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Invasive Aquatic Plants as Potential Sustainable Feedstocks for Biochar Production and as an Innovative Approach for Wastewater Treatment

K. M. P. I. Jayathilake*, P.M. Manage* and F. S Idroos†
*Centre for Water Quality and Algae Research, Department of Zoology, University of Sri Jayewardenepura, Sri Lanka
†Corresponding author: F. S Idroos; sumaiyaidroos@sci.sjp.ac.lk

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ABSTRACT

Biochar (BC) is a well-established physical treatment method. The high-cost BC limits their use as adsorbents in wastewater. Thus, deriving BC from cheap and locally available waste materials is needed to develop a feasible waste removal technology. Nowadays, BC technology makes it possible to envision a new strategy to manage invasive plants by converting them into value-added products like BC. Hence, the present study was designed to evaluate the potential utilization of BC as an efficient filter medium made by invasive aquatic plants, *Salvinia* spp., and *Eichhornia* spp. A mass of 50 g of prepared activated and nonactivated BC was incorporated in a sand and gravel filter to treat rubber-manufactured wastewater. Wastewater was passed through the filter, and both raw and treated water samples were analyzed for pH, Total Suspended Solids (TSS), Biological Oxygen Demand (BOD_5), Chemical Oxygen Demand (COD), Total Kjeldahl Nitrogen (TKN), Ammoniacal-Nitrogen (NH_3-N), Electrical Conductivity (EC), Total Dissolved Solids (TDS), Total Phosphates (TP), Nitrate (NO_3-N), turbidity and heavy metals (Zinc, Chromium). The control filter was developed only with sand and gravel, excluding BC. Fourier Transform-Infrared Spectroscopy (FT-IR) and Scanning electron microscopy (SEM) were used to analyze BC's chemical and physical characteristics. A brine shrimp lethality assay was carried out for toxicological evaluation. OH stretching (3,550-3,200 cm^{-1}), C=C aromatic stretching (1400-1660 cm^{-1}), and Phenol-O-H bending (1,300-1,400 cm^{-1}) were recorded in all BC samples that involved the adsorption mechanism. Observed images indicated differences in surface morphology of both activated and nonactivated BC were observed under SEM observation. The study concludes that the filter unit incorporated with activated *Eichhornia* spp. Gave the best treatment efficiency when compared to filter units incorporated with other activated and nonactivated BC. The toxicity assay revealed 100% mortality in the control setup and raw wastewater but only 60–70% in the nonactivated BC integrated filters. Activated BC-incorporated filters showed no mortalities. Hence, the study's outcomes suggest a green approach using invasive aquatic plants for sustainable wastewater treatment.

INTRODUCTION

The application of biochar (BC) for the remediation of contaminated water sources may provide a new solution to water contamination issues (Zhang et al. 2013). BC can potentially be applied to decrease and mitigate the bioavailability and leachability of inorganic contaminants like heavy metals and organic contaminants in water sources through adsorption and other physicochemical interactions due to the special properties of BC. BC has been widely used for water conditioning, carbon sequestration, and water remediation. The abundant surface area of BC, the well porosity structure of BC, and the high affinity of functional groups of BCs are reasoned for the proper absorption of heavy metals and aromatic compounds on its surface. Hence, BC can be applied as a low-cost, suitable adsorbent to remove contaminants from wastewater (Mohan et al. 2014, Inyang et al. 2016).

Biological invasions have a massive number of known and potential impacts on community structure and function of ecosystems and seriously affect the ecological status of water sources (Havel et al. 2015, Leuven et al. 2017). The rapid spreading of invasive plants poses a growing threat to the natural environment throughout all countries. One of the most prominent impacts of invasive species is the direct loss of crops due to infestations. Most invasive plants disturb the scenic beauty of the area and can directly or indirectly create concern and stress among local communities and badly affect the tourism industry (Stiers et al. 2011).

BC is usually produced from various sources, such as crop residues, wood biomass, animal litter, and solid waste (Meyer et al. 2011). However, the resource utilization of invasive plants has become an effective strategy for controlling and managing invasive plants, reducing the cost of prevention and control and turning waste into treasure. (Feng et al. 2021). Recent developments in BC technology make it possible to envision a new strategy to manage invasive plants by converting them into value-added products like BC (Zimmerman et al. 2011).

The high cost of BC limits their use as adsorbents in wastewater treatment and other applications. Presently, researchers pay attention to invasive plants to prepare BC as an environmentally friendly and cheap method for different applications including pollution remediation. Most recently, wastewater treatment using biochar (BC) has become a new technology due to specific characteristics that significantly differ from other alternatives. The physical and chemical properties of BC (surface area, porosity, surface charge, functional groups, and mineral contents) play an important role in adsorption (Zhao et al. 2019). Hence, there is growing interest in using BC as a filter medium(absorbent) to treat water and wastewater due to its unique properties of BC (Perez-Mercado et al. 2018). The feedstock type and water content of biomass can significantly influence the structure and properties of BC and, hence, its adsorption capacity (Song et al. 2019). The use of invasive aquatic plants as BC feedstocks is more economical and easily available compared to other biomass waste (Feng et al. 2021). Hence, this study used BC produced from *Eichhornia* spp. and *Salvinia* spp. to prepare the filter medium to treat industrial wastewater. This study will help mitigate and manage the aquatic invasive plants' proliferation and enhance the quality of the chemical wastewater released into the environment.

