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Evaluating the effectiveness of sugarcane waste biochar in the purification of greywater

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ABSTRACT

The study investigated effectiveness of sugarcane waste biochar as a sustainable material for purifying greywater to address environmental pollution and enhance water recycling. Biochar was produced by heating sugarcane waste at 500°C, with half of it activated using potassium hydroxide to enhance adsorption. X-ray fluorescence, X-ray diffraction and Fourier transform infrared spectroscopy were used to characterise the biochar structure. Greywater samples obtained from the kitchen, bathroom and carwash were purified by filtering 100 mL of samples through 10 g of biochar for 5 minutes. The activated and inactivated biochar achieved 92–96% and 80–87% removal efficiency of lead (II) ions, respectively. Chromium (VI) ions removal ranged from 84–92% and 82–86% with activated and inactivated biochar, respectively. Activated biochar removed 76–77% of oil and grease compared to 51–57% for inactivated biochar. Both biochar increased the pH levels, with activated biochar causing a more rise by 63–73%. Total suspended solids removal efficiencies were 21–34% and 40–54% in inactivated and activated biochar, respectively. Slight decrease in sodium dodecyl sulphate detergent, electrical conductivity and total dissolved solids was observed for both biochar. There was significant difference between the purification efficiency of inactivated and activated biochar shown by the |t| statistic values which were above t4 critical value of 2.78 (P = 0.05). Based on the study findings, activated sugarcane biochar was reliable for greywater treatment, especially the removal of heavy metal pollutants, oil and grease.

Introduction

Greywater is wastewater generated from households but does not include wastewater from toilets. Improper disposal and inadequate treatment of domestic wastewater contribute significantly to water pollution, endangering aquatic ecosystems and human health (*Awaleh et al.*, 2014). Carwashes generate a lot of wastewaters, which contribute to environmental pollution as the wastewater flows into the environment without any control or modifications (Firdaus, 2013). Biochar is a charcoal-like substance made by burning organic material from agricultural wastes in a controlled process called pyrolysis (Aly, 2016). Sugarcane biochar is used as an alternative material for water filtration because it is cheaper than other types of filters, has boundless supply of

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carbon materials, it is grown in many areas of the country and we get to utilise waste from sugarcane (*Goscianska et al*., 2015).

Sugarcane bagasse, a byproduct waste of the sugar industry, is abundantly available and often under-utilised, leading to waste management challenges. Converting sugarcane bagasse into biochar offers a promising approach to address these issues. Biochar, derived from the pyrolysis of organic waste, has demonstrated significant potential in a range of environmental applications, particularly in the purification of water. (*Goscianska et al*., 2015).

Sugarcane biochar has a great deal of potential for treating greywater because of its extraordinary physical and chemical characteristics. The adsorption capability, porosity, and high surface area of this material enable it to effectively remove organic debris, oils, detergents, and trace pollutants from home sources such as washing machines, sinks, and showers from greywater (*Bernd et al*., 2013). The high surface area and porous structure of sugarcane biochar allow it to efficiently absorb organic pollutants from greywater. Dissolved organic carbon (DOC), which is made up of a variety of organic molecules that pollute water and harm aquatic ecosystems if left untreated, can be eliminated by using biochar, according to studies. Biochar's high carbon content which frequently exceeds 60% improves its capacity to adsorb and retain organic molecules (*Ruxandra et al*., 2020).

Sugarcane biochar is also effective in adsorbing heavy metals and reducing microbial contamination. By interacting with metal ions, its surface functional groups hydroxyl, carboxyl, and carbonyl groups, allow heavy metals like lead, cadmium, and zinc to be removed from greywater. Furthermore, because of its adsorption capability and its antibacterial qualities, biochar can lower pathogen levels, adding an extra degree of security to greywater reuse applications (Lehmann & Joseph, 2015). Sugarcane biochar's porous nature allows it to hold onto water, increasing its filtration system efficiency. Greywater treatment can be achieved more effectively by using biochar to enhance the hydraulic properties of the filter material in biofilters or built wetlands. Better pollutant removal is made possible by its capacity to hold onto water while allowing for gradual filtration, which allows direct and prolonged contact between the biochar material and greywater (Aly, 2016). This study investigated the use of sugarcane waste biochar as a sustainable material for purifying greywater from kitchen, bathroom, and carwash sources. The work underscores the potential use of sugarcane biochar to address environmental pollution challenges and enhance water recycling.

Materials and Methods

Collection of Greywater Samples

Three different types of greywater samples (kitchen, bathroom and carwash) were collected from various sources around the Meru University of science and Technology. The Samples were carefully collected in one-litre polypropylene bottles, pre-acid washed to eliminate any potential sources of external contamination. Three samples were taken in each case for purification and analysis in the laboratory.

