Effect of Hydraulic Retention Time on the Performance and Cleaning Mechanisms of Coconut Biochar Filtration Systems for Wastewater Treatment

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ABSTRACT

Re-purposing wastewater is necessary to circumvent water shortage for vegetable farmers in urban areas and to reduce public health hazards associated with using contaminated water for irrigation. The study investigated the efficiency of 40 cm and 30 cm thick coconut biochar filtration systems in removing Cu, Pb, total coliform, and E. coli from wastewater at 24-, 48-, and 168-hour hydraulic retention times (HRT). Fourier Transform Infrared Spectroscopy analysis and Scanning Electron Microscopy imaging were used to characterise the biochar. Atomic Absorption Spectrophotometer (AAS) was used to analyse Cu and Pb while total coliform and E. coli were analysed using the incubation method. Characterization showed the properties of the biochar that enhances the removal of pollutants in wastewater. The optimal hydraulic retention time (HRT) was 168 hours, at which the biochar filtration systems achieved Pb removal efficiencies of up to 99.9%, Cu removal efficiencies of 100%, and Total Coliform removal efficiencies of up to 94.7%. However, the systems were ineffective in the removal of E. coli. This has implications for further research to explore double filtration systems for the removal of other parameters and emerging pollutants.

Keywords: Biochar filtration systems, Fourier Transform Infrared Spectroscopy (FTIR), Hydraulic retention time (HRT), Scanning Electron Microscopy (SEM), Surface morphology

1.0 INTRODUCTION

Biochar filtration systems are designed with bio-materials, mostly biowastes such as coconut coir, corn cobs, corn husks and rice husk in the environment as an adsorbent to remove pollutants from wastewater (Kumar et al., 2021). The use of wastewater for irrigation supplements rain-fed agriculture especially in urban and peri-urban areas. Thus, treatment of wastewater is necessary to reduce public health risks associated with eating vegetables irrigated with wastewater. Filtration systems are low-tech, low-cost well-suited systems for reducing organic load, pathogens and heavy metals in wastewater. Re-purposing biowastes and

and wastewater are key to achieving a circular economy (Möslinger et al., 2023).

Wastewater treatments methods include precipitation, ion exchange, and adsorption (Singh et al., 2021). Precipitation involves the removal of contaminants from wastewater by transforming them into insoluble solid particles (Saleh et al., 2022). Ion exchange improves wastewater quality by replacing contaminant ions with non-objectionable ones (Saravanan et al., 2021) and adsorption causes substances to adhere to materials particularly on solids (Enaime et al., 2020). Although these methods are highly effective, they are expensive, prone to fouling and clogging, have limited capacity, and require technical expertise.

Filtration systems reduce pollutant load by sieving and having contaminants settle on the media. Biofilm formed on the media enables the cleaning of the wastewater (King-Nyamador et al., 2021). The design characteristics of filtration systems influence the quality and efficiency of treatment. The design characteristics of slow sand filtration systems have been studied and well documented. The focus of this study is to test the efficiency of coconut coir biochar filtration systems by examining key operational parameters such as bed thickness, effective size, optimal hydraulic retention time (HRT) and the cleaning mechanism (Gupta et al., 2022).

Biochar is biowaste such as wood, crop residues which has been re-purposed, re-engineered and reused as an adsorbent, a porous, carbon-rich material for soil improvement, which is produced by heating biomass, in a low-oxygen environment by a controlled process called pyrolysis (Tomczyk et al., 2020). Sachan and Kumar (2022) reports that coconut biochar has a high adsorption capacity due to its high surface area, microporosity, and low ash content which influences its cleaning mechanism in wastewater. Biochar filtration systems allow water to flow through a bed of biochar, where contaminants are adsorbed onto the surface of the biochar particles. It is particularly advantageous for developing countries due to its multiple environmental and agronomic benefits, which distinguish it from other affordable water treatment methods (Gwenzi et al., 2015). It is low-cost, biodegradable, environmentally friendly, easy to produce and requires minimal maintenance. The system has high adsorption capacity leading to a high removal efficiency for a wide range of contaminants, including heavy metals, organic pollutants and pathogens.

