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Surface Wastewater Treatment in WASH Systems Using Biochar: A Nature-Based Sustainable Approach

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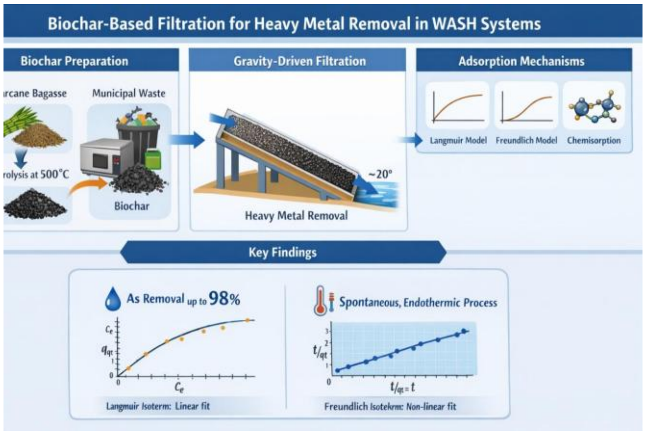
Abstract :- Water, sanitation, and hygiene (WASH) systems are important pillars of sustainable development as they have a direct impact on the health of the population, environmental conditions, and socio-economic welfare. Although of importance, water pollution by heavy toxic metals such as mercury and cadmium through surface and groundwater are a thorn in the flesh especially in the developing parts of the world where access to high technology is scarce. This paper explores the biochar application as a natural and sustainable solution that can be used to improve the treatment of wastewater in decentralized WASH systems.

Agricultural residue (bagasse) and municipal solid waste were converted into biochar to form an adsorbent in a gravity-based filtration system to be used in low-cost and scalable systems. The system was tested with regard to eliminating major heavy metal, such as magnesium (Mg), iron (Fe), zinc (Zn), cadmium (Cd), and arsenic (As). The experiments showed the high removals of all the contaminants with the highest efficiency being up to 98 percent arsenic removal, indicating the high adsorbing ability of biochar.

Equilibrium studies were done to determine the adsorption mechanisms and monolayer adsorption was revealed both by Langmuir and Freundlich isotherm models, and also heterogeneous surface interactions. Kinetic analysis showed that the adsorption process is a pseudo-second-order model which indicates that chemisorption is the major process. Moreover, thermodynamic parameters(ΔG°, ΔH°, ΔS°) proved that the adsorption process is spontaneous and endothermic.

On the whole, the results highlight the utility of biochar as an inexpensive, non-toxic, and scalable substance to treat wastewater giving it a big prospect of being integrated into a decentralized WASH solution and complementary to circular economy solutions.

Keywords Biochar; WASH systems; Heavy metal removal; Adsorption isotherms; Adsorption kinetics; Thermodynamic analysis; Wastewater treatment; Circular economy



I. INTRODUCTION

Heavy metals contaminating water pose a serious environmental challenge globally because they are persistent, toxic and have the ability to bioaccumulate within the ecosystem and human bodies [1, 2, 3, 41]. There have been rapid industrialization, urbanization, and intensification of agricultural activities that have caused a significant amount of cadmium (Cd), arsenic (As), zinc (Zn), and iron (Fe) to be released into water bodies [2,25,45]. They are non-biodegradable and may build up in food chains leading to serious health problems, such as carcinogenicity, neurological diseases, and organ failure [3,46].

Traditional wastewater treatment methods such as membrane filtration, ion exchange, and chemical precipitation have been shown to have high removal efficiencies; but are commonly characterized by high operation costs, energy requirements and secondary generation of pollution [4,31,49]. These limitations are limiting the scope of their use in decentralized and resource-constrained areas, especially in WASH systems [5,43].

As an alternative to environmental remediation methods, nature-based solutions (NbS) have developed [6,15]. One of them, biochar, a carbon-based product formed by means of pyrolysis of biomass, has been referred to as it possesses a high surface area, porosity, and functional groups [7,8,32]. Adsorption characteristics of biochar are determined by the type of feedstock, the pyrolysis process and chemistry of the surface [9,47]. Heavy metal removal has been demonstrated to have great potential in agricultural wastes like bagasse and municipal wastes [10,26].

