2024 Scienceline Publication

Journal of Civil Engineering and Urbanism

Volume 14, Issue 3S: 182-190; September 25, 2024 **ISSN-2252-0430**

DOI: https://dx.doi.org/10.54203/jceu.2024.18

Fixed-Bed Adsorption Dynamics of Total Organic Carbon from Gamodubu Landfill Leachate Using Biochar Derived From Gaborone Wastewater Treatment Plant Sewage Sludge

Lamong Duke Tshenyego[1], Philimon T Odirile[1] and Gilbert. K. Gaboutloeloe[2]

[1]*Department of Civil Engineering, University of Botswana, Private Bag UB0061, Gaborone, Botswana*
[2]*Department of Agricultural Engineering and Land Planning, Botswana College of Agriculture, Private Bag 0027, Gaborone, Botswana*

Corresponding author's Email: tshenyegol@ub.ac.bw

RESEARCH ARTICLE

PII: S225204302400018-14

Received: June 25, 2024

Revised: September 09, 2024

Accepted: September 13, 2024

ABSTRACT

In developing countries like Botswana, addressing leachate treatment presents considerable difficulties, especially regarding the management of sewage sludge (SS). This research evaluated the capacity of activated biochar, derived from sewage sludge, to adsorb Total Organic Carbon (TOC). Biochar was produced under conditions with limited oxygen, by placing approximately 50 grams of dried sewage sludge in sealed porcelain crucibles and heating them at a rate of 10°C per minute to 400°C for four hours. The resulting biochar (WWSBC400) was then stored in plastic bags in a dry environment. The pyrolysis yield was calculated as the ratio of the weight of the produced biochar to the initial weight of the dry sewage sludge. The study identified the maximum adsorption capacities (qm) for TOC in landfill leachate solutions, highlighting surface precipitation as a key adsorption mechanism for WWSBC400. Additionally, the removal of carbon ions using biochar produced from sludge at Gaborone's wastewater treatment facility was investigated. Continuous adsorption columns were utilized to demonstrate TOC solution adsorption, with performance evaluated in a fixed-bed column through model simulation. The Thomas model was used to compare experimental kinetic data, with the experimental data generally aligning well with the Thomas model, achieving a correlation coefficient (R^2) of 0.9114 for the first round of activated biochar removal. The adsorption capacity of the biochar was recorded at 389.265 mg/g after 14.5 hours of column adsorption, with regeneration studies showing varying adsorption capacities of 742.82 mg/g, 875.47 mg/g, 682.13 mg/g, and 735.21 mg/g for successive rounds. Surface precipitation was found to be a vital process for carbon adsorption onto WWSBC400. In conclusion, using sewage sludge biochar for co-contaminated soil shows potential for heavy metal immobilization, presenting a viable option for environmental rehabilitation.

Keywords: Biochar Adsorption kinetic models; Fixed-bed column, Total Organic Carbon, sewage sludge, environmental remediation.

INTRODUCTION

The relentless march of technology has transformed every aspect of our lives, becoming an indispensable part of our existence. However, this rapid advancement comes with significant consequences, notably the looming spectres of climate change and heavy metal pollution. Climate change has already inflicted profound damage upon our planet, while heavy metal pollution pervades every corner of our ecosystem (Mladenov et al., 2005). Once heavy metals infiltrate the environment, they persist across different spheres, wreaking havoc on wildlife, vegetation, and the environment at large. Urgent action is imperative to mitigate the impacts of climate change and curb heavy metal pollution before irreparable harm is done. The choices we make today to safeguard the environment and secure a sustainable future will determine the legacy we leave for generations to come. Recent research conducted by Lehmann et al. (2011), Zhang et al. (2019), and Wang et al. (2022) has highlighted biochar as an effective solution for addressing climate change and heavy metal contamination. Biochar is a carbon-rich material produced through the thermochemical conversion of biomass under oxygen-restricted conditions. Its physical and chemical characteristics are influenced by factors such as pyrolysis temperature and the type of feedstock used, as noted by Binti et al. (2007). Biochar has shown significant potential in reducing the bioavailability and leachability of heavy metals in soils, thereby mitigating contamination as shown

To cite this paper: Tshenyego LD, Odirile PT and Gaboutloeloe GK (2024). Fixed-Bed Adsorption Dynamics of Total Organic Carbon from Gamodubu Landfill Leachate Using Biochar Derived From Gaborone Wastewater Treatment Plant Sewage Sludge. *J. Civil Eng. Urban.*, 14 (3S): 182-189. DOI: https://dx.doi.org/10.54203/jceu.2024.18

in Figure 1,. Additionally, it can improve soil quality and reduce the uptake of heavy metals by crops. The production of biochar provides a sustainable approach to managing biomass waste, as it can be generated from various biomass sources. Advances in this field have also demonstrated biochar's role in combating climate change, producing biofuels, and enhancing soil productivity. In this study, biochar was utilized to analyze the adsorption dynamics of Total Organic Carbon (TOC) from Gamodubu landfill leachate.