The efficiency of these filtration systems is dependent on factors such as HRT, optimum bed thickness, effective size and cleaning mechanism has been extensively documented for slow sand filtration than for biochar filtration systems (Gupta et al., 2022). King-Nyamador et al., (2021) conducted a study to investigate and establish some design parameters namely bed depth and effective size and how they lead to the improvement in quality of treated wastewater. Previoous experiments and studies on biochar filtration systems have focused on the removal efficiency of physical and biological contaminants such as E.

coli and total coliform, however, not much has been explored on the design parameters and biochar characteristics that contribute to the removal efficiency (Enaime et al., 2020; Gupta et al., 2022) resulting in reduced efficiency and increased operating costs.

The HRT is the amount of time water spends in the filtration system, thus, the longer the HRT, the more time contaminants interact with biochar and get adsorbed, resulting in cleaner water (Waqas & Bilad, 2019). Chen et al., (2023) confirms that HRT is a critical factor in determining the efficiency of biochar filtration systems. Studying HRT and cleaning mechanisms helps to provide more insight into the design of biochar filtration systems by outlining the significant role these design parameters play in improving the overall treatment process. This is significant in the optimization of treatment efficiency, improvement in design, and validation of performance of biochar filtration systems (Chaukura et al., 2016). Wastewater reuse is recommended for irrigation especially in urban areas as it reduces over-reliance on treated water for watering crops, however, public health risks need to be minimised and therefore designing filtration systems from biowastes is helpful. Biochar filtration systems lead to reducing methane emission as waste from the environment is repurposed (Kaetzl et al., 2020; Perez-Mercado et al., 2019).

The cleaning mechanism of biochar filtration system involves physical, chemical and biological processes. The adsorption of contaminants onto the biochar particles is a physical process of attraction between the biochar surface and contaminants (Agboola & Benson, 2021; Kaetzl et al., 2020). This attraction is due to the chemical characteristics of the biochar, such as its surface chemistry and functional groups (Appiah et al., 2023; Agboola & Benson, 2021). Biochar also provides a surface for microbial growth or biofilm called Schmutzecke which removes contaminants through biological processes such as biodegradation and bio-reduction by the formation of the contaminants (Appiah et al., 2023; Agboola & Benson, 2021; King-Nyamador et al., 2021; Kaetzl et al., 2020).

This study focuses on determining the optimal HRT and the biochar characteristics for the enhancement of pollutants removal from wastewater. The design and operation of biochar-based wastewater treatment systems will be significantly impacted by the findings (Enaime et al., 2020; Gupta et al., 2022; Gwenzi et al., 2015).

The use of coconut biochar filtration systems for wastewater treatment has the potential to generate a cost-effective, environmentally friendly, and efficient solution to the challenges of wastewater pollution and contamination. Additionally, the reduction of waste in the environment makes the use of coconut biochar an effective solid waste management prospect which also contributes to reduction in carbon emissions. This study again contributes to circular economy concepts that aims to minimize waste and maximize resource utilization through closed-loop sytems (Babbitt et al., 2018).

2.0 METHOD

2.1 Description of study site

Wastewater was obtained from a nearby stream around Okponglo, near Nii-Kwablah Ashong Avenue in the Greater Accra region of Ghana (5°38'12.8"N, 0°10'31.1"W). Runoff water collected through drains, flow from different areas into streams, which the residents rely on for small-scale cultivation of crops such as cabbage, okra, lettuce and tomatoes.

