-shell biochar has shown great capability to bind Cr(VI) due to redox reactions to convert harmful Cr(VI) to an less harmful Cr(III) which is then adsorbed (Kizito et al., 2015). Cu^{2+}, Zn^{2+}, and Ni^{2+} have also been reported to be removed using sugarcane bagasse biochar which is motivated by the porous nature of structure and the heterogeneous surface chemistry (Melo et al., 2016). All these studies support potential of biochar as low-cost, efficient and reusable adsorbent.

Application of industrial wastewater has also proved to be promising. Corn stover biocchar recorded massive elimination of various metals present in the metallurgical effluent (Zhang et al., 2013). Depending to treat the electroplating wastewater with Cr and Ni, the anthropogenic biochar made out of bamboo waste has shown a competitive ability in the adsorption processes with activated carbon (Liu et al., 2017). Moreover, other researchers indicate the capability of biochar to preserve adsorption potential throughout multiple regeneration cycles, which in turn points to its financial viability (Hale et al., 2016).

2.6 Research Gaps and Limitations

Although biochar is beneficial, it has drawbacks in the process of remediation. Adsorption capacity depends broadly on the type of feedstock, the pyrolysis setting and the nature of the effluent (Inyang et al., 2016). Depending on the dissolved organic carbon or minor minerals contained in biochar, it can be released and affect water quality (Huang et al., 2017). In practice, the adsorption in actually industrial effluents can be decreased by other ions, thus underscoring multi-metal and multi-wastewater research (Renu et al., 2017). Massive manufacturing and implementation need to have a destination quality control, costs analysis, and life-cycle evaluations. Also, as much as the environmental effects of green synthesis strategies are minimised, minimisation of low-energy techniques is still a research topic in progress.

3. Materials and Methods

This paper aims at reviewing the green production of biochar using agricultural waste and its use in the removal of heavy metals in industrial effluents. Every step was calculated to lead to the use of few chemicals, less use of energy, and focus on sustainability.

3.1 Biomass Selection and Pre-treatment

The agro residues such as rice husk, sugarcane bagasse, and groundnut shell were chosen depending on high availability, low price and desirable compositional properties like lignocellulosic content and internal mineral properties. The local agricultural processing units were used to collect the samples of the biomass. All feedstock was then washed thoroughly using distilled water in order to remove soil particles and impurities. They were dried in the hot-air oven at 105ºC to 24 hours to make sure that all moisture was gone. The samples dried were then ground to fine and sifted using a 1 mm mesh in order to have the same size of the particles to be subjected to pyrolysis.

Table 1: ***Selected Agricultural Waste Feedstocks and Their Key Properties***

Feedstock	Major Components (Approx.)	Sustainability Advantage
Rice Husk	Silica, lignin, cellulose	Abundant agro-waste; often burned in fields
Sugarcane Bagasse	Cellulose, hemicellulose, lignin	Widely available; renewable and biodegradable
Groundnut Shell	Lignin-rich biomass	Low-cost residue; high carbon yield

3.2 Green Synthesis of Biochar

Low energy slow pyrolysis was used to prepare biochar by way of a muffle furnace under low oxygen conditions. Each of the pre-treated samples of biomass was weighed around 200 g and put in ceramic crucibles and pyrolyzed in high 450°C and at the rate of 10ºC every minute. No activating agents seen to be chemical were used. Rather, activation was carried out by mild thermal treatment through introducing regulated moisture during the cooling phase in order to produce improved pore structure without producing dangerous residues. The ensuing biochar was left to cool naturally then by hand and stored in airtight containers.

3.4 Biochar Characterization

The samples of biochar were also characterized to define their structural and chemical properties to use in adsorption of heavy-metals.

- pH and Electrical Conductivity: The ratios in biochar-water were taken as 1:10.
- Proximate Analysis: Proximate analysis is done to analyze content in terms of moisture content, volatile contents, fixed carbon, and ash content.
- Surface Functional Groups: These were obtained by Fourier Transform Infrared Spectroscopy (FTIR).
- Surface Morphology and Elementary Composition: Tested with Scanning Electron Microscopy with Energy-Dispersive X-ray Spectroscopy (SEM-EDS).
- Surface Area and Porosity: Detected by nitrogen adsorption analysis using the Brunauer-Emmett - Teller(BET) method.