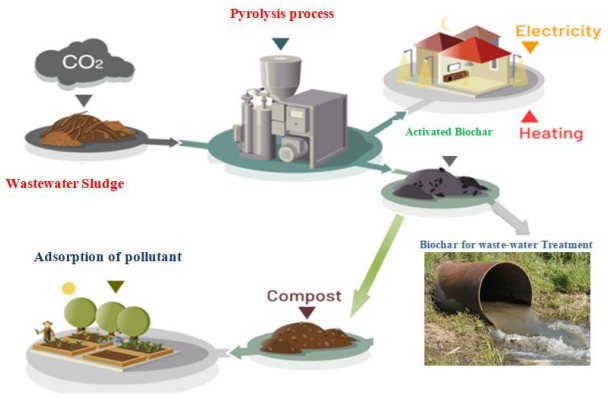

Figure 1. Conversion of Wastewater Sludge to Biochar for electricity, leachates' and soil treatment

According to Voivontas et al., (2001) metals present in industrial effluents pose risks to both human health and the environment. Biochar on the other hand which is, an economical alternative, shows promise in soil improvement such as metal adsorbent, agricultural soil improving by increasing organic content of the soil and improving water retention, thus enhancing plant resilience against harsh weather conditions. As industrial leachate treatment poses challenges, biochar can efficiently absorb hazardous elements like lead and cadmium, thus reducing their concentrations in leachate before discharge (Mladenov et al., 2005). Addition of biochar to soil amendments can also improve nutrients uptake in fields, leading to increased crop yields and promoting sustainable farming practices shown in Figure 1.

Liu et al., (2014) further highlight biochar's potential in remediating leachate and improving soil health, thereby reducing water shortage in agriculture. As the demand for sustainable farming methods rises, biochar emerges as a versatile and effective tool in addressing environmental concerns of point-source and nonpoint-source pollution. Its diverse applications, from soil enhancement to leachate treatment, contribute to building a more sustainable future for our planet.

The study examines the use of sludge-derived biochar as a sustainable solution for waste management and resource recovery in Gaborone. The study examined the effects of activated and regenerated biochar quality, and its suitability for removal of metals from leachate. By understanding how different pyrolyzed biochar affect adsorption of metals from leachate, this study will optimize the process to produce biochar with the desired properties for use in adsorption for in agricultural irrigation.

The primary goal of this study is to examine the viability of biochar as a sustainable method for long-term environmental remediation. The research objectives are to evaluate the effectiveness of biochar made from wastewater sludge in adsorbing organic carbon, to analyze the physiochemical properties and operational characteristics of the biochar, to assess the efficiency of biochar derived from wastewater sewage sludge in removing organic pollutants like Total Organic Carbon (TOC) from landfill leachate, and to determine the long-term adsorption capacity of biochar to confirm its suitability for sustainable leachate treatment and environmental remediation (Lehmann et al., 2011).

MATERIALS AND METHODS

Sampling and Sample Preparation

Sludge samples were collected from the primary settling tank and sludge drying beds at the Gaborone Wastewater Treatment Plant (GWWTP) using plastic buckets with a capacity of five liters. These samples were representative of the sewage sludge generated at the plant. In the laboratory, the sludge samples underwent a series of preparation steps before analysis. This included drying, ash content analysis, and solid substance content assessment, following established standard methods such as those outlined in the Association of Official Agricultural Chemists (AOAC) 1995 procedure.

Drying of Wastewater Sludge Samples

Drying reduces the moisture content of wastewater sludge, before pyrolysis process. This minimizes energy requirement, making the process more efficient and cost-effective. Drying improved biochar quality and leads to higher yields and better properties while reducing greenhouse gas emissions and ash content. Drying experiments were conducted using a laboratory model oven dryer (Uniscope SM 9053 A laboratory oven, Surgifriend Medicals, England). Approximately 30 g to 70 g of sludge samples were loaded onto a metal tray and

dried at specified temperatures (60°C for initial experiments, and 80°C for subsequent trials). The drying process was monitored at regular intervals, with weights recorded until final moisture content of a dry weight basis (db) was achieved.

Moisture content was calculated using Equation 1, where MC represents the moisture content, W_o is the initial sludge weight, and W_F is the final moisture content of the sludge. The moisture content (MC) was calculated from Equation 1 as shown:

$$MC = \frac{W_0 - W_F}{W_0} \quad (1)$$

. The dimensionless moisture ratio (MR) during drying was calculated using Equation 2, where M represents the average moisture content at time t, M_O is the initial moisture content, and M_E is the equilibrium moisture content on a dry basis.

$$MR = \frac{M - M_E}{M_0 - M_E} \quad (2)$$

where: MR is the dimensionless moisture ratio, M, the average moisture content at time t, M_O the initial moisture content, and M_E, the equilibrium moisture content on dry basis.

During layer drying of wastewater sludge, the equilibrium moisture content was not determined and since this is usually not high in most of materials (Waewsak et al., 2006) the equilibrium moisture content was assumed to be zero. Thus, the moisture ratio (MR) was simplified according to Equation 3 (Kingsly et al., 2007) and Equation 2 becomes:

$$MR = \frac{M}{M_O} \quad (3)$$

The recorded moisture ratios for each sample were then used to plot the drying curves. The drying rates of the sample for each treatment were calculated based on the weight of water removed per unit time per kilogram of dry sludge, expressed in units of $kg.kg^{-1}$ $1h^{-1}$ (Sankat et al., 1996; Kingsly et al., 2007; Babalis et al., 2006).