Preparation and Characterisation of Sugarcane Biochar

The pieces of sugarcane waste (bagasse) were washed thoroughly with distilled water before being dried out in an oven for 24 hours. The dried pieces were then divided into two batches for inactivated and activated biochar preparation. For inactivated biochar, one batch underwent pyrolysis in a kiln at 500°C for 3 hours, followed by a 24-hour cooling period in a desiccator. The second batch was activated using potassium hydroxide (KOH) pellets in a ratio of 2:1 (Sugarcane: KOH). This was accomplished by soaking for four hours and baking dry for 12 hours at 150°C. The chemically activated sugarcane then underwent pyrolysis in a kiln at 500°C for 3 hours followed by a 24-hour cooling period in a desiccator. After which rinsing in distilled water and 0.1 M hydrochloric acid was done until the washing was free of base medium and the pH fell to 5. Then dried in an oven at 105°C for 12 hours and crushed into powder form using mortar and pestle (*Jangkorn et al*., 2011). Sugarcane biochar structure was characterised using X-ray diffraction (XRD), X-ray fluorescence (XRF), and Fourier transform infrared (FTIR) spectroscopy.

Purification of Greywater

Water samples measuring 100 mL were passed through 10 g of biochar for 5 minutes using a pump. Physical and chemical properties of greywater were analysed in turn prior and after the purification process to determine the efficiency of each type of biochar.

Physicochemical Analysis of Greywater

Physical properties analysed were total suspended solids (TSS), total dissolved solids (TDS), electrical conductivity (EC) and pH while chemical properties included chromium (VI) and lead (II) ions (heavy metals), detergent (sodium dodecyl sulphate), oil and grease.

Total Suspended Solids (TSS)

A clean, pre-dried filter paper was first prepared, and its original mass determined by weighing it using an analytical balance. A gravity filtration setup was used to filter 100 mL of the greywater sample via the filter paper. After filtration, the filter paper that contained the suspended solids was carefully taken out, dried at 103 to 105°C in a laboratory oven to maintain a constant weight, and then weighed again. The weight difference between the filter paper before and after filtering volume, was used to determine the TSS concentration (APHA, 2017). The same procedure was carried out for the untreated greywater.

Total Dissolved Solids (TDS)

TDS was measured using a multiparameter meter. The conductivity probe of the multi-parameter meter was rinsed with distilled water to ensure there were no contaminants affecting the measurement. The conductivity probe was immersed in the water sample, ensuring that the TDS sensor was completely submerged without touching the sides or bottom of the container. The reading was allowed to stabilise, which took up to two minutes. Once the value on the display remained steady, the TDS measurement was recorded.

Electrical Conductivity (EC)

The conductivity probe of the multiparameter meter was rinsed with distilled water and then calibrated KCl standards with 84 µS/cm, 1413 µS/cm, and 12.88 mS/cm conductivity range. The conductivity probe was submerged into the water sample and allowed a few moments for the reading to stabilise. The reading was recorded. Analysis of EC in the samples was carried out before and after treatment with each sugarcane waste biochar.

pH Measurement

The pH meter was calibrated using standard buffer solutions of 4.01, 7.0 and 10.0 pH values. The pH electrode was immersed into the filtered water sample. Sufficient time was allowed for the pH reading to stabilise, in a few seconds to a minute (*Dehghani et al*., 2018). The pH reading displayed on the pH meter was recorded.

Lead (II) Ions and Chromium (VI) (Heavy Metals)

The samples were spiked with known amounts of lead (Pb) ions and chromium (Cr). A 100 mL of each water sampled was passed through 10 g of biochar for 5 minutes. Lead (II) ions and Chromium (VI) were determined by atomic absorption spectroscopy (AAS) method after instrument calibration with the Lead nitrate and Chromium nitrate salts. The calibration standards ranging from 10, 20, 30 and 40 ppm were prepared for Pb2+ ions and 2, 4, 6 and 8 ppm for Cr6+. The absorbance was measured at 283.3 nm and 357.9 nm for Pb2+ and Cr6+, respectively.

Analyses of heavy metal Pb2+ and Cr6+ ions present in the samples were carried out before and after sample treatment with inactivated and activated sugarcane waste biochar.

Sodium Dodecyl Sulphate Detergent

A 100 mL water sample was passed through 10 g of biochar for 5 minutes. A 1000 ppm stock solution of sodium dodecyl (lauryl) sulphate standard was prepared in 1 L solution using deionised water. A 100 ppm working solutions was prepared from the stock solutions by serial dilution. Then 0.2, 0.4, 0.6, 0.8 and 1 ppm calibration standard solutions were prepared from the working solutions by serial dilution.

A 20.0 mL of each calibration standard solution was added into 50 mL plastic beaker and then 10.0 mL chloroform and 200 µL methylene blue solution were added. The mixture was oscillated for 1 minute. The mixture was left for layering to take place and the upper solution sucked out. The UV-VIS spectrometer was set to zero using chloroform. The absorbance of the bottom extraction solution at 650 nm wavelength was measured to obtain a calibration graph.

A 20.0 mL of each water sample was added into 50 mL plastic beaker then 10. 0 mL chloroform and 200 µL methylene blue solution was added. The mixture was oscillated for 1 minute. The mixture was left for layering to take place and suck out the upper solution. The instrument was set to zero using chloroform. The absorbance of the bottom extraction solution at 650 nm wavelength was measured. Concentration of detergent in the samples was established from the calibration curve. The samples were diluted with appropriate dilution factor if the absorbance was higher than that obtained for 10 ppm standard, and multiplied with the concentrations measured with the respective dilution factors.