Table 2: ***Summary of Biochar Characterization Techniques***

Parameter	Technique Used	Purpose
Functional groups	FTIR	Identifying metal-binding chemical groups
Surface area & porosity	BET analysis	Understanding adsorption capacity
Surface morphology	SEM	Observing pore development and structural integrity
Elemental composition	EDS	Assessing mineral content aiding metal capture
pH & EC	pH/EC meter	Determining suitability for adsorption environments

3.4 Metal Solutions and Effluent Samples Preparation

Analytical-grade salts were used to make synthetic solutions of heavy-metal (Pb^{2+}, Cd^{2+}, and Ni^{2+}) to control experimental conditions. Also, actual samples of industrial effluent were taken to a local

electroplating plant, filtered drunk of suspended solids labeled and then preserved at 4ºC before tests were conducted on them.

3.5 Batch Adsorption Experiments

Experiments involving batch adsorption were carried out in order to test the adsorption capacity of both types of biochar. The parameters influencing the key operational parameters, such as pH (3-8), dosage of the biochar (0.5-3 g/100 mL), contact time (10-180 minutes), initial metal concentration (10-100 mg/L) and temperature (25-45ºC) were varied systematically. The samples were shaken at 150 rpm and filtered with measurement of metal concentrations done by the use of Atomic Absorption Spectroscopy (AAS). The standard mass balance equations were used to calculate the adsorption capacity.

3.6 Regeneration Studies

The evaluation of sustainability was done by conducting agents of regeneration experiments in the form of mild acid washing (0.1 M HCl) followed by the rinsing and dry out. Biochar has been used to test up to five adsorption-desorption cycles in order to see reusability.

4. Results

The adsorption experiment used detailed characterization and the adsorption experiment was conducted to determine the performance of the green-synthesized biochar of rice husk, sugarcane bagasse and groundnut shell. The findings boost the role of feedstock type, structural peculiarities, and work conditions on the elimination efficiency of heavy-metals. Noteworthy results of characterization studies, adsorption behavior, isotherm and kinetic modelling and regeneration work are provided below.

4.1 Biochar Characterization

It was observed that physicochemical characteristics of the three biochars were quite different because they had compositional differences, and different pyrolysis behaviors. Rice husk biochar (RHB) had a high level of ash with a high content of silica, which supported the rigid and micro-mesoporous organization. The cause of the high surface area being recorded by the Sugarcane bagasse biochar (SBB) was the cellular structure that was fibrous thus it increased the pore development during pyrolysis. Groundnut Shell biochar (GSB) showed the greatest load of carbon fixed capacity and therefore, better structural stability and aromatic surfaces.

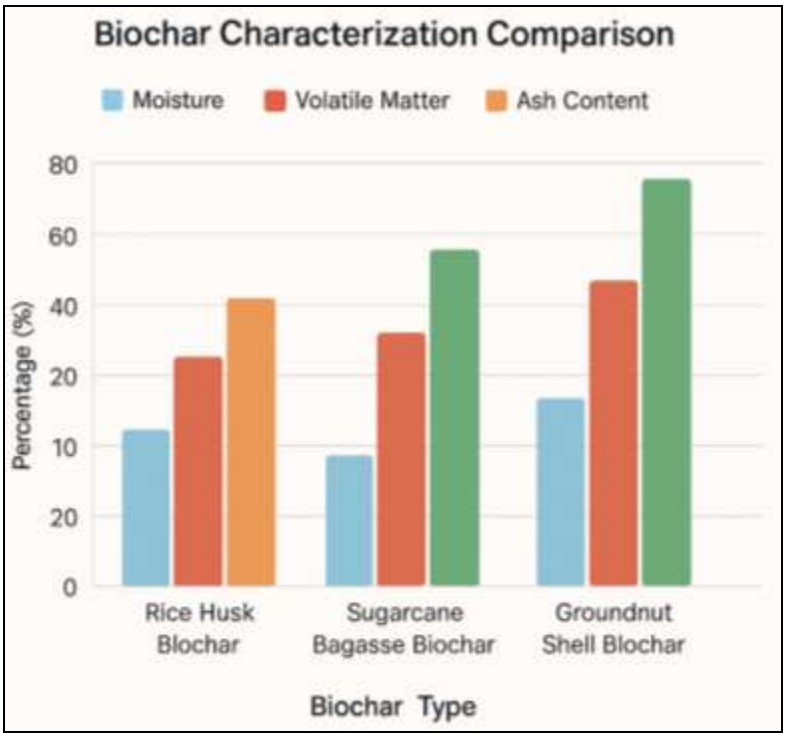
Table 3: ***Proximate Analysis of Biochar Samples***

Parameter (%)	**RHB**	**SBB**	**GSB**
Moisture	2.1	2.4	2.0
Volatile Matter	27.5	32.8	25.9
Ash Content	38.2	12.4	9.8
Fixed Carbon	32.2	52.4	62.3

FTIR analysis showed that all samples contain hydroxyl (-OH), carboxyl (-COOH) and carbonyl (C=O) groups, but RHB displayed additional Si C O O H peaks because of its silica-based matrix. The images of SEM showed that SBB had the most well-developed pore network and that RHB had irregular and angular pores that relate to silica structures. GSB had smoother surfaces that had scattered micropores.