Dry wastewater sludge optimal conditions for pyrolysis

Conducting of series of experiments varying the temperature, heating rate and feedstock ratios to determine the optimal conditions for pyrolysis was carried out using blast furnace to simulate and control the pyrolysis process. Biochar production occurred under oxygen-limited conditions, with approximately 50 g of dry sewage sludge placed in porcelain crucibles and sealed to prevent air ingress. Heating at a rate of 10°C per minute to 400°C for four hours yielded biochar (WWSBC400), stored separately in plastic bags in a dry environment. The pyrolysis yield was calculated as the ratio of generated biochar weight to initial dry sewage sludge weight.

$$\text{Biochar yeild (\%)} = \frac{\text{char weight}}{\text{Dry waste water Sludges}} * 100 \quad (4)$$

Characterization of WWS Biochar by Physical and Chemical Properties

Laboratory tests were conducted to assess the chemical composition and physical properties of the produced biochar. The pH, porosity, and nutrient content of the biochar were measured to determine its suitability for leachaate treatment applications. The Use of standard methods and equipment, such as pH meters, surface area analyzers, and nutrient analysis kits, to obtain accurate data.

Concentration and accessibility of nutrients

The biochar's total nutritional concentration is the sum of all of its nutrients. The portion of the total nutrients that plants can absorb is known as the bio-available nutrient concentration. Nutrient extraction studies using Diethyl-enetriamine-pentaacetic acid (DTPA) extraction were used to estimate the havey metal in the samples.

Determination of Heavy Metals

Acid digestion was utilized to identify heavy metals. Each sample was soaked in 10 ml of 65% HNO_3 for 2 hours. About 0.3 g of each sample was used. Following filtration, the supernatant were collected for examination. The total heavy metal content in the pyrolyzed WWS biochar generated were assessed using inductively coupled plasma-mass spectrometry (7500 cx ICP-MS connected to an ASX-500 auto sampler, Agilent Kolosionis et al., (2021). Elemental analysis experiments were carried out with Thermo-Flash 2000 CHN-S elemental analyzer using the ASTM-D5373-16 method (ASTM-D5373 2018) (Kolosionis et al. 2021a) at the enviromental science laboratory.

Adsorptive Properties of Activated, Regenerated WWS Biochar

Accoding to Saadi and Fazaeli (2013), adsorption and removal of contaminants from leachate was conducted with the use of batch or continuous flow experiments using real leachate samples containing contaminants. Pyrolyzed biochar samples was monitored to remove of

heavy metals, organic pollutants, and nutrients over time. The concentration of contaminants before and after adsorption using appropriate analytical techniques, such as atomic absorption spectrophotometry was measured (Turro et al., 2011).

Adsorption Tests

The adsorption test used Botswana Gamodubu Landfill Leachate (GLL) as the initial solution. The color was measured in a continuous adsorption mode from the effluent collector. Activated WWS Biochar was added to the column, and a peristaltic pump was used to deliver concentrated solution through the column at specific flow rate as shown in Figure 2 (Kolosionis et al., 2021b).

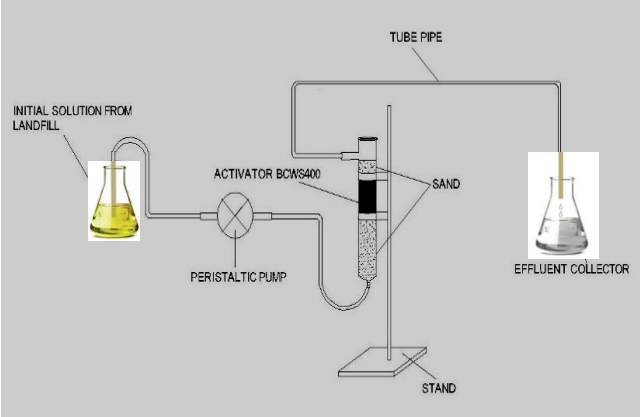

Figure 2. Column Adsorption experimental setup for adsorption of pollutants from leachate effluent

Fixed bed adsorption data analysis

To construct, optimize, and manage an adsorption column for water treatment, understanding the influence of operational parameters on breakthrough curves (BTC) and the maximum capacity of the fixed bed is essential. BTC modeling and simulation utilized linearized equations from models such as the Thomas, Yoon-Nelson, and Adams-Bohart, as adopted from Brion-Roby et al. (2018). These models are actively researched for large-scale removal of heavy metal effluents, with practical studies determining breakthrough curves and saturation points of the adsorption process.

$$\text{In}\left[\frac{Ct}{C_0-Ct}\right] = (Kt) - \text{KT} \quad (5)$$

For Yoon Nelson Equation 5 where; C_o is Influent concentration, C_t is Outlet Concentration at time t (mg/L), K is Rate constant and T is time required for 50% adsorbate breakthrough and

$$\text{In}\left[\frac{C_t}{C_0}\right] = (K_{AB}C_0t) - K_{AB}N_0(\frac{Z}{U_0}) \quad (6)$$

For Adams Bohart Equation 6 where Co isInfluent concentration, C_t is Outlet Concentration at time t (mg/L), K_{AB} is Kinetic constant, Z is Bed depth of the fixed bed column, U_o is Superficial velocity (cm/min and N_o is Saturation Concentration.

$$\text{In}[\frac{C_t}{C_0}] - 1 = K_{th}\ (\frac{q_o\, m - C_0 t}{Q}) \quad (7)$$

For Thomas model Equation 7 where: C_0 is Influent concentration, C_t is Outlet Concentration at time t (mg/L) K_{th} is Thomas rate constant, q_o is equilibrium adsorption uptake (g), Q is The flow rate (ml/min, t is v/Q (v)ml (v) the effluent volume and , N_o is Saturation Concentration. The Tomas model was used in this article.