MATERIALS AND METHODS

Sample Collection

Salvinia spp. and *Eichhornia* spp. were collected from the Bellanwila-Nedimala Aththidiya canal, Sri Lanka (6.838037,79.892105) were used as the biomass for biochar (BC) preparation. Wastewater samples were received from a rubber glove manufacturing plant in Colombo, Sri Lanka. The samples were collected in pre-cleaned plastic containers and transported to the laboratory.

Preparation of BC

BC was prepared according to the method described by Agrafioti et al. (2013) with minor modifications of the pyrolysis process. The *Salvinia* spp. and *Eichhornia* spp. were chopped into small pieces. Feedstock was sun-dried. Dried samples weighing 250 g were placed in a muffle furnace (Thermolyne, 30400). The feedstock of *Salvinia* spp and *Eichhornia* spp were heated at 300 ^{o}C/hour and 350 ^{o}C/hour, respectively.

Activation of the BC

A modified approach described by Chen et al. (2017) was used to activate the BC. A weight of 10 g dried BC was activated with 100 mL distilled water containing $ZnCl_2$ at a final concentration of 0.1 gm.L^{-1}. The mixture was stirred for 1 hour at 50 ^{o}C. The sample was aged for 12 hours at room temperature. The mixture was filtered and dried overnight at 105 °C. The impregnated sample was heated to 450 ^{o}C, held for 1.5 h under a nitrogen environment in the muffle furnace, and cooled to room temperature with a continuous nitrogen flush. The product was rinsed with 1.0 M HCl and distilled water until it obtained a neutral pH. The sample was then dried in an oven for two hours at 105 °C. The prepared BC was sorted into a size range of 125-250 μm using a sieve set. Both activated and non-activated BC from *Eichhornia* spp. and *Salvinia* spp. were labeled as AE, NAE, AS, and NAS, respectively.

BC Characterization

The microstructures and chemical structure of BC were analyzed using a scanning electron microscope (SEM) (CARL ZEISS EVO 18) and Fourier-transform infrared spectroscopy (FTIR) (Thermo Scientific Nicolet S10). OMNIC Specta TM, a data-gathering software application, was used to analyze spectral data.

Preparation of the Filter Unit and its Operation

Filter bed was prepared by 6 cm height of sterilized fine sand (0.065- 0.125 mm), 50 g of BC layer (125-250 μm), 2.5 cm height of sterilized coarse sand (2-4 mm), and 2.5 cm height of sterilized gravel layer (4-8 mm), respectively. Control filters were constructed without a BC layer. 1.5 L of raw water sample was passed through the filter unit for the treatment process. The flow rate was kept at 0.3 L.min^{-1} using a commercially available aquarium pump (NS 160). Each treatment was performed for three hours of retention time.

Analysis of Water Quality Parameters and Selection of the Efficient BC Sample

Water quality parameters such as pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), turbidity, and Biological Oxygen Demand (BOD_5) were measured using standard meters. Total Suspended Solids (TSS), Chemical Oxygen Demand (COD), Total Kjeldahl Nitrogen (TKN), Ammoniacal Nitrogen (NH_3-N), Total Phosphates (TP), nitrate, and heavy metals (Zinc, Lead, Chromium, and cadmium) were analyzed using the standard analytical methods. (AOAC, 2000, APHA, 2017). The results were compared with the nationally recommended water quality parameters described by the Board of Investment (BOI) to determine the most effective BC sample.

Bioassay for Toxicity

A brine shrimp lethality assay was carried out for the toxicological evaluation of raw and treated water samples according to the method described by Olowa & Nuneza (2013). Commercially available brine shrimp eggs (Nildiya Aquarium, Wattegedara) were purchased and allowed for hatching using 1 L of natural saltwater. Ten newly hatched nauplii were added separately for every 10 mL of raw and treated water samples. The control was created using distilled water. After 24 hours, the dead nauplii were counted. The experiment was carried out in triplicate.

Analytical Statistics

A one-way ANOVA was carried out using SPSS version 21. The Tukey HSD, a multiple comparison test, was applied to find differences between both treatments.

RESULTS AND DISCUSSION

Chemical industrial wastewater consists of numerous inorganic and organic contaminants. At present, biochar (BC) has become a suitable absorbent for wastewater treatment. Hence, in this study BC has been used to treat chemical wastewater. Depending on the industry, different levels of contaminants are released into the environment directly or indirectly through effluent sources (Massoudinejad et al. 2015). In the present study, BC was prepared by two selected invasive plants in Sri Lanka: *Eichhornia* spp and *Salvinia* spp. These invasive aquatic plants pose a serious threat to the ecosystems. Hence, their use in BC preparation will be a sustainable control and management method.