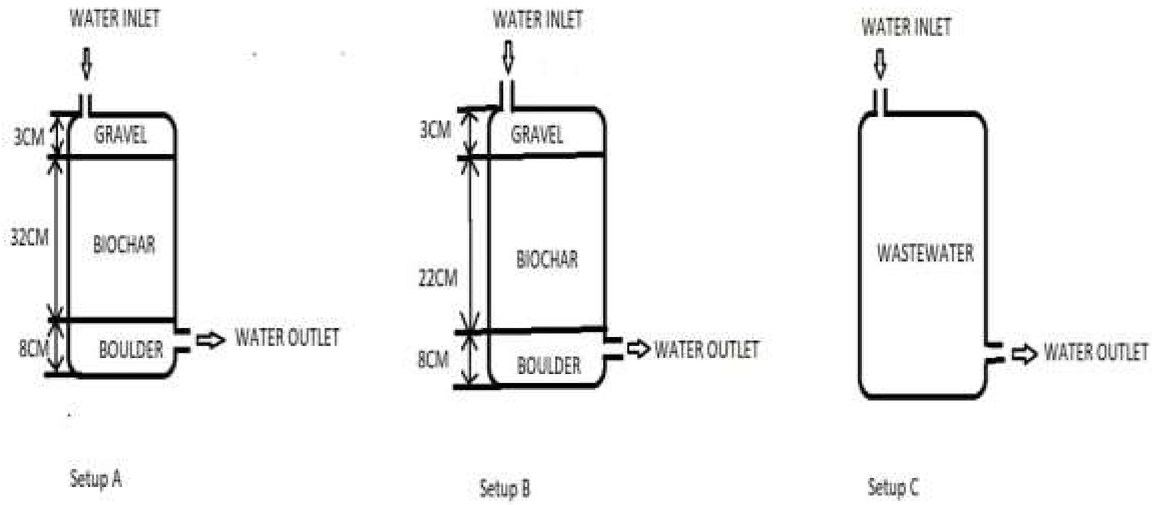
Figure 1: Picture of Study site

2.2 Preparation of Adsorbent

Coconut coir was procured and dried for approximately six weeks at the Agricultural Engineering workshop. They were sorted into two distinct sizes of average diameters; 21 cm and 5 cm. Representative samples were measured accurately using a thread and a meter rule. Biochar preparation involved pyrolysis of coconut coir at the School of Engineering Sciences, University of Ghana. A controlled temperature of 405℃ was maintained for 2 to 3 hours. After cooling, biochar was packed into sacks for transportation.

2.3 Materials and Experimental Setup

The experimental setup was designed at the Agricultural Engineering workshop using three identical barrels labelled A, B, and C. Barrels had a height of 91 cm, diameter of 53 cm and a volume of 200 litres. Setup A had a 40 cm layer of biochar beneath a 10 cm layer of gravel, while Setup B had a 30 cm layer of biochar below a 10 cm layer of gravel. Setup C served as the control experiment with no biochar or gravel. Setup A has an 8 cm layer biochar with an average diameter of 21.2 cm at the bottom, and a 32 cm layer with an average diameter of 5.24 cm above. Setup B followed a similar arrangement. The tap at the base of all three barrels facilitated water sampling for testing and for controlling effluent flow rate. The filtration system was designed for a vertical, downward flow of wastewater through the filter media by gravity. This approach enhanced the contact between the



A

B

Figure 2: A. Schematic diagram of experimental setup B. Experimental Setup

wastewater and the biochar which improved the efficiency of the system in removing contaminants. The vertical flow design was also to facilitate the uniform distribution of wastewater for the optimization of HRT critical for effective filtration. The design promoted better filtration dynamics by allowing pollutants to be trapped within the porous structure of the biochar while maintaining steady flow rates.

2.4 Filtration Process and Wastewater Sampling

Water from the study area was transported to the Agricultural Engineering workshop. Setups A and B were filled until the water was above the gravel layer; Setup C served as the control. Water samples were collected after 24 hours, 48 hours, and 168 hours (1 week) in 500 ml plastic bottles and sent to the Ecology laboratory at University of Ghana for testing. Samples were stored in sterilised 500 ml plastic bottles and placed in an ice chest to maintain a consistent temperature at 4°C and minimize exposure to sunlight and reduce the risk of bacterial growth.

For heavy metal analysis, Atomic Absorption Spectrophotometer (AAS) was used to analyse Cu and Pb. 2 ml of HNO_3 was added to the samples lowering the pH, keeping the metals in their ironic (dissolved) state and preventing precipitation (Akram et al., 2015). HNO_3 is particularly suitable because it is a strong oxidising acid and does not introduce interfering ions and effectively dissolves most metals. This is in accordance with guidelines and standard protocols recommended by the EPA and ISO 5667-3 (Water Quality – Sampling) stating that water samples intended for heavy metal analysis be acidified to a pH of less than 2 with HNO_3. Biological contaminants signified by total coliform and E. coli were tested using membrane filtration method where the diluted sample is filtered with a membrane and on a selective agar medium and incubated for 24 hours at a temperature of 35 °C (USEPA, 2000). Escherichia coli (E. coli) was selected as an indicator organism due to its widespread use in evaluating faecal contamination in water and wastewater systems. The organism serves as a reliable indicator of pathogenic contamination and treatment performance because it originates from the intestinal tract of warm-blooded animals and is commonly associated with wastewater pollution.