BET analysis confirmed that SBB had the highest specific surface area (≈185 m²/g), followed by GSB (≈146 m²/g) and RHB (≈92 m²/g). Such differences had direct effects on the adsorption performance.

Figure 1: ***Biochar Characterization Comparison***



4.2 Performance of Adsorption with Heavy-Metal

Optimized lab test conditions were analyzed in order to determine adsorption capability of Pb^{2+}, Cd^{2+}, and Ni^{2+}. High affinity to Pb^{2+}, moderate to Cd^{2+} and low to Ni^{2+} were observed in all the three types of biochar. Removal of Pb^{2+} was greater with higher ionic radius and more stability due to the formation of stable complexes with oxygen functional groups.

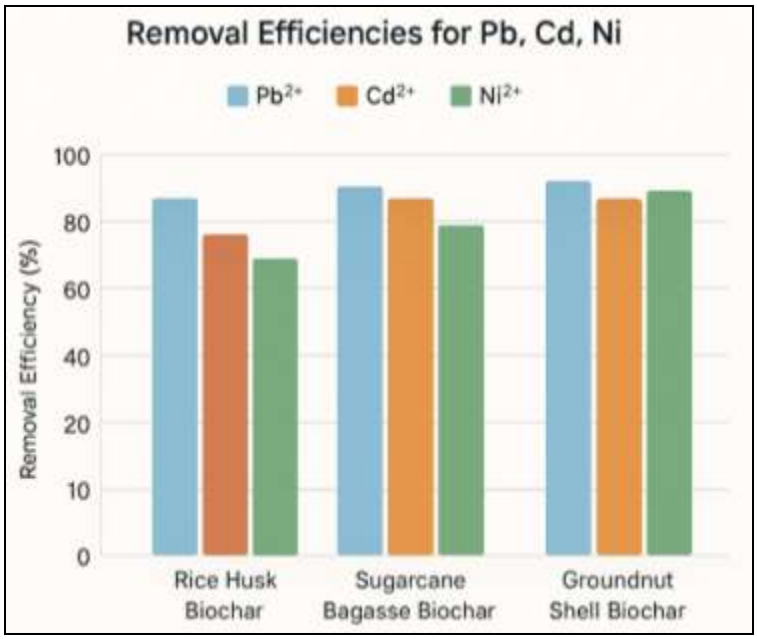
Table 4: ***Removal Efficiency (%) Under Optimized Conditions***

Biochar Type	**Pb^{2+}**	**Cd^{2+}**	**Ni^{2+}**
RHB	93.4	78.6	65.2
SBB	96.1	82.3	69.7
GSB	94.7	80.1	67.4

Sugarcane bagasse biochar was always superior to the other two because of its high surface area and high concentration of reactive functional groups. pH played a significant role in adsorption with the best performance registered at the range of pH 5 to 6. Competition by H+ ions to binding sites was detected below pH 4, whereas above pH 7 metals precipitated and complicated the mechanisms.

Raising the concentration of biochar also enhanced removal of metals showing diminishing returns with increasing concentration of biochar beyond 2 g/100 mL. Experiments of contact time revealed that there was rapid initial adsorption during the experiment which acclimated gradually at equilibrium at 120 minutes indicating a mixture of surface adsorption and intra-particle diffusion.

Figure 2*: Removal Efficiencies for Pb, Cd, Ni*



4.3 Adsorption Kinetics and Adsorption Isotherms

The kinetic model revealed that the adsorption of all the three metals was governed by the pseudo-second-order model, which implies that the process was chemisorbed. Plots of intra-particle diffusion intimated that resistance at the boundaries played an important role at the beginning of the adsorption process prior to entering the pores by diffusion.