BC Yield

BC conversion rates of selected biomass differed for both plants. Table 1 presents the percentages of BC produced from 250 g of each plant. In this study, the percentage of BC production of *Salvinia* spp. and *Eichhornia* spp was respectively 34.70% and 35.54%. Enaime et al. (2020) have shown that the generally slow pyrolysis process is reasoned to produce 27 – 37% of BC.

Chemical Characterization of Activated and Nonactivated BC

FTIR spectroscopy can provide direct information on the existence of different surface functional groups present in the organic matter of BC. The adsorption rate of BC also depends on the types and levels of surface functional groups (Qambrani et al. 2017).

In this study (Fig. 1), broadband was found at 3200-3400 cm^{-1} (O-H stretching) in all the BC samples, including AS, AE, NAS, and NAE. This O-H stretching may be attributed to the presence of hydroxyl groups. Similar FTIR spectra were reported by Song et al. (2019) for the rice straw BC with broad bands of 3411 cm^{-1} representing the O-H stretching. Moreover, a sharp band was observed at the 1400-1660 cm^{-1} range (C=C stretching) in all the BC samples. This C=C stretching may be attributed to the presence of aromatic groups. Song et al. (2019) have reported similar FTIR spectra for the pig manure BC with bands 1417 cm^{-1} representing the C=C aromatic stretching.

Qian et al. (2013) have reported that the peaks around 1375 cm^{-1}, corresponding to the O-H bending of phenols, were found in chars derived from red cedar and sorghum. This study found sharp peaks in the 1300-1400 cm^{-1} range, corresponding to phenol O-H bending, in all the BC samples. Similar FTIR spectra were reported by Song et al. (2019) for the rice straw BC with broad bands of 1088.3 cm^{-1} representing the C-O stretching. The peaks in the 1080-1300 cm^{-1} range, corresponding to C-O stretching C-O-C groups and aryl ethers, phenolic C-O associated with lignin, were found in the AE BC sample.

Chen et al. (2017) have reported similar FTIR spectra for tobacco stem BC, with the band in 1057 cm^{-1} representing the C–O–C stretching. Also, in this study, the peaks in the 980-1080 cm^{-1} range, corresponding to C-O-C stretching, were observed in AS and NAE BC samples. Qian et al. (2013) reported that the peaks around 780 cm^{-1}, corresponding to aromatic C-H bending, were clearly visible in red cedar, sorghum, and switchgrass-derived BC. In this study, peaks in the 680-860 cm^{-1} range, corresponding to aromatic C-H bending, were found in the AE BC sample.

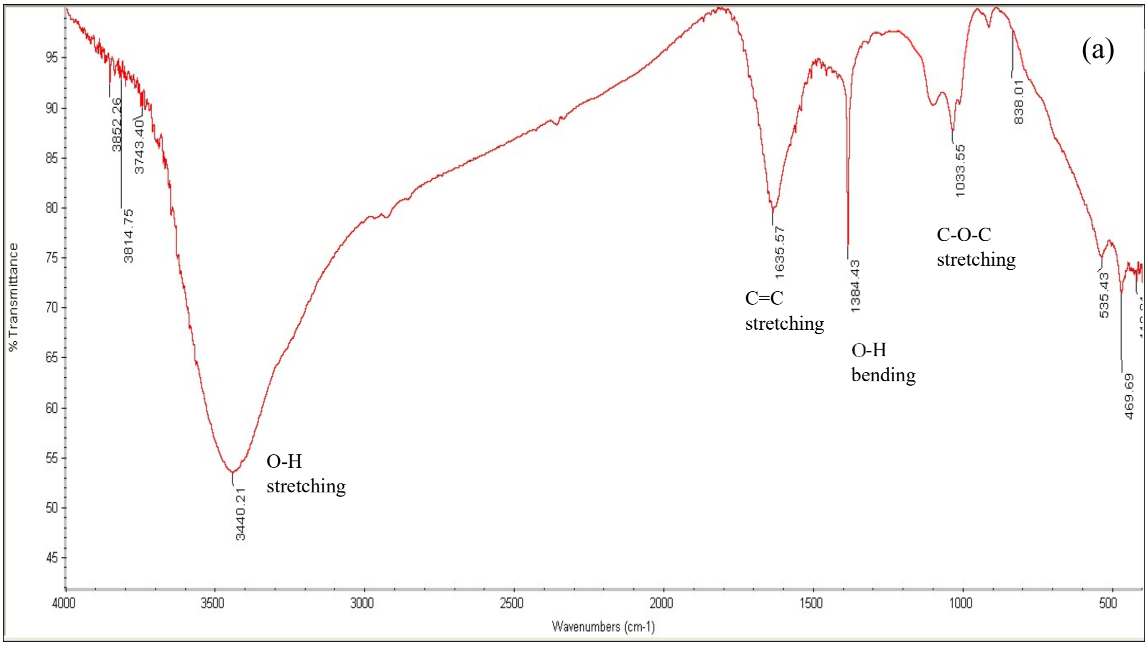
More peaks were observed in activated BC samples than in nonactivated BC samples. These peaks represented functions that involve the adsorption mechanisms. These functional groups in activated BC attributed higher water treatment efficiencies compared to nonactivated BC samples. Most peaks could be observed in the AE sample compared with AS, NAS, and NAE samples.