Oil and Grease

A 100 mL of the greywater sample was measured and poured into the separating funnel. 1 mL of dilute hydrochloric acid (1:1) was added to the water to clear any suspended solids. A 20 mL of petroleum ether was added to the solution. The solution in the separating funnel was shaken to mix properly. The lid was opened for any gas formed to escape. The mixture was allowed to settle for 20 minutes. The water below the oil layer was drained into a beaker. All the oil content was discarded into the petri-dish. The heating mantle was pre-heated. The petri-dish was placed in the heating mantle to evaporate the water and solvent to be left with the oil content. The petri-dish was allowed to cool down at room temperature. The final weight of the petri-dish was measured and noted. The same procedure was repeated for the purified greywater. The concentration of oil and grease was calculated as follows:

$$Oil\ and\ Grease\ \left(\frac{mg}{L}\right) = \frac{(\mathrm{Wf-Wi})\ \times 1000)}{Vsample} \qquad (1)$$

Where, Wf = *final weight of the petri-dish containing oil and grease (mg)*

Wi = weight of empty petri-dish (mg)

Vsample = volume of sample (mL)

Results and Discussion

X-ray Fluorescence (XRF) Characterisation of Biochar

The elemental composition of activated and inactivated biochar using X-ray fluorescence spectrometer model S1 Titan are presented in **Table 1**

XRF analysis provides valuable insights into the elemental composition of sugarcane waste biochar, which in turn influences its performance in adsorption. The results revealed that biochar contained significant amounts of elements such as potassium (K), calcium (Ca), phosphorus (P) and chlorine (Cl). Trace elements like nickel (Ni), copper (Cu), zinc (Zn), chromium (Cr) and iron (Fe) were also found in the biochar. These elements are typically derived from the inorganic content of the sugarcane plant and are retained after pyrolysis. Calcium and potassium oxides, for instance, often appear in moderate amounts and can enhance the biochar's cation exchange capacity, making it more effective in binding heavy metals and nutrients (Hassan *et al*., 2023). Activated biochar contained a high percentage of potassium since the biochar was activated using potassium hydroxide. This showed that the biochar activation was successful.

Element	% Inactivated Biochar	% Activated Biochar
Si	18.46±0.423	0
P	4.46±0.121	0.59±0.073
S	1.69±0.052	0.41±0.038
Cl	6.78±0.010	2.72±0.004
K	26.36±0.072	75.70±0.12
Ca	6.16±0.041	2.82±0.036
Ti	0.08±0.008	0
Cr	0.01±0.004	0
Mn	0.02±0.009	0.06±0.007
Fe	0.87±0.013	0.20±0.007
Ni	0.06±0.005	0
Cu	0.03±0.003	0.01±0.002
Zn	0.04±0.002	0
Rb	0.07±0.002	0.02±0.002
Sr	0.02±0.002	0
Y	0.01±0.002	0
Au	0.01±0.004	0

Table 1: *XRF characterisation of inactivated and activated biochar*

According to research by Uchimiya *et al*., (2017) the other elements come from the inherent mineral content of the sugarcane bagasse or from the ash produced during the pyrolysis process. The study emphasizes how crucial mineral content and functional groups are in determining how efficient biochar are for the adsorption.

Biochar Characterisation using X-ray Diffraction (XRD)

Figure 1 below shows the results for characterisation of inactivated biochar, using the XRD instrument Bruker D6 phaser model.