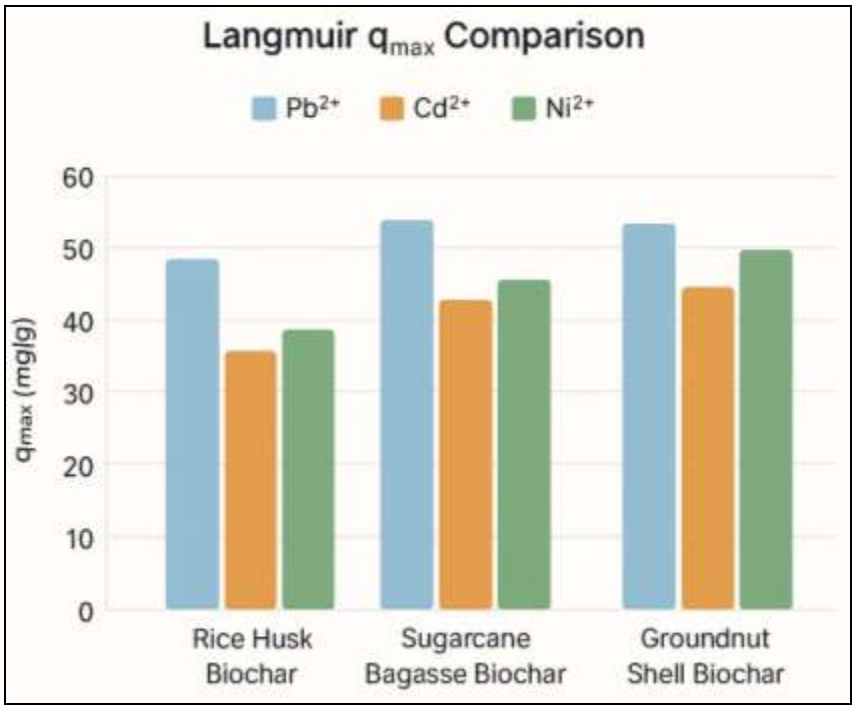
Equilibrium data has been used to model the Langmuir and Freundlich isotherms. The Langmuir model provided a better fit ($R^2 > 0.96$), indicating monolayer adsorption on homogeneous active sites. Sugarcane bagasse biochar had the greatest maximum adsorption capacities (qmax).

Table 5: *Langmuir Isotherm Parameters*

Biochar	Metal	qmax (mg/g)	KL (L/mg)	R^2
RHB	Pb^{2+}	48.2	0.221	0.964
SBB	Pb^{2+}	52.9	0.245	0.973
GSB	Pb^{2+}	50.7	0.238	0.968
RHB	Cd^{2+}	28.4	0.142	0.952
SBB	Cd^{2+}	32.1	0.156	0.961
GSB	Cd^{2+}	30.6	0.151	0.954

The increase in KL values of sugarcane bagasse biochar means that the affinity of binding to all the metals is higher.

Figure 3: ***Langmuir qmax Comparison***



4.4 Performance using Real Industrial Effluent

Effluent released by an electroplating plant with Cr, Ni and Pb was disposed of using SBB in optimized laboratory conditions. Elimination effectiveness was a bit less than in synthetic solutions as a result of competing ion and organic matter and however, significant:

Pb: 89.6%

Cr: 84.3%

Ni: 63.7%

These findings illustrate that green-synthesized biochar has a realistic application in the treatment of industrial wastes in water.

4.5 Regeneration and Reusability

Biochar that had been used five times could keep more than 70 per cent of its initial adsorption capacity. SBB maintained the highest stability (≈78%), followed by GSB (≈74%) and RHB (≈71%). Little structural degradation was noted which verified that biochar can be reused in treatment mechanisms.

5. Discussion

As the findings of this work show, Chinese synthesized biochar, obtained by using the agricultural waste, namely, rice husk, sugarcane bagasse, and groundnut shell, has a great potential in being used as the agent of removing the heavy metals contained in the industrial effluents. The differences in performance of the adsorption of biochars can be explained by the fact that they had varying structural, chemical and mineralogical properties all of which were influenced by the composition of the biomass used and the conditions used during pyrolysis.

Among the main observations, sugarcane bagasse biochar (SBB) turned out to be the most efficient as it always exhibited the highest removal efficiencies towards Pb^{2+}, Cd^{2+}, and Ni^{2+}. This is attributed to its large surface area as well as to its high pore structure besides a large number of oxygen carrying functional