2.5 Characterization of Biochar Sample

To understand the cleaning mechanism of wastewater, the chemical and physical characterization of biochar was conducted using Transform Infrared Spectroscopy (FTIR) and Scanning Electron Microscopy (SEM) analysis respectively (Kaetzl et al., 2020; Appiah et al., 2023). Biochar samples were pulverised, and FTIR (Alpha II Spectrometer) was used at the School of Engineering Sciences, University of Ghana to identify the functional groups. Subsequently, biochar samples were also prepared and analysed at the Earth Science Department of the University of Ghana using SEM (PhenomTM ProX Desktop).

2.6 Determination of Hydraulic Retention Time

The process of determining the hydraulic retention time for the coconut coir filtration system involved setting up the system for Setups A, B, and C at intervals of 24, 48, and 168 hours was determined using flow rates and filter bed volume as shown below:

$$HRT(hours\ or\ days) = \frac{Volume\ of\ filter\ bed\ (m^3 or\ litres)}{Flow\ Rate\ \left(\frac{m^3}{hour} or \frac{litres}{hour}\right)}$$

2.7 Statistical Method

To measure significant differences in the percentage removal of pollutants from wastewater, a one-way Analysis of Variance (ANOVA) was employed at significance level (α) of 0.05. The null hypothesis for the wastewater quality analysis is in two parts: first, there is no significant difference among the percentage removal of setups A, B and C which have bed depths of 30 cm and 40 cm respectively. Second, there is no significant difference among the percentage removal at HRTs of 24, 48 and 168 hours. As with all ANOVA tests, the null hypothesis is rejected if Fcalculated > Fcritical else we fail to reject (or accept). With respect to p-values, the null hypothesis is rejected if *p-value<alpha=0.05* for the test to be statistically significant.

3.0 RESULTS AND DISCUSSION

3.1 Wastewater Quality Analysis

The results of wastewater quality analysis of heavy metals, biological contaminants, physical and chemical characterisation of biochar as well as the statistical analysis of the efficiency of the biochar filtration system are presented in this section. Table 1 gives results of the analysis of heavy metals in the wastewater before and after treatment. There was significant reduction in the heavy metal concentration even though the influent levels were lower than the FAO (2004) limits for irrigation. With varying HRTs, all setups consistently showed high removal efficiencies of 92% for Pb and 100% for Cu. HRT of one week resulted in nearly 100% removal. In general, the results showed that Setup A which is 40 cm thick bed shows a lower removal efficiency than Setup B of 30 cm bed thickness. Previous work with slow sand filtration systems showed contrary results where higher bed thickness resulted in higher removal efficiency (King-Nyamador et al., (2021).

It was thus expected that a 40 cm thick biochar bed had more media and should have more biofilm formed on media to reduce pollutant level better than the 30 cm thick bed. Biochar filtration systems must therefore be further studied as results are inconsistent with lessons learnt from slow sand filtration systems. The better performance of the

Table 1: Results of Heavy Metals Analysis and Biological Contaminants

Time (hours)	Setup	Heavy metals	Influent (mg/L)	Effluent (mg/L)	FAO (2004) (mg/L)	Biological Contaminant	Influent (cfu/mL)	Effluent (cfu/mL)	FAO (2004) (cfu/mL)
24	A	Pb	0.993	0.081	5	Total Coliform	3330	2210	100
		Cu	0.021	0	0.2	E. Coli	75	135	10
	B	Pb	0.993	0.045	5	Total Coliform	3330	1270	100
		Cu	0.021	0.006	0.2	E. Coli	75	160	10
	C	Pb	0.993	0.282	5	Total Coliform	3330	610	100
		Cu	0.021	0	0.2	E. Coli	75	100	10
48	A	Pb	0.993	0.001	5	Total Coliform	3330	1450	100
		Cu	0.021	0	0.2	E. Coli	75	310	10
	B	Pb	0.993	0.004	5	Total Coliform	3330	1115	100
		Cu	0.021	0	0.2	E. Coli	75	65	10
	C	Pb	0.993	0.001	5	Total Coliform	3330	120	100
		Cu	0.021	0	0.2	E. Coli	75	75	10
168	A	Pb	0.993	0.002	5	Total Coliform	3330	185	100
		Cu	0.021	0	0.2	E. Coli	75	120	10
	B	Pb	0.993	0.001	5	Total Coliform	3330	175	100
		Cu	0.021	0	0.2	E. Coli	75	50	10
	C	Pb	0.993	0.001	5	Total Coliform	3330	125	100
		Cu	0.021	0	0.2	E. Coli	75	60	10

30 cm bed compared to the 40 cm bed may be associated with improved flow distribution and reduced clogging within the filter media. Excessively thick biochar layers may reduce hydraulic conductivity and create preferential flow pathways that limit effective contaminant-media interaction (Liu et al., 2016).