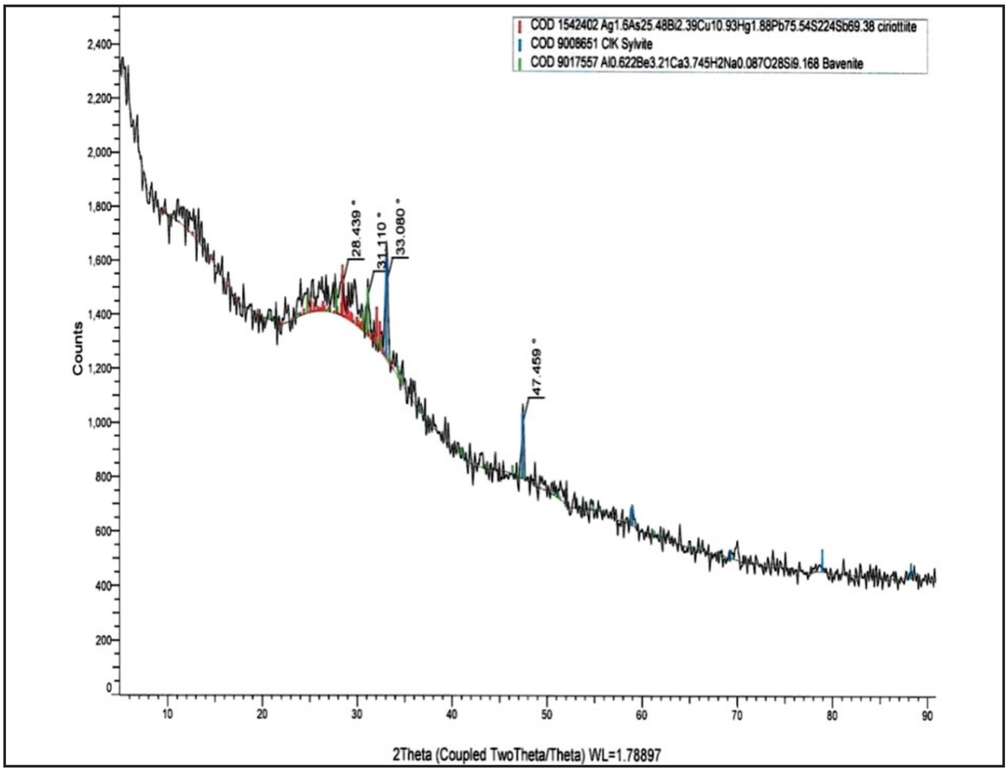

Figure 1: *XRD analysis for inactivated biochar.*

The large hump at 20-30° 2θ, which corresponds to disordered carbon, indicates that the inactivated biochar is primarily amorphous. Low-temperature pyrolysis is compatible with little graphitization, as evidenced by the lack of prominent peaks for graphitic carbon and amorphous carbon predominate (Mukome et al., 2013). The XRD peaks showed the presence of residual minerals such as 36% Ciriottite Cu(Cu,Ag)3Pb19(Sb,As)22(As2)S, 15.4% sylvite KCl, and 48.6% Bavenite $Ca_4Be_2Al_2S_{i9}O_{26}(OH)_2$ in the inactivated biochar.

Figure 2 shows the XRD characterisation of activated biochar. Sharper peaks in the activated biochar compared to the inactivated biochar indicated that mineral phases like quartz or leftover salts from chemical activation had been exposed or reorganised. The peaks were identified as 32.7% kalicinite $CHKO_3$, 24.4% petrovite $Na_{10}CaCu_2(SO_4)_8$, and 43% Bustanite CaMnSi2O6, minerals. The enhanced potential for adsorption applications and potential improvement of electrochemical properties are highlighted by these structural changes (*Bai et al.*, 2015).

The activated biochar XRD pattern showed a mostly amorphous structure with a large hump at around 20-30° 2θ, which is a sign of disordered carbon.

Sugarcane biochar is very porous and ideal for adsorption applications due to its amorphous form (*Chen et al.*, 2015). The cellulose, hemicellulose and lignin components of sugarcane bagasse is usually converted into amorphous carbon structures through the pyrolysis process. Broad peaks, which are a sign of amorphous or disordered carbon in biochar as opposed to well-ordered crystalline carbon, like graphite, are frequently seen in XRD data. Sugarcane biochar is very porous and ideal for adsorption applications due to its amorphous form (*Chen et al.*, 2015).

XRD is useful in identifying the residual crystalline phases of various minerals following pyrolysis. Because the initial biomass had a high silica content, silicon dioxide (SiO_2) is one of the main crystalline phases in sugarcane biochar. It is not uncommon to find quartz (SiO_2) in XRD spectra, particularly at higher pyrolysis temperatures. Depending on the mineral composition of the feedstock, other minerals such calcium compounds (CaO, $CaCO_3$) and potassium salts (K_2CO_3) are also found (*Bai et al.*, 2015; *Mukome et al.*, 2013).

Characterisation using FTIR Spectroscopy

The results from the characterisation of inactivated biochar, using the FTIR instrument Shimadzu model IRSpirit-T are shown **Figure 3**

The following stretching diagnostics peaks were observed in the IR spectrum: 3500-2500 cm-1