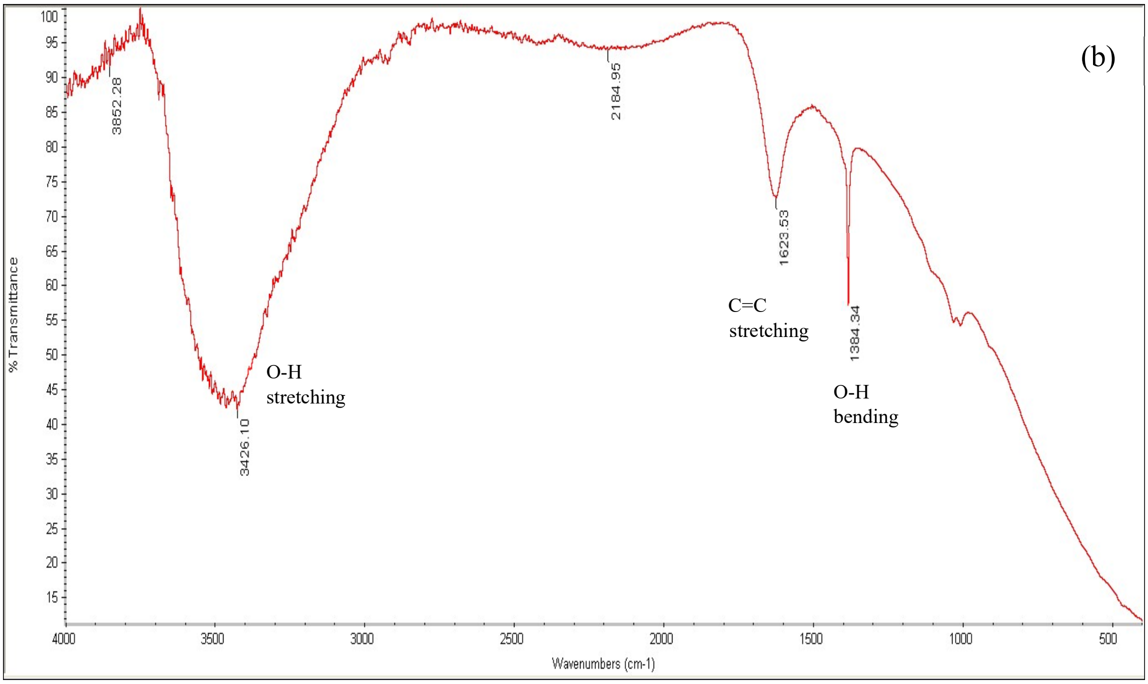
Table 1: Results on percentage biochar production of selected aquatic invasive plants.

Aquatic invasive plant	Initial dry weight before pyrolysis [g]	The weight after pyrolysis [g]	Percentage biochar production
Eichhornia spp.	250.00	88.85	35.54%
Salvinia spp.	250.00	86.76	34.70%

Physical Characterization of Activated and Nonactivated BC

SEM technique was used to observe the surface morphology of nonactivated and activated BC. Fig. 2 shows BC's scanning electron microscope (SEM) images under (10K ×) magnifications. There are clear differences between the surface morphology of the activated BC samples, and nonactivated BC samples. Cracks, crevices, and some grains of various sizes in large holes appeared on both activated and nonactivated BC samples (Fig. 2). The SEM images of the BC (both activated and nonactivated) revealed a