With biological contaminants, there is a steady reduction in the removal of total coliform after 24 48 and 168 hours which is expected as pollutants have a longer contact time with media (even though the effluent quality exceeds FAO (2004) limits). E. coli however, unexpectedly increased after 24- and 48-hours HRT appearing as though the system is more conducive for E. coli to increase rather than decrease as one would have expected. This is difficult to explain because E. coli counts are usually expected to increase only when the media becomes saturated. The flow rate can however be further studied to rule out the possibility. After 168-hours however, E. coli levels reduced in Setup B (30 cm) and in the control but not in Setup A. Slow sand filtration systems consistently showed a better performance with a 40 cm bed than the 30 cm one which leaves room for more studies on biochar filtration systems.

On the other hand, heavy metals, Cu and Pb which were tested, the levels reduced consistently for all setups even in Setup C which is the control. The consistent reduction in Cu and Pb levels with increasing HRT implies they break down or precipitate in wastewater when allowed to settle or exposed to open air. after HRT of 168 hours where there was a minimal reduction. The concentration of E. coli in the effluent exceeded FAO limits implying that coconut biochar can only improve wastewater after about a week. As with the heavy metal removal, Setup B still performs unexpectedly better than setup A. A summary of the removal efficiency of both heavy metals and biological contaminants is presented in Table 2. As explained earlier, Setup B which has a bed thickness of 30 cm performed better than setup A of 40 cm in the removal of all contaminants tested. The study is however not conclusive on bed thickness as a higher bed thickness did not perform better. According to King-Nyamador et al., (2021), 40 cm minimum bed depth is adequate for contaminant removal in the slow sand filtration system but inconsistent in biochar filtration system. As indicated earlier bed thickness for biochar filtration system needs to be further studied. The results show that for the coconut biochar filtration system, HRT has a great influence on the treatment efficiency. The performance of the coconut biochar filtration system was significantly enhanced when the hydraulic retention time was increased to 168 hours. The improved performance observed at higher hydraulic retention times may be attributed to prolonged contact between the wastewater and the biochar media. Longer retention periods increase the interaction time available for adsorption, sedimentation, diffusion, and microbial activity within the porous structure of the biochar. This enhances the adsorption of heavy metals onto active functional groups and allows greater settling of suspended contaminants. Additionally, extended HRT may improve biofilm activity on the biochar surface, contributing to increased degradation and removal of pollutants.

Similar observations have been reported in biochar-based and slow sand filtration systems where longer retention periods improved contaminant removal efficiency (Gupta et al., 2022; King-Nyamador et al., 2021). The control experiment (setup C) without any filter bed surprisingly improved consistently with increasing HRTs. The decrease in concentration of contaminants in setup C as shown in Table 1 may be due to sedimentation, adsorption onto the filtration tank and oxidation over wastewater residence time (King-Nyamador et al., 2021).

Table 2: Percent removal of contaminants

Setup	HRT (hours)	Percentage Removal			
		Pb	Cu	Total Coliform	E. Coli
A	5.6	91.876	100	33.63	-80
	4.27	99.899	100	56.46	-313.33
	4.64	99.799	100	94.44	-60
B	5.98	95.502	71.429	61.86	-113.33
	4.34	99.631	100	66.52	13.33
	4.5	99.899	100	94.74	33.33
C	6.51	71.601	100	81.68	-33.33
	4.28	99.899	100	96.4	0
	3.77	99.899	100	96.25	20

3.2 Statistical Analysis

The results of a one-way Analysis of Variance (ANOVA) performed to establish the significance in percentage removal of contaminants of different biochar bed thicknesses (30 cm, 40 cm and the control) and HRT on the effective removal of contaminants from the wastewater is presented in Table 3. It can be seen from all setups that p-values for the removal of heavy metals and total coliforms, obtained from the analysis, are lower than the significant level of 0.05. This implies a significant difference in percentage removal of heavy metals among the setups, providing strong evidence to reject the null hypothesis. This suggest that the removal efficiency is affected by the changes in HRT and the bed thickness as heavy metal removal improved with increasing HRT.