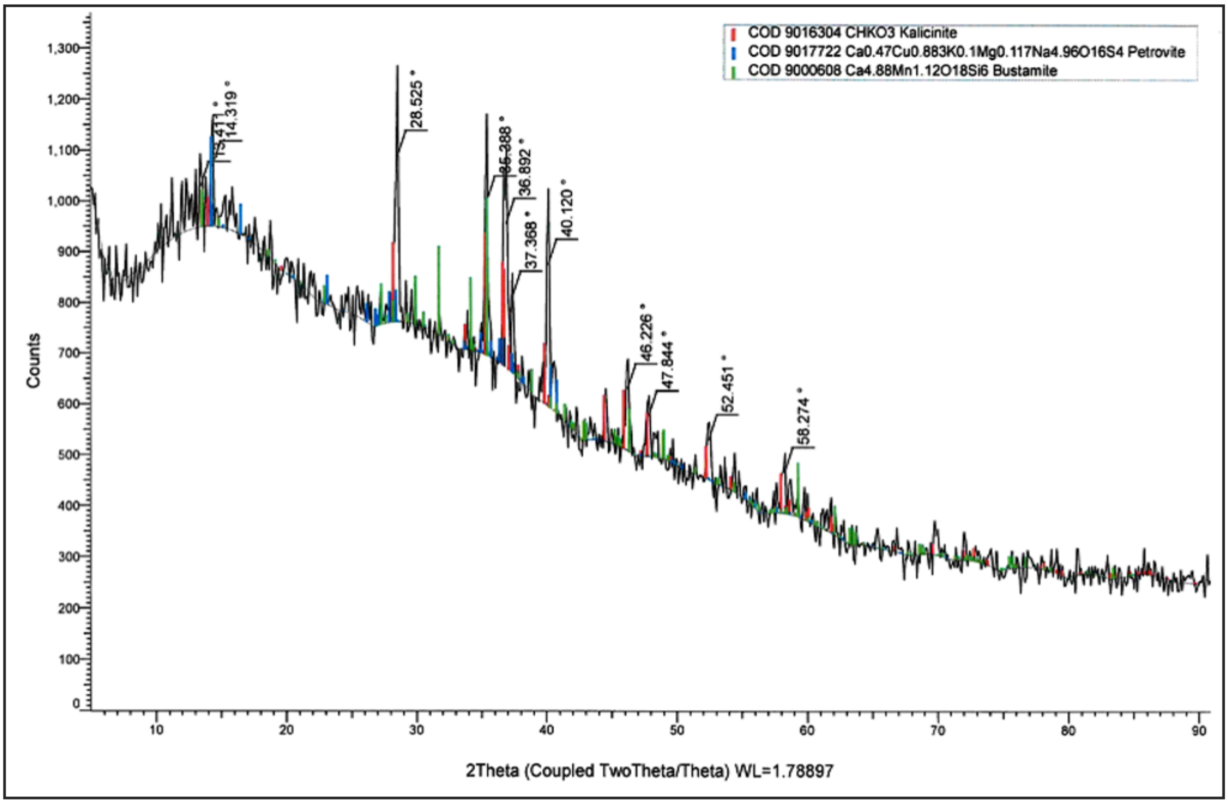

Figure 2: *XRD Analysis for activated biochar*

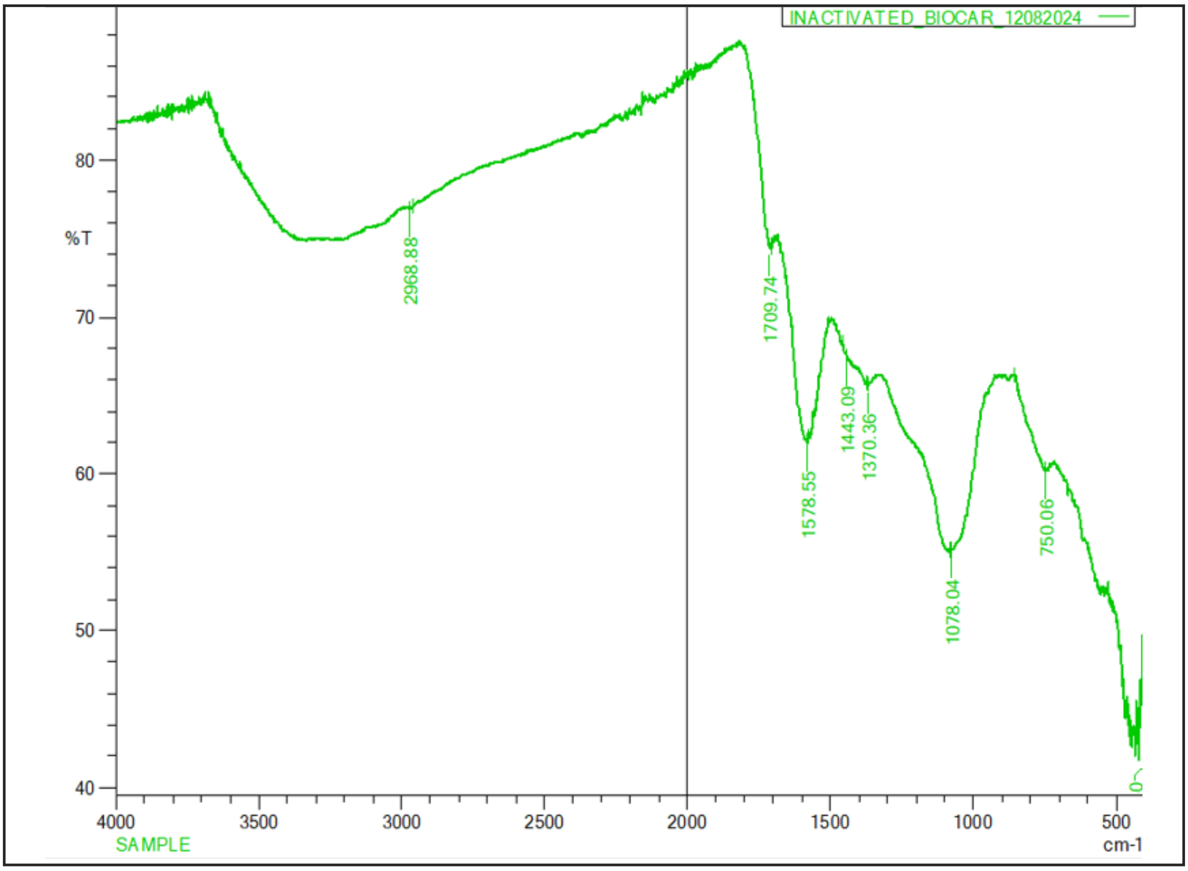

Figure 3: *Inactivated biochar FTIR characterization*

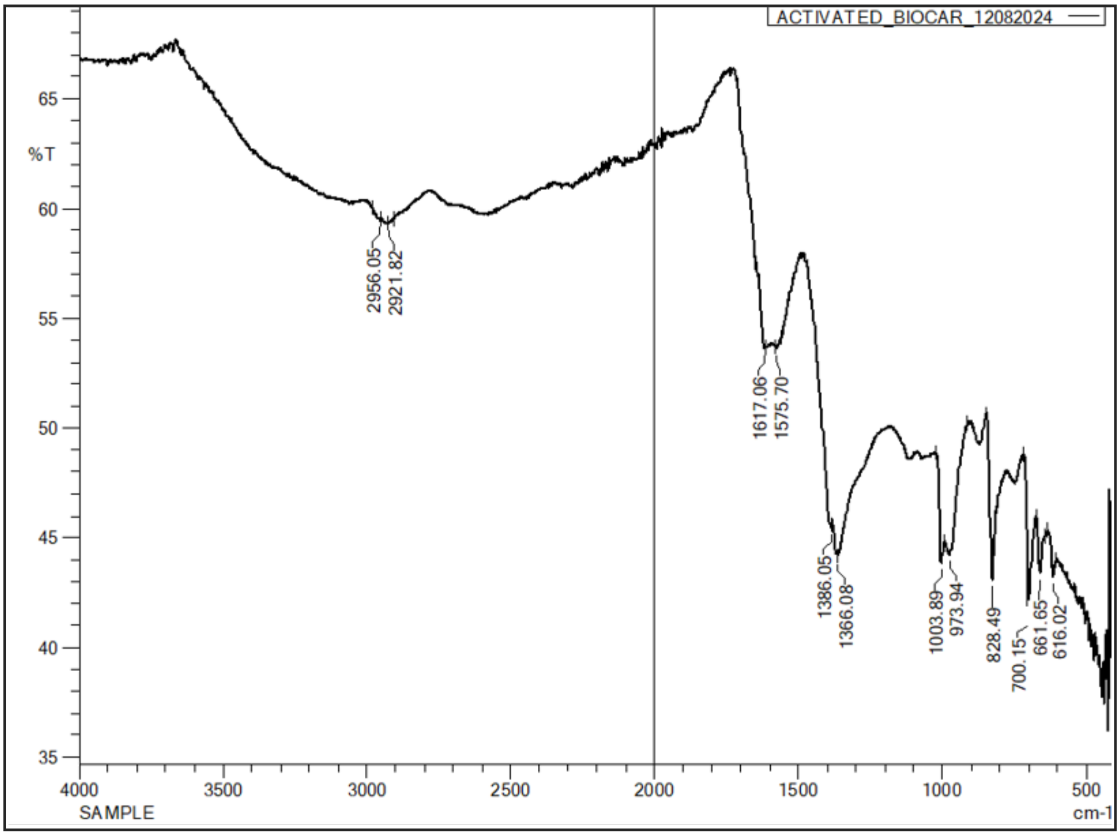

Figure 4: *Activated biochar FTIR characterization*

COOH, 2968.88 cm^{-1} –C-H, 1709.74 cm^{-1} C=O, 1578.55 cm^{-1} aromatic C=C and 1078.04 cm^{-1} C-O.

COOH shows a broad absorption peak at 3600-2500 cm^{-1}. Absorption peaks due to stretching were observed at 2956.05 cm-1 and 2921.82 cm^{-1} represent -C-H. Peaks at 1617.06 and 1575 cm^{-1} represents alkene C=C and aromatic C=C, respectively. Bending peaks occur at 1386.05 cm^{-1} and 1366.08 cm^{-1} for -C-H and 100.89 cm^{-1}, 973.94 cm^{-1} and 828.49 cm^{-1} for =C-H (both alkene and aromatic).

FTIR spectroscopy offers important insights into the functional groups that are present on the surface of the biochar and are crucial to the water filtration performance of the biochar. The hydroxyl group (-OH) is one of the main functional groups detected by FTIR; it usually manifests as a broad peak in the 3200–3600 cm^{-1} region. These hydroxyl groups are known to improve the adsorption of organic contaminants and heavy metals and are frequently connected to adsorbed water molecules or organic matter on the surface of the biochar. Due to the strong interaction between metal ions and hydroxyl groups via hydrogen bonding and surface complexation, studies have shown that biochar rich in hydroxyl groups effectively eliminates metal ions such as lead (Pb) and cadmium (Cd) from water (*Hossain et al*., 2015). In sugarcane biochar