Regeneration studies

Colum adsorption was carried out using washed biochar, using the same flow rate of 1.12 m/s and the same adsorption test setup as in Figure 2, the results were compared in order to determine the efficacy of the column for repeated usage after adsorption (Patel, 2019). An evaluation of the reusability of the biochar by performing multiple adsorption-desorption cycles was made .This finding is important for practical applications where the biochar column may need to be regenerated and reused multiple times. This finding is promising for industries looking to implement sustainable and cost-effective treatment methods for leachate or wastewater purification. Further research is needed to optimize the regeneration process and maximize the longevity of the biochar column for continuous use in various applications (Chen et al., 2016). The following equations (Khadhri et al., 2019) were used to calculate the total mass of the TOC retained in the column q_{tot} (mg), the maximum column adsorption capacity qc (mg/g); the total mass of TOC pumped into the column m_{tot} (mg) and the removal percentage R : The equations used to calculate these parameters are as follows:

$$q_{tot} = (C_0 - C_t) \times V \quad (8)$$

$$q_c = q_{tot}/m \quad (9)$$

$$m_{tot} = C_0 \times V \quad (10)$$

$$R = \frac{m_{tot} - q_{tot}}{m_{tot}} \times 100 \quad (11)$$

where C_0 is the initial concentration of the carbon adsorbate, C_t is the concentration at time t, V is the volume of the column, *m* is the mass of the adsorbent, and R is the removal percentage. These Equations 8-11 provide a quantitative analysis of the organic and inorganic carbon adsorption process in the column (Binti et al., 2007).

RESULTS AND DISCUSSION

Sludge drying results

The drying times for WWTP sewage sludge exhibit significant variation across different sample regions, particularly as the drying beds descend. This variation can result in drying periods of up to nine hours. The drying process is notably influenced by both the moisture content and the moisture ratio loss pivotal factors that impact the efficiency of the drying process as shown in Figure 3. Notably, sludge from Layer 1 of the drying bed demands additional energy for drying, making it the most energy-intensive layer, followed by layers two and three In contrast, drying wastewater sludge (WWS) from the GWWTP primary settling tank proves to need highest energy and time-consuming.

The drying rate presented by Figure 4, observed at a constant temperature of 80°C, displays a linear trend, signifying consistent moisture loss over time. To visually represent this trend, a moisture ratio curve was constructed for each sample, offering a clear indication of the moisture loss progression.

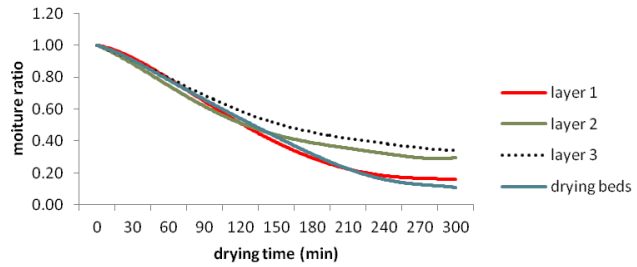

Figure 3. Comparison of sludge moisture ratios drying temperature of 80 ^{0}C

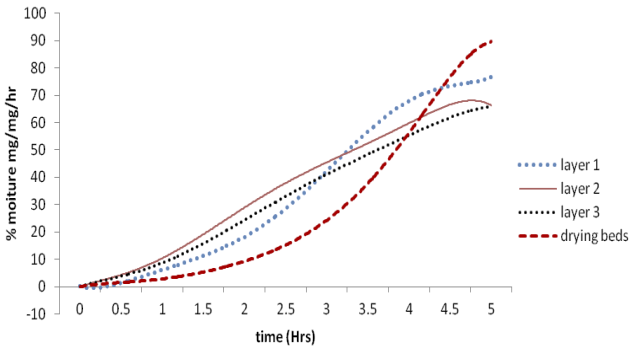

Figure 4. Comparison of Sewage Drying Rates at at temperature of 80 ^{0}C

Layer 1, from Figure 3 is characterized by a higher initial moisture ratio, exhibits more pronounced variation between the start and end of the drying experiment, while Layer 3, owing to its higher solid content, demonstrates comparatively less variation. An intriguing observation emerges when comparing the drying behavior of Layer 1 samples with that of sludge from the GWWTP primary settling tank, suggesting similarities in their drying characteristics. This is the fact that they both have highest initial moisture content. Drying WWS at elevated temperatures expedites the process, as evidenced by a corresponding increase in the moisture ratio versus time curve. Despite the higher energy requirement associated with higher temperatures, this method demonstrates the potential for rapid sludge drying.

The study further explores the impact of drying rate on temperature changes and the speed at which samples dry at different temperatures. While the majority of moisture is lost per hour in the drying beds as shown in Figure 4, layers two and three exhibit less comparable moisture loss rates. However, the overall drying process exhibits a gradual decrease in speed, with a notable shift observed from three and a half hours to five hours for achieving 90% moisture elimination.