groups. All these properties make it more effective in binding heavy metals through different mechanisms including surface complexation, electrostatic attraction and ion exchange. Conversely, rice husk biochar had a low amount of surface area but a high percentage of silica, which could ensure more binding by surface precipitation. The performance of groundnut shell biochar with its high fixed carbon and aromaticity was positively compared to SBB in offering structurally stable adsorption sites, although its performance was relatively lower that of SBB owing to the relatively smaller number of available pores.
The pattern in the adsorption affections was that of pseudo-second-order, which corresponded to the dominance of chemisorption throughout the entire biochars. This is consistent with earlier research yielding that surface chemical interactions, as opposed to simple physical adsorption are a significant contributor to the uptake of heavy-metal by biochar. In addition to this, the good adherence to the Langmuir isotherm model indicates monolayer adsorption on comparatively homogenous active sites. This is not only a significant discovery, as it suggests reproducible and uniform adsorption behavior, which is useful in the design of treatment systems.
Experiments on the treatment of actual industrial effluents indicated the experimental practicability of biochar, even though the removal efficiencies were at least marginally lower because of competing ions and the abundance of organic matter. This highlights the importance of additional optimization in the situation involving complex wastewater matrices. However, the observation that sugarcane bagasse biochar recorded removals of more than 80 percent of Pb and Cr in the real field conditions underscore its strength and application in an industrial context.
Biochar derived out of agricultural waste is further sustainable, according to regeneration studies. All biochars with the capacity of over 70 percent remained in the adsorption capacity after 5 cycles, which indicates a high level of structural integrity and reusability. This is not only lowering the operating costs of the long term but also the environmental foot prints as a result of generating less waste.
Comprehensively, the results confirm the idea of transforming agricultural residues into value-added products to clean the environment. Biomass cost of production is low, it is abundant, and there is a limited use of chemicals, which are in accordance with green synthesis values and the value of a circle economy. Although the present study has established the viability of biochar as a competent adsorbent, future directions of the research should focus on its hybrid biochar composites, modification by the help of environmentally friendly activators and modeling its performance in the context of a dynamic flow. These types of developments can also increase adsorption capacity and expand the range of applications to a greater number of pollutants.

6. Green Synthesis Framework Proposed

An effective and scalable system to greenly synthesize biochar is essential in converting agricultural waste into effective adsorbents that can be used in remediating heavy-metals. The innovative framework combines the low-energy processing, low chemical requirements, waste re-use, and the principles of the circular economy to make the environment and economy sustainable.
The framework starts with the feedstock selection (favouring agricultural residues which are available in large quantities e.g. rice husk, sugarcane bagasse, and groundnut shell). These biomasses have desirable lignocellulosic nature, native mineral constituents, and zero cost, and therefore it makes them good targets of large-scale transformation. The feedstocks are also processed in a simple manner that is; washed, dried, ground and sieved without the use of any chemical additives to uphold the green synthesis philosophy.

The second process is the thermochemical conversion that is eco friendly. Pyrolysis at moderate temperatures of (350-500ºC) is advisable because it consumes less energy and has the capacity of retaining functional group that aid in metal binding. This is supplemented by natural methods of activation like steam or CO_2 activation that increase porosity and surface area without forming any dangerous chemical wastes. High-moisture biomass can also be processed with hydrothermal carbonization, therefore, allowing energy-efficient processing at relatively low temperatures.

After the synthesis, characterization of the biochar is done to measure the functional groups, surface morphology, mineral composition, and structural stability. These parameters provide a basis of optimization to intended industrial uses. The biochar is used then in the wastewater treatment systems whereby it adsorbs the heavy metals by ion exchange, surface complexation, and microstructural activity. One of the features in the framework is the process of regeneration and reuse where mild solvents are used or thermal treatment is done to regenerate adsorption capacity with respect to several cycles. Lastly, spent biochar can also find use as a soil cure or immobilization agent, which will promote a waste-to-resource closed-loop method. Such holistic structure strengthens sustainability, lowers the environmental effects, and helps to manage industrial wastewater both in the rural and urban environment.

7. Conclusion

This paper shows that agricultural sector-based green-synthesized biochar is a very effective, sustainable and low-cost technology in removing heavy-metals in industrial effluents. The rice husk, sugarcane bagasse, and groundnut shells feedstocks are also capable of facilitating the valorization of waste products in addition to offering a consistent source of functional and porous carbon adsorbents. Sugarcane bagasse biochar showed the best adsorption behavior among tested materials owing to its high surface area and a high composition of functional groups although all biochars still had a good adsorbers behavior when optimized.

Kinetic and isotherm studies proved that the major mechanisms involved were chemisorption and monolayer adsorption describing the stability and predictability of the adsorption process. The biochars also showed good performance in actual industrial wastewater as they continued to have high removal efficiencies regardless of the presence of competing ions. Moreover, high regeneration capacity of the materials highlights that they are applicable to long term economic viable uses.

All in all, the results indicate the possibility to integrate agricultural-waste-derived biochar into the industrial water treatment systems as a more complex structure of green-technology and to make the system more environmentally inclusive towards a more comprehensive green-technology and the recursions of a circle strategy. Further development of the area of practical application of biochar-based remediation technologies will be imminent with future work that concentrates on hybrid composites, field-scale testing, and performance assessment in the long run.

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