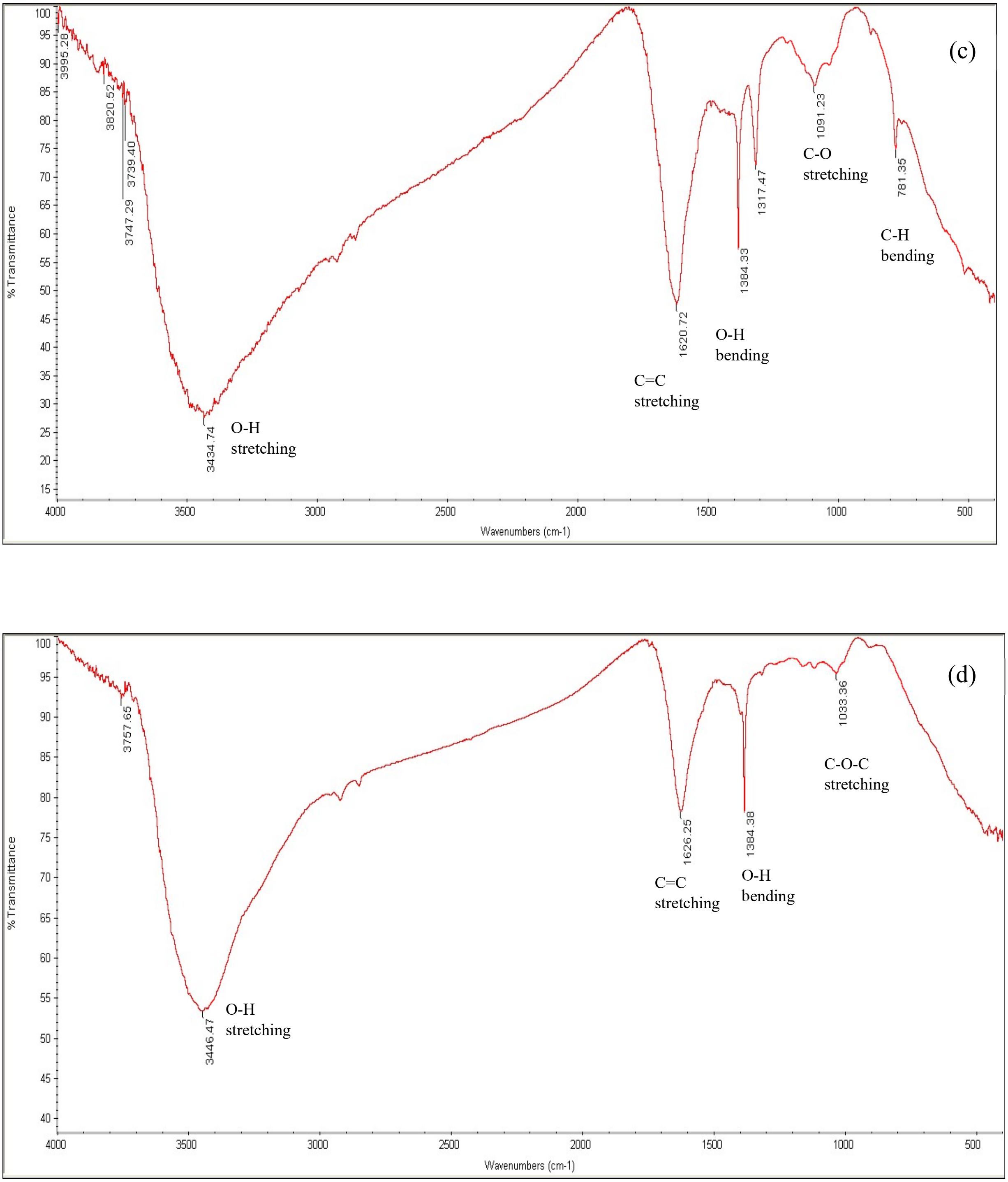


Fig. 1: Fourier-transform infrared spectroscopy (FT-IR) spectra of biochar (a) Activated *Salvinia* spp. (b) Non-activated *Salvinia* spp. (c) Activated *Eichhornia* spp. and (d) Non- Activated *Eichhornia* spp.

random pore structure on the material's surface and pores that appeared to be distributed all over the BC surface. Pores of various sizes and shapes could be observed. Masto et al. (2013) have shown that when the biomass is heated under the pyrolysis process, volatile matters are released out of the feedstocks, which make micropores on the surface of BC,