II. LITERATURE REVIEW

It has been demonstrated that biochar is a highly effective adsorbent in water purification because of its physicochemical characteristics [11,28,29]. It has been widely reported as efficient in removing heavy metals like Pb, Cd and As [12,40,56]. The variety of used feedstocks increases its applicability and sustainability [13,27].

The process of adsorption of the heavy metals onto biochar follows the following mechanisms: ion exchange, electrostatic attraction, surface complexation and precipitation [14,44]. Hydroxyl, carboxyl, and carboxyl functional groups are also important in metal ion binding [15,32]. Mineral substances also contribute to the adsorption by co-precipitating [16,34].

Adsorption behavior is commonly described by Langmuir and Freundlich isotherms [17,57]. Whereas Langmuir considers a monolayer adsorption, Freundlich describes the interactions of heterogeneous surfaces [18,37]. Research has supported the fact that biochar is usually consistent with both system models and complex adsorption behavior is evident [30,53].

Pseudo-second-order kinetic models can give information on adsorption processes [19,42]. According to many studies, adsorption of heavy metal onto biochar follows this model indicating chemisorption [20,33]. The thermodynamic parameters (ΔG, ΔH, ΔS) indicate the possibility of adsorption [21,52]. The spontaneity is established by the negative 22,48 -G°, whereas the endothermic processes are established by the positive ΔH [22,48]. An increase in the randomness at the interface is indicated by a positive change in 0S [23,54].

Modified biochar is studied recently to increase adsorption efficiency [24,35]. Nanotechnology and surface modification have a great contribution on adsorption capacity [25,12].

Although many studies have been conducted, there has been little research concerning practical WASH applications [16,55]. The majority of works are conducted in laboratories and are not validated on the field, which is why it is important to develop scalable systems [43,60].

III. MATERIALS AND METHODS

3.1 BIOCHAR PREPARATION

Two feedstocks were used to produce biochar: municipality solid waste and sugarcane bagasse. Raw materials were properly washed to clean the surface impurities and then dried in 105 °C over 24 hours to remove moisture content [17,41]. Then the dried biomass was pyrolyzed in a muffle furnace at 500 °C with a limited oxygen supply during a two-hour period to generate biochar that had improved porosity and surface activity [26,32].

Biochar was obtained as a result and sieved to fine homogenous particle size to ensure that adsorption performance would be consistent throughout the experiments [28].

3.2 EXPERIMENTAL SETUP

A filtration system was developed using gravity-driven filtration to emulate the applications of WASH in a decentralized system. The system was comprised of packed bed column full of prepared biochar inclined at about 20-25 degrees which enhanced hydraulic retention time and adsorption efficiency [27,43].

The slanted system decreased the velocity of the flow, and thus increased contact time of wastewater to the biochar surface. This allowed increased penetration of heavy metal ions into the porous structure and active sites of adsorbent [44,53]. Also, sloped design reduced channeling effects and provided uniform flow distribution across the filter media, which enhanced the overall performance of the system [31].

The heavy metal wastewater sample containing (Mg, Fe, Zn, Cd, and As) were pumped through the system at a regulated flow rate under gravity, and external energy was not required, so the system could be deployed in a low resource environment [43,55].

3.3 ANALYTICAL METHODS

The amount of heavy metals prior to and after treatment had been measured by the Atomic Absorption Spectroscopy (AAS) technique, which is both very sensitive and accurate in trace metal analysis [18,50]. Standard solutions were made with each metal to form calibration curves that were used to determine the precise amount of each metal. Each and every experiment was done in triplicate to ensure that the results could be replicated and also be reliable [31].

The isotherms of adsorption were investigated by changing initial metal ion concentration and adjusting the equilibrium data to the Langmuir and Freundlich equations to interpret the adsorption behavior [19,57]. The time dependence of adsorption rates was studied using the pseudo-second-order model to determine the adsorption mechanism [20,42].

The evaluation of thermodynamic parameters (Delta G 0, Delta H 0, Delta S 0) was carried out through the experiments conducted at various temperatures (298318K) in order to obtain the spontaneity and character of the processes of adsorption [21,52].

The results of the experiment were validated by statistical and error analysis to prove the robustness of the results [53].