Wastewater Sludge Pyrolysis under Optimal Conditions

The study utilized desiccators to preserve dried Wastewater Sludge (WWS) samples prior to pyrolysis experiments. WWS was finely crushed to 0.5 mm particle sizes, dried at 105°C for 24 hours, and stored in airtight plastic containers. Pyrolysis, following the method described by Yuan & Xu (2012) was employed to produce WWS Biochar. Approximately 50 g of dried wastewater sludge was placed in porcelain crucibles, sealed to exclude air, and subjected to heating in a furnace for four hours. Following cooling, the samples were crushed and weighed to determine the combined weight of ashes and biochar. The resultant chars were designated as Wastewater Sludge Biochar 400 (WWSBC400) and stored in individual plastic bags within a dry environment. Acid-washed biochars are recognized for their thermal stability, facilitating steady combustion.

Table 1. Mass Reduction and ash produced after pyrolysis

Measures of Central Tendency.	Sample Mass (g)	Mass reduction %	Mass of ash (g)	final mass (g)
Total	353.83	372.77	6.11	347.72
Average	27.22	28.67	0.47	49.67
Standard Deviation	5.23	0.91	0.09	85.93
Standard Error	2.27	2.39	0.04	4.14

Thirteen experiments on sludge pyrolysis revealed an average mass reduction of 28.67% as shown by Table 1. The consistency observed across data sets suggests a reliable and consistent reduction in mass, underscoring the viability of pyrolysis as an effective sludge treatment method. The substantial average reduction in final mass (71.33%) highlights the efficacy of pyrolysis in organic material elimination and sludge volume reduction. The low standard deviation and standard error values further affirm the precision and reliability of the results obtained, consolidating pyrolysis as a promising treatment avenue.

The char yield percentage was determined as per Equation 12. The high char yield percentage indicates that sewage sludge has the potential to yield a significant amount of biochar through pyrolysis. This elevated char output underscores the efficient adsorption capabilities of biochar derived from sewage sludge, encompassing both organic and inorganic carbon molecules.

$$\text{Char yeild (\%)} = \frac{\text{char weight}}{\text{Dry Micro Sieved Sludges}} * 100 \qquad (12)$$

$$\text{Char yeild (\%)} = \frac{347.72}{353.83} * 100 \qquad = 98.27\%$$

WSBC400 Char Activation and Water Washing Techniques

The study involved washing samples by adding 40 g of BCWSS400 to a conical flask containing 100 ml of washing water solutions. The mixture was shaken at 200 rpm for 24 hours, separated by filtration, washed and dried at 105°C for 24 hours to remove moisture. The supernatants were then filtered with PTFE 0.45 µm syringe filters, acidified, and stored for column adsorption. Chars produced at moderate temperatures (400°C) were not resistant to these washing techniques, indicating unstable forms. The efficient decrease in yield after washing suggests that ash components in the char did not remain intact and could not compromise the fuel's heating value as mentioned by Kolosionis et al., (2021b) .

Char Yield Percentage after Washing about 96.1%. The resulting WWSBC400 was then impregnated with a 2 grams per grams of (NaOH) sodium hydroxide solution, then put in porcelain crucibles and heated for two hours at 800 °C at a heating rate of 5 °C per minute in a furnace. The samples were then cooled then washed through distilled water and filtered with PTFE 0.45 µm syringe filters resulted in Activated Biochar (WWSABC400), which was rinsed in 0.1 moles per litre (mol/L) hydrochloric acid and then washed with water distilled in a Soxhlet extractor until neutralization to pH range between six and eight (6- 8). WWSABC400 was then dried for 24 hours at 105°C. Lastly the WWSABC400 was Crushed and sieved, and kept in desiccator ready for adsorption column test, Khadhri et al., (2019)

Characterization WWS Biochar by Physical and Chemical Properties

Proximate Analysis

Table 2 presents the findings of the proximate analysis for solid wastewater sludge, pyrolyzed wastewater sludge, and activated wastewater sludge.For WWSBC400, and WWSABC400, Table 2 solid sample had an ash content that was 56.80 weight percent greater than that of the activated wastewater sludge and 55.43 percentage weight higher than that of the pyrolyzed samples.

The pyrolyzed samples exhibited lower fixed carbon concentrations than activated sewage sludge, indicating improved biochar adsorption. The pyrolysis process eliminated volatile organic molecules, rendering biochar more stable and eco-friendly. The volatile content of sewage sludge significantly decreased during pyrolysis and activation, suggesting biochar may preserve both types of carbon. The higher fixed carbon content suggests better carbon adsorption capabilities compared to the original sewage sludge with very low fixed carbon.

Table 2. Proximate results for Solid, Pyrolysed and Activated Sludge

Proximate analysis parameter	Solid Sample	pyrolysed Sample WWSBC400	activated Sample WWSABC400
Volatile	75.09	15.07	12.65
Ashe	86.54	31.11	29.74
fixed Carbon	-61.63	53.82	57.61

Determination of Heavy Metals

To identify heavy metals, an acid digestion process was used. Approximately 0.5 grams of each sample were subjected to digestion in Aqua Regia, a mixture consisting of 2 ml of 65% hydrochloric acid (HCl) and 6 ml of nitric acid (HNO_3). The samples were processed in a microwave digester at 100°C for 120 minutes, as described by Kolosionis et al. (2021).