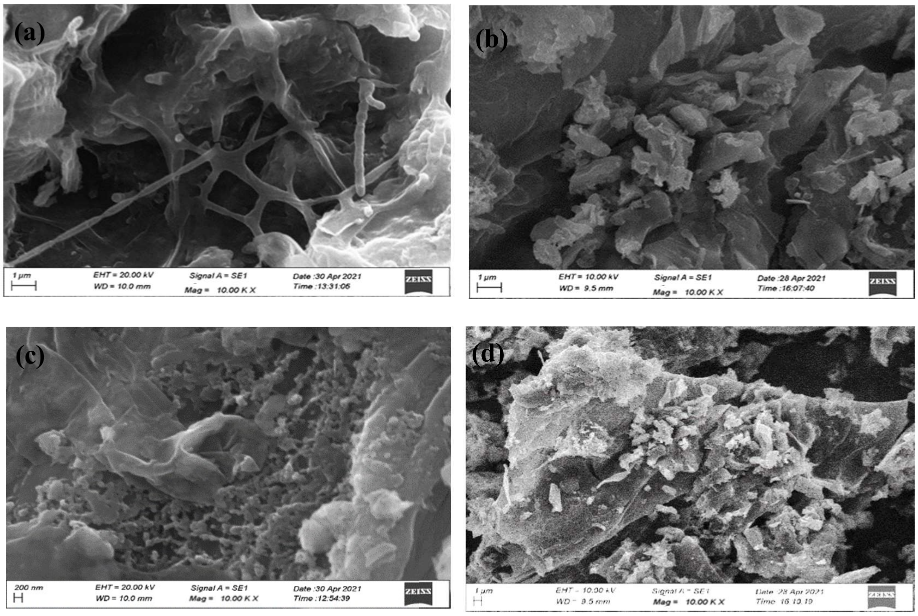
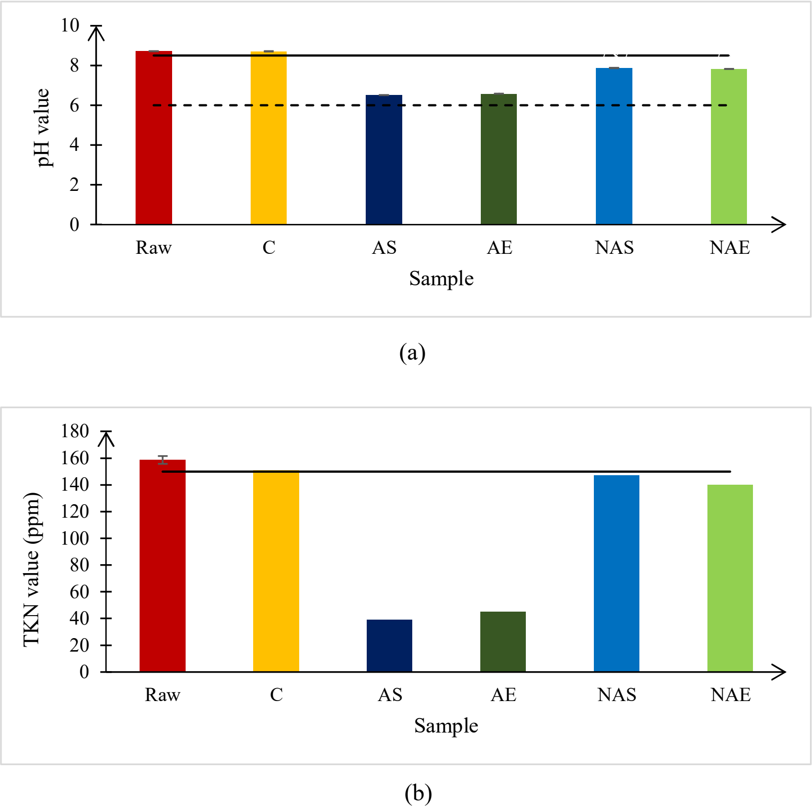


Fig. 2: Scanning electron microscope images of biochar (a) Activated *Salvinia* spp (10K ×) (b) Nonactivated *Salvinia* spp. (10K ×) (c) Activated *Eichhornia* spp. (10K ×) (d) Non-Activated *Eichhornia* spp. (10K ×).

while the volatiles trapped inside the feedstocks expand the microstructure. Thus, the resulting BC has with high surface area and porosity. These two properties are particularly useful for increasing the water holding capacity and are also reasoned for enhancing adsorption mechanisms and capacity by providing huge surface areas (Enaime et al. 2020).



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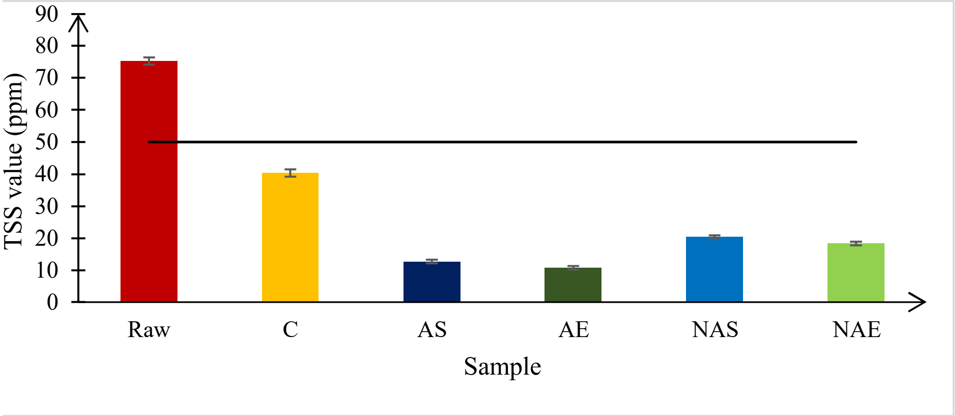

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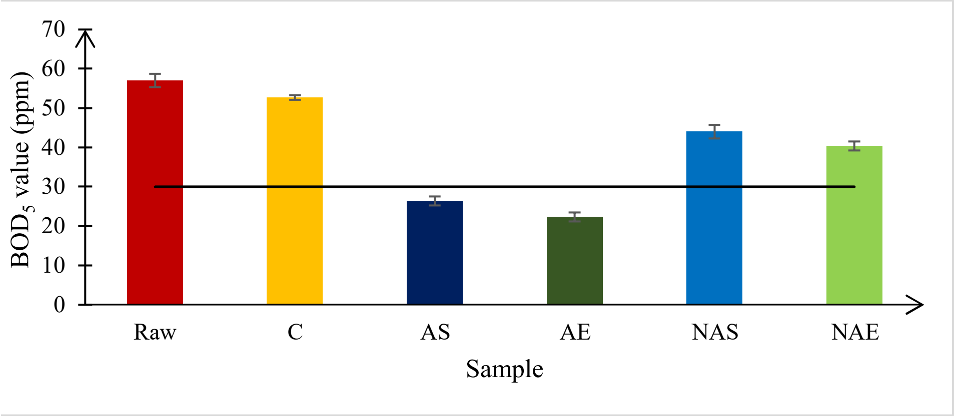