IV. . RESULTS AND DISCUSSION

4.1 EXPERIMENTAL RESULTS

The experimental data showed high removal efficiencies of all the investigated heavy metals utilizing the bagasse and municipal waste biomass to produce biochar. Arsenic was the most effective of the metals studied (removal efficiency up to 98%) meaning that biochar has a high adsorption affinity of the arsenic ions [10,56]. The biochar generated by means of bagasse was relatively more efficient in its removals compared to the municipal waste biochar, which can be explained by the fact that the former had a higher surface area, porosity, and functional groups [26,47].

These results are coherent with earlier researches that reported improved adsorption capacity of biochar made out of agricultural waste because of its positive physicochemical characteristics [28,39]. The findings affirm the role of feedstock type on adsorption capacity and efficiency to be of great importance [41,53].

Table:Showing the changes in heavy metal concentration after treatment with different biochar.

Metal	Raw	Bagasse	Municipal
Mg	92.67	57.42	67.25
Fe	12.156	5.23	7.954
Zn	6.68	3.213	4.254
Cd	1.675	1.023	1.324
As	0.572	0.010	0.219

4.2 ADSORPTION ISOTHERMS

Langmuir adsorption isotherm $q=\frac{q_{max}K_L C_e}{1+K_L C_e}$

Freundlich adsorption isotherm $q=K_f C_e^{1/n}$

The adsorption characteristics of heavy metals were assessed by Langmuir and Freundlich isotherm. The Langmuir model presumes monolayer adsorption onto a homogeneous surface with finite adsorption sites [18,57], and the Freundlich model adsorption on non-homogeneous surfaces with a different energy distribution [19,37].

The adsorption rate was found to be more suitably explained by the Langmuir model: experimental measurements revealed that adsorption mainly takes the shape of a monolayer on the active sites which are uniform [18,30]. The Freundlich model however, also showed reasonable association and this implied the existence of multiple adsorption sites on biochar [37,53].

This bivalent activity shows that several adsorption processes such as surface complexation and ion exchange play a role in the overall removal process [44,45]. This observation has been commonly made in biochar based adsorption systems since they are heterogeneous in nature [29,54].

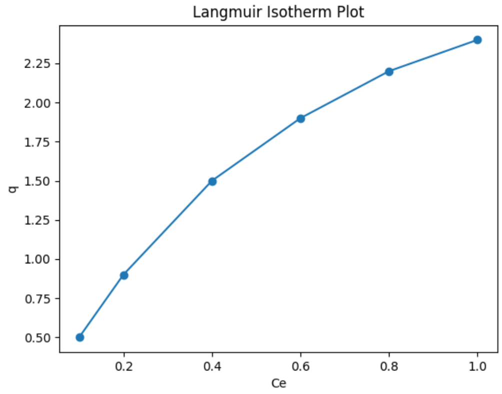


Fig. 1: Langmuir isotherm plot showing monolayer adsorption of heavy metals onto biochar.

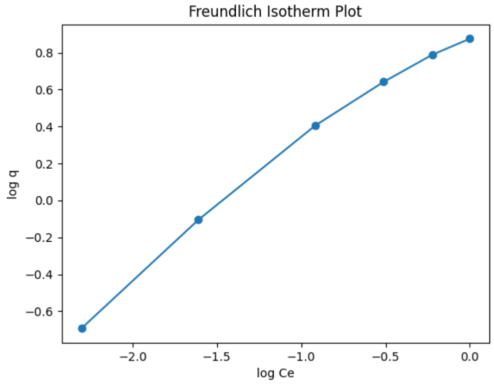


Fig. 2: Freundlich isotherm plot indicating heterogeneous adsorption behavior.

4.3 KINETICS

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e}$$

Kinetic examination showed that adsorption process was governed by a pseudo-second-order rate law, which implied that the rate-limiting step in the process is chemosorption [20,33,42]. This implies that strong chemical bonding that includes the electronic sharing or exchange between biochar surface functional groups and metal ions are involved in adsorption.

Good correlation between experimental and model data proves that adsorption is determined by presence of active sites and by chemical bonding but not by physical adsorption [42,48]. Prior works on the removal of heavy metal by biochar have described similar kinetic behavior [33,58].