The extract was filtered and diluted with deionizer water before analyzing the heavy metal content of raw sludge SMMSS, WWSBC400, WWSABC400, and regenerated biochar. Inorganic elements were concentrated in MSBC400, which was produced during pyrolysis. The average adsorption capacities of various metals were

evaluated for SMSS, PS, AS, and RS. SMSS biochar exhibited high adsorption capacities for Fe, Cu, and Al, suggesting its potential for removing these metals from leachate as shown in Figure 5. However, further research is necessary to understand the adsorption mechanisms and optimize biochar utilization for carbon adsorption (Agrafioti et al., 2013; Zhou et al., 2017).

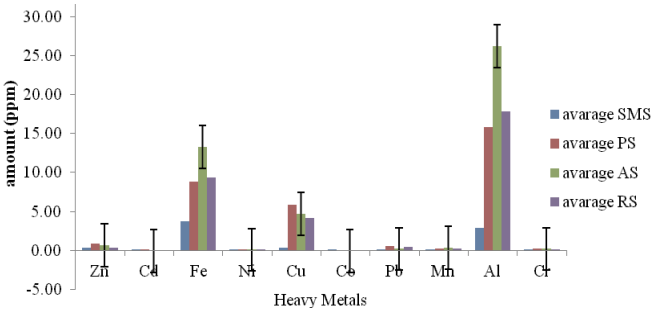

Figure 5. Elementary results of raw sludge SMSS, pyrolyzed sludge PS, activated sludge AS, and Regenarated Sludge RS.

The higher heating values (HHVs)

The results as presented in Figure 6 showed that biochar derived from sewage sludge had a high potential for both organic inorganic carbon adsorption and energy generation. The HHVs of the samples were found to be within the range of 20.834 magajoule per kilograms (MJ/kg) to 24.834 MJ/kg, indicating significant energy content. This suggests that biochar produced from micro sieved sewage sludge can be a valuable resource for carbon sequestration and energy production.

The study investigated the Heating Values (HHVs) of sewage sludge samples and found biochar to be a promising renewable energy source due to its substantial energy content. The combined average HHV was calculated to be 24.834 MJ/kg, with a standard deviation of 0.655.

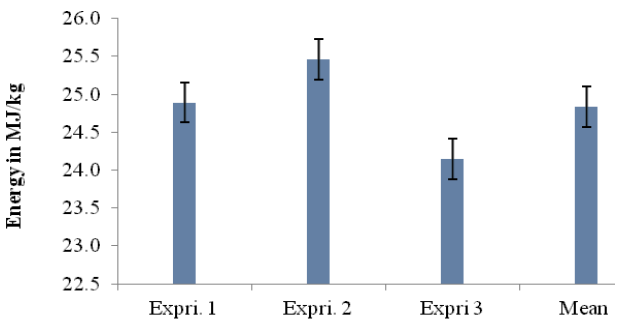

Figure 6. Experiment for Bob calorimeter WWS Biochar Calorific Value

Variations in HHV levels across different experiments may be attributed to differences in feedstock or manufacturing processes. However, despite these fluctuations, the average HHV remains within a useful range for carbon adsorption applications, highlighting the potential of biochar for carbon sequestration (Kolosionis et al., 2021b). For the calculation of the Fuel Ratio (FR), the following Equation 12 was utilized:

$$HHV_{af}(\%) = \frac{\text{HHV}}{(100 - \text{ash}\%)} \times 100 \quad (12)$$

$$HHV_{af}(\%) = \frac{24.834}{(100 - 6.11\%)} \times 100 = 26.45$$

For the calculation of the fuel ratio (FR), the following Equation 13 were used:

$$FR\ for = \frac{\text{Fixed carbon}}{\text{Volatile matter}} \quad (13)$$

$$FR\ for = \frac{57.61}{12.65} = 4.5541$$

Biochar derived from sludge, characterized by a higher proportion of fixed carbon compared to volatile matter, demonstrates potential for energy production. With a Fuel Ratio (FR) value of 4.55, indicating its high energy content, it qualifies as a suitable fuel source for energy production as supported by Voivontas et al., (2001).

Adsorptive Properties of Activated, Regenerated WWS Biochar

The study employed the linear Thomas adsorption model to simulate the adsorption process of Total Organic Carbon (TOC from landfill influent using Wastewater Sludge Biochar (WWSABC400) as the adsorbent medium. Results indicated a notably high adsorption capacity, underscoring the effectiveness of WWSABC400 in contaminant removal. This robust adsorption capacity, coupled with its potential for energy generation, positions biochar sludge as a promising contender for sustainable solutions across various environmental remediation endeavours Graves et al., (2022). Figures 7 and 8 depict the adsorption of TOC from Gamodubu landfill leachate experiment data after multiple rounds of biochar regeneration.

The application of the Thomas kinetic model to the activated wastewater sludge biochar resulted in a linear plot of $\ln(C_0/(C_t - 1))$ versus time for TOC as presented in Figure 7. The slope of -0.9089 for TOC corresponds to the multiplied influent concentration ($-K*C_0$) of the Thomas model constant, with an intercept of 6.5107 corresponding to Equation 7 (Kq_0*m/Q). The linear Tomas model exhibited a high degree of conformity with the experimental data, achieving an R^2 value of 0.9114 for the first round of activated biochar removal.