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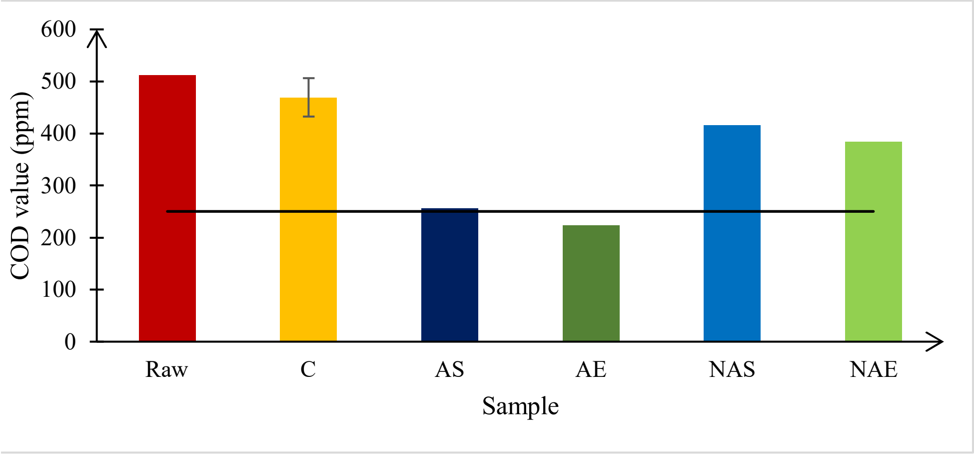

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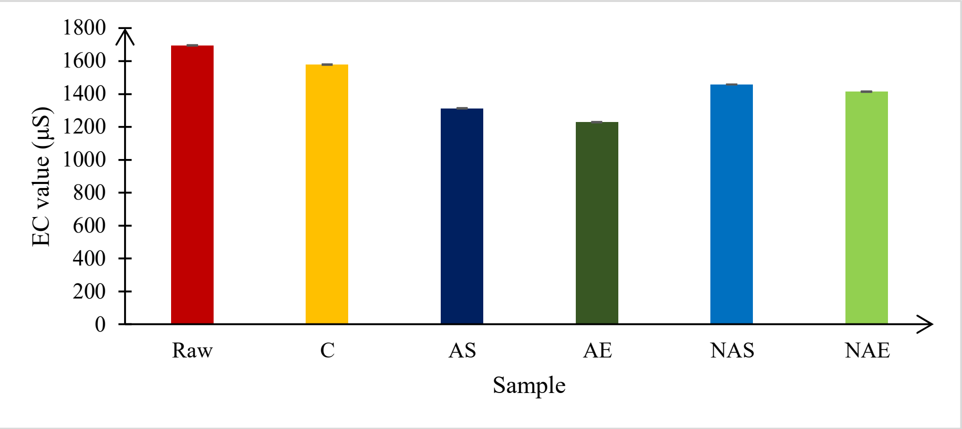

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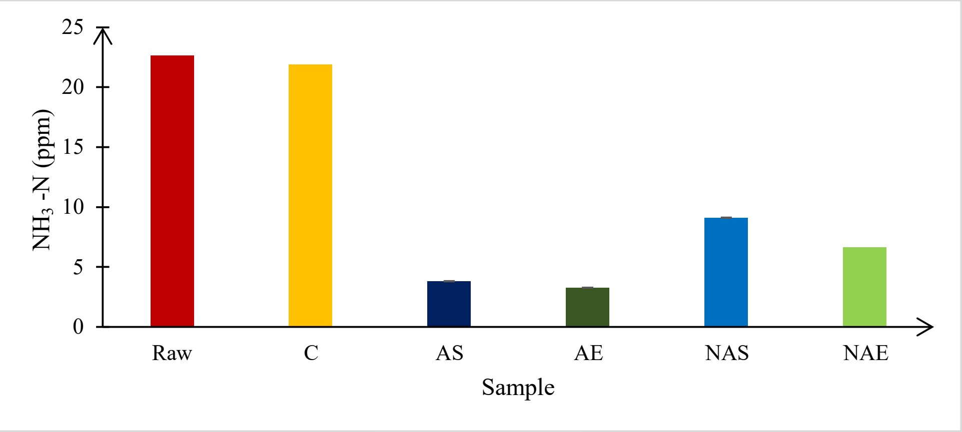