Table 2: ANOVA analysis for Heavy Metals and Biological contaminants

HEAVY METALS	Setup	Parameters	*Source of Variation*	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
	A	Pb	Between Groups	12794.1	1	12794.1	1181.2	4.28×10^{-6}	7.7
			Within Groups	43.3	4	10.8			
			Total	12837.4	5				
		Cu	Between Groups	13584.1	1	13584.1	57653.4	1.8×10^{-9}	7.7
			Within Groups	0.9	4	0.2			
			Total	13585.0	5				
	B	Pb	Between Groups	13086.5	1	13086.5	3796.9	4.15×10^{-7}	7.7
			Within Groups	13.8	4	3.4			
			Total	13100.3	5				
		Cu	Between Groups	10974.7	1	10974.7	80.4	0.0	7.7
			Within Groups	545.8	4	136.5			
			Total	11520.5	5				
	C	Pb	Between Groups	10994.38	1	10994.38	81.7	0.0	7.7
			Within Groups	538.0981	4	134.5245			
			Total	11532.48	5				
		Cu	Between Groups	13579.33	1	13579.33	12790.0	3.67×10^{-8}	7.7
			Within Groups	4.246867	4	1.061717			
			Total	13583.58	5				
BIOLOGICAL CONTAMINANTS	A	E. Coli	Between Groups	36479.0	1	36479.0	3.7	0.1	7.7
			Within Groups	39673.9	4	9918.5			
			Total	76153.0	5				
		Total Coliform	Between Groups	4817.8	1.0	4817.8	10.2	0.0	7.7
			Within Groups	1888.1	4.0	472.0			
			Total	6705.9	5.0				
	B	E. Coli	Between Groups	1106.8	1.0	1106.8	0.3	0.6	7.7
			Within Groups	12652.3	4.0	3163.1			
			Total	13759.0	5.0				
		Total Coliform	Between Groups	7231.5	1.0	7231.5	45.6	0.0	7.7
			Within Groups	634.7	4.0	158.7			
			Total	7866.2	5.0				
	C	E. Coli	Between Groups	129.642	1.0	129.642	0.4	0.6	7.7
			Within Groups	1455.906	4.0	363.9765			
			Total	1585.548	5.0				
		Total Coliform	Between Groups	11246.74	1.0	11246.74	305.5	6.29×10^{-5}	7.7
			Within Groups	147.2421	4.0	36.81053			
			Total	11393.98	5.0				

With respect to bed thickness, *p-values* indicate a significant difference in the removal efficiency suggesting that we reject the null hypothesis, suggesting that heavy metal removal increases with bed thickness though wastewater quality analysis shows otherwise. For biological contaminants, *p-values* for total coliform removal with varying HRTs indicates a significant difference between the two setups and the control. The null hypothesis is also rejected in this case. Consistently, a positive trend in percentage removal is observed with increasing HRT (Tunçsiper et al., 2012).

On the other hand, *E. coli* removal for all setups gave higher *p-values* than the significance level (0.05). This indicates that there is no significant difference, and we fail to reject the null hypothesis in *E. coli* removal among the setups. The negative percentage removal (as shown in table 4), suggest that *E. coli* removal is not effective. *E. coli.* removal from biochar treatment systems and the influence of bed thickness in reducing contaminant load will be further studied.

3.3 Cleaning Mechanism

An understanding of the cleaning mechanism of the coconut biochar filtration system was investigated by examining the physical and chemical properties of the biochar that permit adsorption. FTIR and SEM techniques were used to investigate the surface characteristics of biochar. The results are presented and analysed in the next sections.

3.3.1 FTIR Characterization

The FTIR results of the coconut biochar sample before and after filtration provided insights into the changes in the functional groups and their potential implications for the cleaning mechanism of the filtration system.