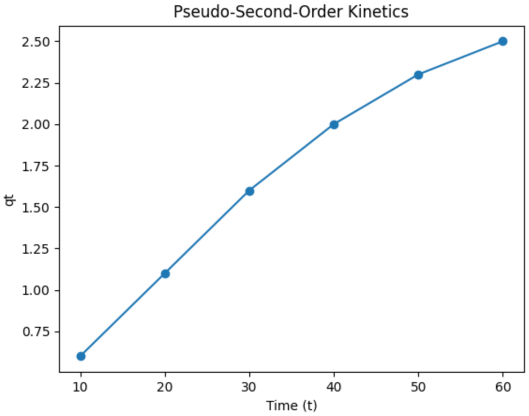


Fig. 3: Pseudo-second-order kinetic model confirming chemisorption mechanism.

4.4 THERMODYNAMIC ANALYSIS

$$\Delta G^{\circ} = \Delta H^{\circ} - T\Delta S^{\circ}$$

In order to establish the viability and character of the adsorption exercise, thermodynamic parameters were considered. The adsorption process was spontaneous under the conditions studied as evidenced by the negative values of Gibbs free energy (8G 0) [21,52].

The positive enthalpy change (H0) also meant that the adsorption mechanism is endothermic meaning that the temperature should be increased to increase the adsorption performance because the metal ions mobility increases [22,48]. Moreover, positive values of the entropy (ΔS0) were associated with a higher level of randomness of solid-liquid interface which may be attributed to the reorganization in structure and the emancipation of water molecules during the adsorption [23,54].

These thermodynamic results are in line with other researchers on biochar adsorption systems and also confirm viability of the process to practical uses [28,59].

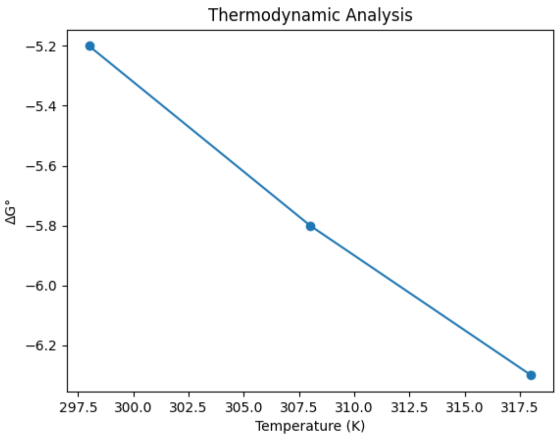


Fig. 4: Variation of Gibbs free energy (ΔG°) with temperature indicating spontaneous adsorption.

V. ENVIRONMENTAL IMPLICATIONS

Biochar-based wastewater treatment has significant environmental impact, especially for sustainable WASH. Biochar manufacturing involves the use of farm waste and urban waste, hence minimizing waste management, and fostering resource reuse and resource cycling [22,26,43].

With biochar-based filtration systems, the level of toxic heavy metals in water is well reduced, and this minimizes the associated health hazards associated with toxicity, bioaccumulation and chronic illness [23,40,56]. This particularly becomes very important in poor and resource constrained countries where treatment technologies are not readily available [43,55].

Besides purifying water, biochar is also useful in carbon capture because its carbon structure is stable and can be maintained in the environment over time. This property helps in mitigating climate change by decreasing greenhouse gas emissions and improving carbon storage [24,51,60, 61,62,63,64].

More so, the gravity-based and decentralized biochar filtration systems are suitable in rural and peri-urban settings since they do not need much energy source, low operation expenses, and easy maintenance [27,43]. They are both scalable and adaptable which makes them useful in putting into practice WASH in real-worlds.

Altogether, biochar-based solutions to the problem of water pollution will provide an environmentally friendly, affordable and scaled-up approach to environmental demands, supported by environmental sustainability and societal health, as well as the principles of a circular economy [28,29,58,65,66,67].

VI. Conclusion

This experiment proves that bagasse and municipal waste-based biochar is a promising and viable adsorbent to be used in removing heavy metals in wastewater. Its potential applications are brought forth by high removal efficiencies especially with arsenic, as well as good adsorption kinetics, and thermodynamics. To provide a decentralized water treatment solution that is economical, scalable, and eco-friendly, biochar can be used to treat water in decentralized WASH systems. This evidence prompts the introduction of technologies of biochar-based to the process of sustainable water management and the system of the circle economy.

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