specifically, this -OH peak is notable and comparable to that found in rice husk biochar and wild sugarcane biochar: while both materials show strong -OH bands, variation in intensity reflects differences in oxygen-containing surface groups (*Barría et al*., 2023).

Sugarcane biochar's FTIR spectra frequently display absorption peaks in the 2800–3000 cm^{-1} range, which is consistent with aliphatic C–H stretching. These aliphatic groups reflect incomplete carbonization and hint that the biochar may contain unpyrolyzed organic components. But lower aliphatic content biochar, which indicate more thorough pyrolysis, typically have larger surface areas and are better at adsorbing organic contaminants like pesticides and dyes (Angin, 2014). This is important because the more porous structure of well-pyrolyzed biochar increases the surface area available for pollutant adsorption, improving filtration efficiency.

The carbonyl (C=O) group, which ranges from 1600 to 1750 cm^{-1} in the FTIR spectra of sugarcane biochar, is another important functional group found in the sample. Heavy metals and organic contaminants can be adsorbed from water by carbonyl groups, such as carboxyl, aldehyde, and ketone functional groups. It has been discovered that carbonyl-rich biochar can create stable complexes with metal ions like copper (Cu) and zinc (Zn), which increases the adsorption capacity of the metal ions (*Manyà et al.*, 2018). Consequently, biochar containing carbonyl functional groups exhibits enhanced performance in water filtration, particularly due to its effectiveness in removing metal ions from aqueous solutions.