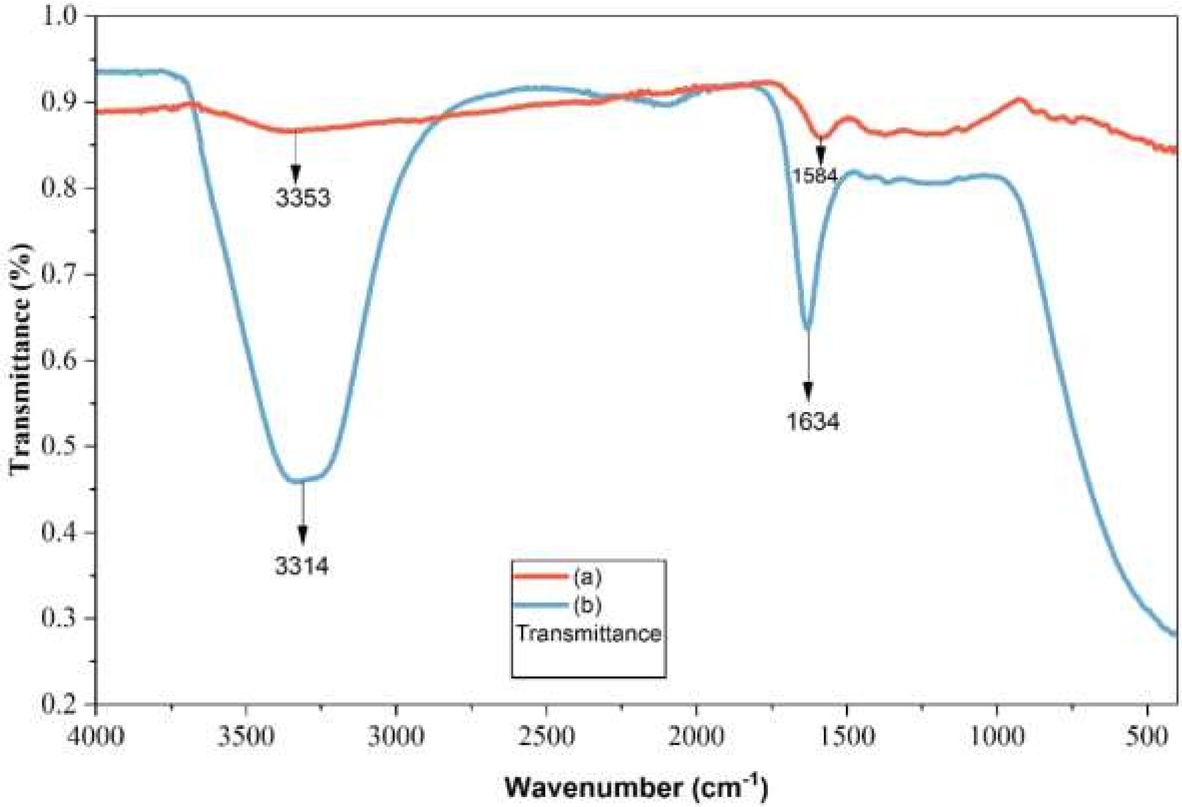


Figure 3: FTIR spectra of biochar sample before (a) and after adsorption (b)

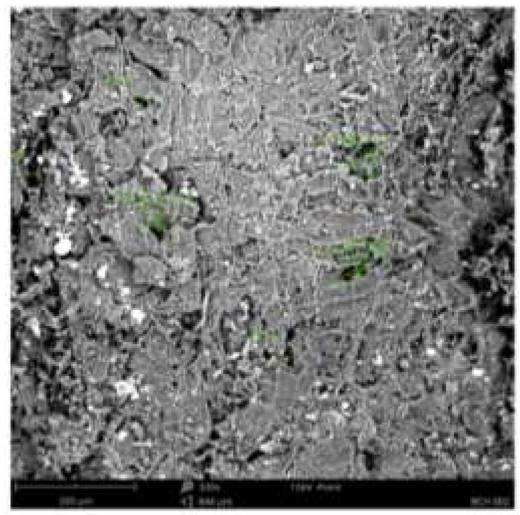
The spectrum of the biochar sample shown in Figure 3 (a) gives characteristic peaks related to specific functional groups. According to the Infrared Spectroscopy Absorption table from the University of California Santa Cruz, the presence of a peak at 3353 cm-1 suggests the existence of an O-H stretching vibration, which indicates the presence of hydroxyl (-OH) groups. The broad peak indicates hydrogen bonding, suggesting interactions between the biochar surface and water molecules and play a role in the adsorption of contaminants (Poissier et al., 2011). Similar studies conducted on rice husk (RH) and orange-peel powder (OPP) by Appiah et al., (2023) for arsenic removal showed a peak at 3400 cm-1 for RH, representing OH stretching. OPP also exhibited a peak between 3324 cm-1 and 3365 cm-1, indicating bonded OH groups (Appiah et al., 2023). These findings collectively contribute to a deeper understanding of adsorption processes and molecular interactions in the context of contaminant removal from wastewater.