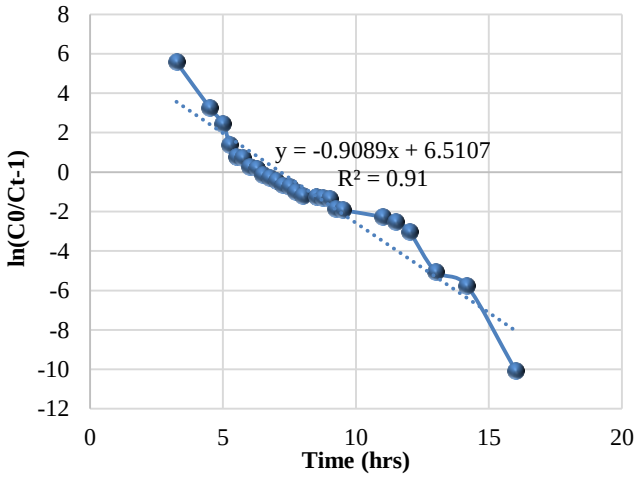

Figure 7. First round Activated biochar Adsorption (WWSABC400) of TOC for Gamodubu landfill leachate expriment data fitted to Tomas linear model

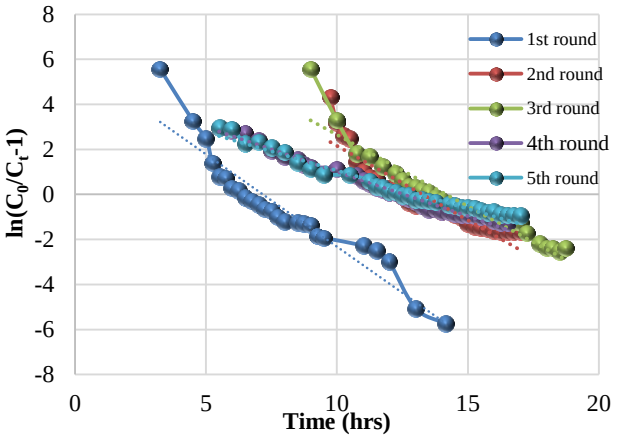

Figure 8. Comparison between Regenerated biochar (2nd round to 5th round) and Activated biochar for Adsorption of TOC for Gamodubu landfill leachate expriments all fitted to Tomas linear model.

The study utilized the linear Thomas adsorption model to assess the adsorption of Total Organic Carbon (TOC) from Gamodubu landfill leachate using activated WWS biochar WWSABC400. The biochar exhibited an adsorption capacity of 389.265 mg/g after 14.5 hours of column adsorption for the first round. Successive rounds of regeneration yielded varying adsorption capacities, with values of 742.82 mg/g, 875.47 mg/g, 682.13 mg/g, and 735.21 mg/g observed after the first, second, third, and fourth regenerations, respectively. The results depicted in Figures 7 and 8 suggest that, activated and regenerated WWS biochar exhibits substantial adsorption capacity for TOC, with promising potential for sustainable environmental remediation applications.

CONCLUSION

In conclusion, This study demonstrated the potential of biochar derived from sewage sludge at the Gaborone Wastewater Treatment Plant (GWWTP) for the adsorption of Total Organic Carbon (TOC) from Gamodubu landfill leachate. The research found that biochar produced under controlled pyrolysis conditions (WWSBC400) exhibited significant adsorption capacities, making it a viable option for environmental remediation. The biochar showed a remarkable TOC removal rate of 94.89% after 17 hours of column adsorption, highlighting its effectiveness in contaminant removal. The use of sewage sludge biochar offers an innovative approach to recycling waste materials, contributing to a circular economy and reducing waste disposal costs. Beyond leachate treatment, biochar improves soil fertility and water quality, promoting sustainable agricultural practices. The high energy content of biochar (24.834 MJ/kg) suggests its potential as a renewable energy source, further enhancing its utility in sustainable development.

DECLARATIONS

Corresponding Author

Correspondence and requests for materials should be addressed to Lamong Duke Tshenyego; E-mail: Tshenyegol@ub.ac.bw; ORCID: 0000-0002-6545-0980.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Acknowledgements

The authors would like to thank and acknowledge the Office of Research and Development (ORD) at University of Botswana for the graudate and ethical consideration to provideresearch funding opportunity.. Department of Civil Engineering for creating a conducive environment to conduct this research.

Authors' contribution

First Author performed the experiments, analysed the data obtained and wrote the manuscript. Second Author designed the experimental process and revised the manuscript. Both authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests in this research and publication.

REFERENCES

Agrafioti, E., Bouras, G., Kalderis, D., & Diamadopoulos, E. (2013). Biochar production by sewage sludge pyrolysis. *Journal of Analytical and Applied Pyrolysis*, *101*(Iii), 72–78. https://doi.org/10.1016/j.jaap.2013.02.010

Babalis, S. J., Papanicolaou, E., Kyriakis, N., & Belessiotis, V. G. (2006). Evaluation of thin-layer drying models for describing drying kinetics of figs (Ficus carica). *Journal of Food Engineering*, *75*(2), 205–214. https://doi.org/10.1016/j.jfoodeng.2005.04.008

Binti, A. I. N., Thesis, J., & June, S. (2007). *THE PRODUCTION AND CHARACTERIZATION OF ACTIVATED CARBON USING LOCAL AGRICULTURAL*. *Jun https://core.ac.uk/download/pdf/11933114.pdf*.