Aromatic C=C bonds, typically observed between 1500 and 1650 cm-1 in FTIR spectra, signal the formation of stable aromatic ring structures during the pyrolysis of sugarcane biomass. These aromatic frameworks enhance the structural stability of the biochar and improve adsorption of hydrophobic organic contaminants like polycyclic aromatic hydrocarbons (PAHs) through increased π–π stacking interactions (*Haeldermans et al.*, 2019).

Physicochemical Purification Efficiency of Sugarcane Biochar for Greywater

The results for physicochemical analyses and efficiencies of inactivated and activated biochar for greywater purification are summarised in Table 2. The relative standard deviations are included. For each parameter, the biochar's efficiency was expressed as a percentage of adsorption, using the formula:

$$Percent\ Adsorption = \frac{C_0 - Ct}{C_0} \times 100 \qquad (2)$$

where C0 was the initial value of a parameter in the greywater and Ct was its final value after the greywater treatment with inactivated and activated biochar (*Chen et al.*, 2018).

Filtration using sugarcane biochar demonstrated a significant reduction in Total Suspended Solids (TSS), ranging from 21% to 54%, primarily by capturing and removing particulate matter from the water. This finding aligns with the results of Ahmad et al., (2014), who reported that sugarcane bagasse biochar effectively decreased TSS concentrations in wastewater, thereby enhancing water clarity and overall quality.

Similarly, Total Dissolved Solids (TDS) levels were reduced by 11% to 33% following treatment with sugarcane biochar. This reduction can be attributed to the adsorption of inorganic salts, trace metals, and organic matter present in the water. *Kizito et al.*, (2015) found that sugarcane bagasse-derived biochar lowered the TDS levels in piggery manure digestate, underscoring its utility in improving the quality of agricultural effluents. Likewise, Ahmad et al., (2014) observed a substantial decrease in the concentrations of various dissolved ions in contaminated water treated with sugarcane biochar, further supporting its effectiveness in water purification applications.

Filtration with sugarcane biochar led to an increase in pH, with inactivated and activated forms raising it by 33-39% and 63-70%, respectively. *Carvalho et al.*, (2016) reported a similar trend in their study on the treatment of acidic water using sugarcane bagasse biochar, where the pH increased by approximately 67%, from 4.5 to around 7.5, demonstrating the biochar's effective neutralizing properties. The observed rise in pH can be attributed to the alkaline nature of sugarcane biochar, which introduces hydroxide (OH^-) and carbonate (CO_3^{2-}) ions into the water, thus increasing its alkalinity. Further supporting this mechanism, *Chen et al.*, (2018) found that filtration of acidic leachate with sugarcane biochar led to a substantial pH increase from 3.8 to 7.2, highlighting its potential for treating strongly acidic effluents. These findings underscore the buffering capacity of sugarcane biochar, which helps stabilize pH levels in treated water. This property is particularly advantageous in environmental and agricultural applications, where the neutralization of acidic wastewater or runoff is essential for maintaining ecological balance and soil health.

Biochar was observed to reduce the electrical conductivity (EC) of greywater by approximately 8-23%, primarily through the adsorption of dissolved salts and ions, thereby decreasing the overall ionic strength of the water. *Lima et al.*, (2018) demonstrated that sugarcane-derived biochar significantly lowered the EC of saline water, highlighting its potential application in desalination processes and the remediation of salt-affected soils. Similarly, *Novak et al.*, (2016) reported that the application of sugarcane biochar to agricultural runoff resulted in a marked reduction in EC, thus enhancing the quality of water for potential reuse in irrigation systems.

Activated sugarcane biochar demonstrated a high adsorption capacity, effectively removing 92-96% of Pb^{2+} ions and 84-90% of C^{6+} ions from solution. The reduction in the concentration of lead (II) and chro-

Physicochemical Parameter	Inactivated Biochar Efficiency (%)			Activated Biochar Efficiency (%)		
	Bathroom	Carwash	Kitchen	Bathroom	Carwash	Kitchen
Total suspended solids (TSS), mg/L	34 ± 6.4	21 ± 0.6	29 ± 8.7	51 ± 2.5	40 ± 0.6	54 ± 2.0
Total dissolved solids (TDS), mg/L	13 ± 1.0	17 ± 1.5	11 ± 0.6	23 ± 0.6	33 ± 1.2	24 ± 0.6
Electrical Conductivity (EC), µS/cm	8 ± 0.0	11 ± 0.6	9 ± 0.6	20 ± 0.6	23 ± 0.0	17 ± 0.0
pH	33 ± 5.6	40 ± 2.9	39 ± 0.6	63 ± 4.5	73 ± 2.9	70 ± 0.6
Lead (II) ions, mg/L	85 ± 4.0	80 ± 11.6	87 ± 10.5	94 ± 2.0	96 ± 1.0	92 ± 5.0
Chromium (VI) ions, mg/L	86 ± 8.1	84± 2.9	83 ± 3.5	90 ± 5.0	93 ± 2.6	86 ± 2.6
Detergent (sodium dodecyl sulphate), mg/L	24 ± 11.4	19 ± 7.2	35 ± 13.5	33 ± 8.7	28 ± 6.2	38 ± 12.5
Oil and grease, mg/L	51 ± 1.5	51 ± 5.0	57 ± 1.0	76 ± 0.6	77 ± 2.3	76 ± 0.8

Table 2: *Purification Efficiency (n = 3) of Inactivated and Activated Biochar*

mium (VI) ions following filtration can be attributed to the strong affinity of the biochar surface for these heavy metals. The findings of this study align with previous research by Nie et al., (2018), which investigated the surface characteristics of sugarcane waste-derived adsorbents and identified specific interactions such as electrostatic attraction and surface complexation that facilitated efficient heavy metal removal. These results confirm the potential of sugarcane waste biochar as an effective material for treating metal-contaminated water.