Another noteworthy peak is observed at 1584 cm-1, indicating the presence of a C=O stretching vibration. This peak corresponds to beta diketones (enolic) functional groups which are known to exhibit adsorption properties and can capture and remove certain contaminants from the wastewater

(Hansen, 2021). After filtration, the spectrum exhibited similar functional groups as observed in **Error! Not a valid bookmark self-reference.** (b). The presence of the O-H stretching peak (3400 – 3200 cm^{-1}) suggests that the hydrogen bonding capability of the biochar is retained even after the filtration process. This indicates that the biochar is capable of being used for a long time before being discarded. It also indicates the ability to be used to treat a more heavily polluted water than the sample in this study. The presence of the C=O stretching peak (1640 – 1540 cm^{-1}) also suggests the persistence of beta diketones (enolic) functional groups and further indicates that the biochar retains its adsorption potential for capturing certain contaminants (Kumar Biswas et al., 2014).

3.4.2 SEM Characterization

The SEM characterization provided details on the surface characteristics like porosity and topology of the biochar sample as shown by the SEM imaging in **Error! Reference source not found.** (A & B). The images offer a comprehensive view of the biochar's surface features, including its roughness, texture, and structural heterogeneity. The topology plays a crucial role in the adsorption process as it shows the available surface area for interaction with contaminations in water. A rougher surface with irregularities and protrusions provide a larger surface area, facilitating adsorption by offering more active sites for attachment and binding of pollutants (Agboola & Benson, 2021). The structural heterogeneity shows structural variations on the surface of the biochar, manifested as racks, fissures, or unevenness. This contributes to an increased surface area and also altered the flow of contaminants within the biochar material.



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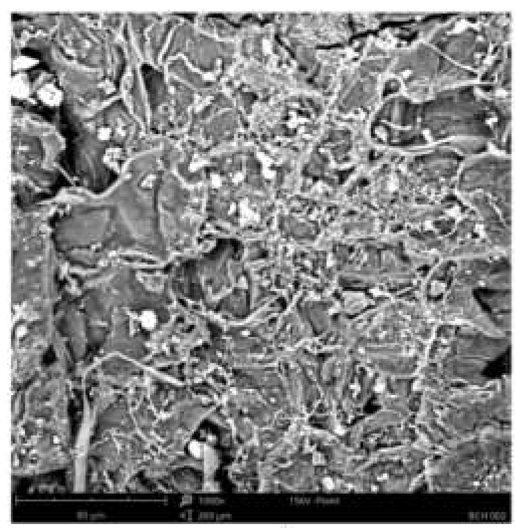

B

Figure 4: SEM images of biochar sample

Furthermore, the SEM images reveal the characterization and evaluation of pore sizes, pore volume, and pore distribution within the biochar (see Figure 4A). Pores of different size ranges were observed on the surface of the biochar as mesopores (2 – 50 µm) and macropores (greater than 50 µm). The presence of these pores contributes to the increased surface area and consequently, enhanced adsorption capability. Mesopores and macropores may accommodate bulky contaminants, while smaller-sized pores are beneficial for the adsorption of molecules or ions with specific dimensions. Also, the specific pore size distribution can influence the kinetics of adsorption. Pores of varying sizes can facilitate faster or slower diffusion of contaminants into the adsorbent material (Appiah et al., 2023).

4.0 CONCLUSION

This study demonstrated the potential of coconut biochar filtration systems for improving wastewater quality for irrigation. The systems showed high removal efficiencies for Pb, Cu, and total coliform, particularly at longer hydraulic retention times, with the 30 cm biochar bed generally outperforming the 40 cm bed. However, inconsistent *E. coli* removal indicates the need for further optimisation of the filtration system. FTIR and SEM analyses confirmed the presence of functional groups and porous surface structures that enhanced adsorption and contaminant removal. Future studies should investigate combined or multi-stage filtration systems to improve microbial removal efficiency and overall treatment performance.

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