Brion-Roby, R., Gagnon, J., Deschênes, J. S., & Chabot, B. (2018). Investigation of fixed bed adsorption column operation parameters using a chitosan material for treatment of arsenate contaminated water. *Journal of Environmental Chemical Engineering*, *6*(1), 505–511. https://doi.org/10.1016/j.jece.2017.12.032

Chen, D., Guo, H., Li, R., Li, L., Pan, G., Chang, A., & Joseph, S. (2016). Low uptake affinity cultivars with biochar to tackle Cd-tainted rice — A field study over four rice seasons in Hunan, China. *Science of the Total Environment*, *541*(October), 1489–1498. https://doi.org/10.1016/j.scitotenv.2015.10.052

Graves, C., Kolar, P., Shah, S., Grimes, J., & Sharara, M. (2022). Can Biochar Improve the Sustainability of Animal Production? *Applied Sciences (Switzerland)*, *12*(10), 1–23. https://doi.org/10.3390/app12105042

Khadhri, N., El Khames Saad, M., Ben Mosbah, M., & Moussaoui, Y. (2019). Batch and continuous column adsorption of indigo carmine onto activated carbon derived from date palm petiole. *Journal of Environmental Chemical Engineering*, *7*(1). https://doi.org/10.1016/j.jece.2018.11.020

Kingsly, R. P., Goyal, R. K., Manikantan, M. R., & Ilyas, S. M. (2007). Effects of pretreatments and drying air temperature on drying behaviour of peach slice. *International Journal of Food Science and Technology*, *42*(1), 65–69. https://doi.org/10.1111/j.1365-2621.2006.01210.x

Kolosionis, A., Kastanaki, E., Veksha, A., Wang, H., He, C., Lisak, G., & Giannis, A. (2021a). The Effects of Washing Techniques on Thermal Combustion Properties of Sewage Sludge Chars. *International Journal of Environmental Research*, *15*(2), 285–297. https://doi.org/10.1007/s41742-021-00312-6

Kolosionis, A., Kastanaki, E., Veksha, A., Wang, H., He, C., Lisak, G., & Giannis, A. (2021b). The Effects of Washing Techniques on Thermal Combustion Properties of Sewage Sludge Chars. *International Journal of Environmental Research*, *15*(2), 285–297. https://doi.org/10.1007/s41742-021-00312-6

Liu, T., Liu, B., & Zhang, W. (2014). Nutrients and heavy metals in biochar produced by sewage sludge pyrolysis: Its application in soil amendment. *Polish Journal of Environmental Studies*, *23*(1), 271–275. https://www.researchgate.net/profile/Arvind-Singh-.

Mladenov, N., Strzepek, K., & Serumola, O. M. (2005). Water quality assessment and modeling of an effluent-dominated stream, the Notwane River, Botswana. *Environmental Monitoring and Assessment*, *109*(1–3), 97–121. https://doi.org/10.1007/s10661-005-5842-8

Patel, H. (2019). Fixed-bed column adsorption study: a comprehensive review. *Applied Water Science*, *9*(3), 1–17. https://doi.org/10.1007/s13201-019-0927-7

Saadi, Z., Saadi, R., & Fazaeli, R. (2013). Fixed-bed adsorption dynamics of Pb (II) adsorption from aqueous solution using nanostructured γ-alumina. *Journal of Nanostructure in Chemistry*, *3*(1), 2–9. https://doi.org/10.1186/2193-8865-3-48

Sankat, C. K., Castaigne, F., & Maharaj, R. (1996). The air drying behaviour of fresh and osmotically dehydrated banana slices. *International Journal of Food Science and Technology*, *31*(2), 123–135. https://doi.org/10.1111/j.1365-2621.1996.332-35.x

Turro, E., Giannis, A., Cossu, R., Gidarakos, E., Mantzavinos, D., & Katsaounis, A. (2011). Electrochemical oxidation of stabilized landfill leachate on DSA electrodes. *Journal of Hazardous Materials*, *190*(1–3), 460–465. https://doi.org/10.1016/j.jhazmat.2011.03.085

Voivontas, D., Assimacopoulos, D., & Koukios, E. G. (2001). *Assessment of biomass potential for power production : a GIS based method*. *20*, 101–112. https://environ.chemeng.ntua.gr/gr/uploads/doc/Papers/Renewable%20Energy/2001.

Waewsak, J., Chindaruksa, S., & Punlek, C. (2006). A mathematical modeling study of hot air drying for some agricultural products. *Thammasat International Journal of Science and Technology*, *11*(1), 14–20.

Yuan, J. H., & Xu, R. K. (2012). Effects of biochars generated from crop residues on chemical properties of acid soils from tropical and subtropical China. *Soil Research*, *50*(7), 570–578. https://doi.org/10.1071/SR12118

Zhou, D., Liu, D., Gao, F., Li, M., & Luo, X. (2017). Effects of biochar-derived sewage sludge on heavy metal adsorption and immobilization in soils. *International Journal of Environmental Research and Public Health*, *14*(7). https://doi.org/10.3390/ijerph14070681