Filtration using inactivated and activated sugarcane biochar resulted in the adsorption of sodium dodecyl sulfate (SDS) detergent in the range of 19-35% and 28-38%, respectively. Previous studies have demonstrated that biochar possesses the capacity to adsorb surfactants, which are the principal active components in detergents. However, the adsorption efficiency of SDS onto sugarcane biochar is comparatively lower than that observed for other pollutants. This is primarily due to the anionic nature of SDS, which features a hydrophilic sulfate head and a hydrophobic hydrocarbon tail, leading to limited interaction with the negatively charged biochar surface. Furthermore, the relatively low abundance of functional groups on sugarcane biochar that can effectively bind with SDS molecules may contribute to the reduced adsorption efficiency (*Zhang et al.*, 2020).

Inactivated and activated sugarcane biochar achieved oil and grease removal efficiencies of 51-57% and 76-77%, respectively. According to *Chen et al.*, (2018), biochar used as a filtration medium in greywater treatment exhibited an oil and grease removal capacity of up to 85%. This high efficiency is primarily attributed to the substantial pore volume and extensive surface area of biochar, which provide ample sites for the entrapment and immobilization of oil molecules. Additionally, hydrophobic interactions facilitated by specific surface functional groups on the biochar enhance the adsorption of oil droplets and reduce their mobility in aqueous systems. The performance of biochar in removing oil and grease from greywater is influenced by several factors, including pyrolysis temperature, particle size, contact time, and the composition of the wastewater. Higher pyrolysis temperatures generally enhance surface area and microporosity, thereby improving the biochar's capacity to adsorb hydrophobic compounds such as oils (*Okoro et al.*, 2023). Conversely, biochar produced at lower temperatures may retain a greater proportion of oxygenated functional groups, potentially enhancing the adsorption of polar pollutants while slightly reducing hydrophobicity (*Yang et al.*, 2020). Particle size also plays a critical role; smaller particles offer increased surface area and adsorption sites but may contribute to clogging in filtration systems, whereas larger particles facilitate higher flow rates but provide less overall surface interaction with oil and grease molecules (*Silva et al.*, 2021).

Table 3 shows below the |t| statistic values between purification efficiencies of inactivated and activated sugarcane biochar, calculated using Microsoft Excel software.

The literature critical value $t_4 = 2.78$ ($P = 0.05$) for two tail and equal variances (Miller & Miller, 2009). Hence, there was significant difference in the purification efficiency between inactivated and activated biochar over a wide range of physicochemical parameters as shown by the t statistic values in **Table 3.** The use of activated sugarcane biochar significantly enhanced the purification performance for

Physicochemical Parameter	|t|-values (P = 0.05, two-tailed test, equal variances)		
	Bathroom	Carwash	Kitchen
Total suspended solids (TSS)	4.52	39.60	4.65
Total dissolved solids (TDS)	15.50	14.47	27.58
pH	7.17	14.00	65.76
Electrical Conductivity (EC)	37.00	37.00	25.00
Chromium	0.73*	2.30*	0.69*
Lead	3.58	2.33*	0.74*
Detergent (sodium dodecyl sulphate)	1.05*	1.72*	0.34*
Oil and grease	25.81	8.13	28.00

Table 3: *t-test Comparison of Inactivated and Activated Biochar Purification Efficiency*

**No significant difference compared with critical value t4 = 2.78 (P = 0.05).*

most measured variables. However, no statistically significant improvement was observed for sodium dodecyl sulfate detergent, chromium in both bathroom and kitchen greywater, and lead in carwash and kitchen greywater. The superior performance of activated biochar is attributed to its enhanced surface area, porosity, and the abundance of functional groups, all of which contribute to improved adsorption capacity (*Leng et al.*, 2021).

Conclusions

Structural characterization revealed that sugarcane biochar contains functional groups that facilitate ion exchange and chemical bonding, particularly with metal ions, thereby enhancing its effectiveness in pollutant removal. The biochar was primarily composed of amorphous carbon, a structural feature known to improve adsorption performance, making it well-suited for greywater treatment applications. Sugarcane biochar demonstrated notable efficiency in removing various contaminants, especially heavy metals, oil, and grease. Statistical analysis using the t-test at a significance level of P = 0.05 confirmed that activated biochar outperformed inactivated biochar in purification efficiency. These findings underscore the potential of sugarcane-derived biochar as a sustainable and cost-effective alternative for water treatment. In particular, potassium hydroxide-activated sugarcane biochar has proven to be an efficient and economical option for remediating greywater contaminated with heavy metals. Furthermore, its high removal efficiency for oil and grease which are the major pollutants in greywater, alongside its capacity to eliminate total suspended solids, highlights its broad applicability in environmental water purification.

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Conflict of Interest

The authors declare no competing interest associated with this publication.

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