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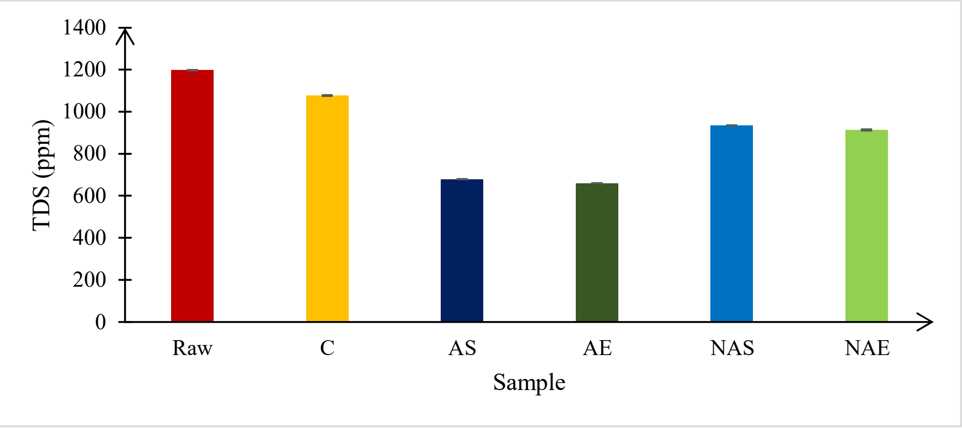

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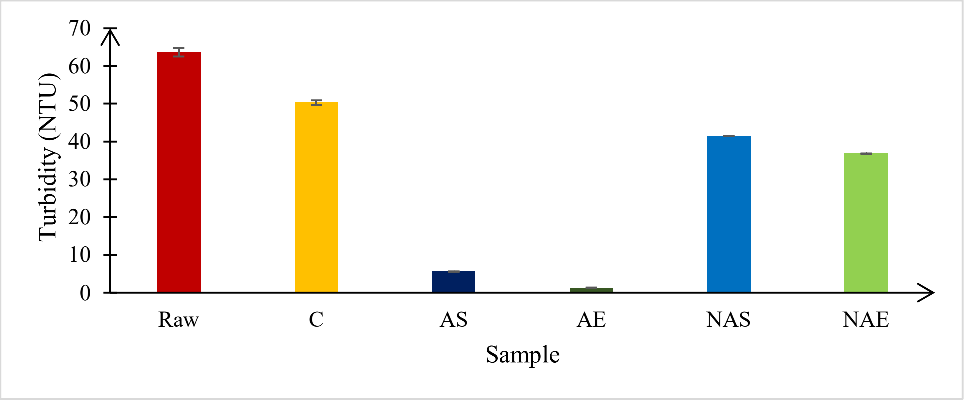
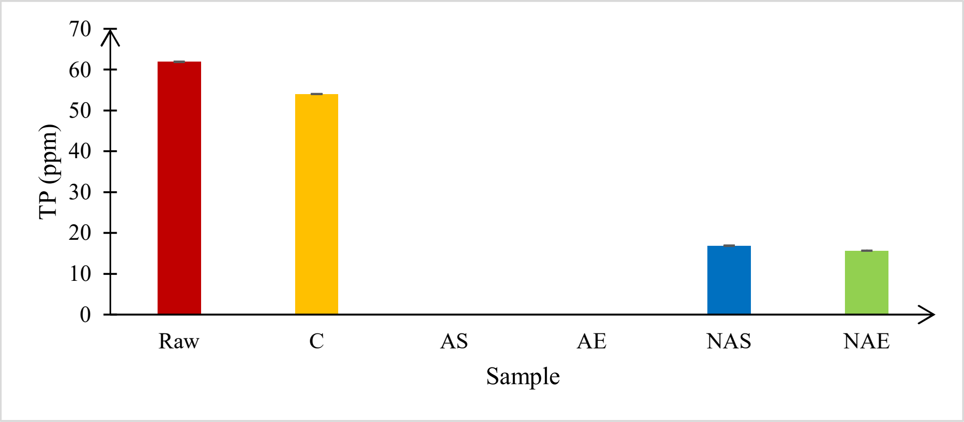


(i)



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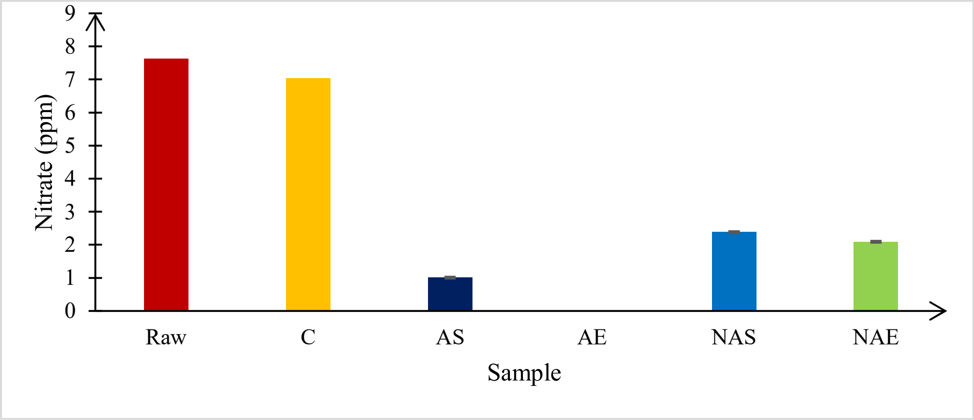

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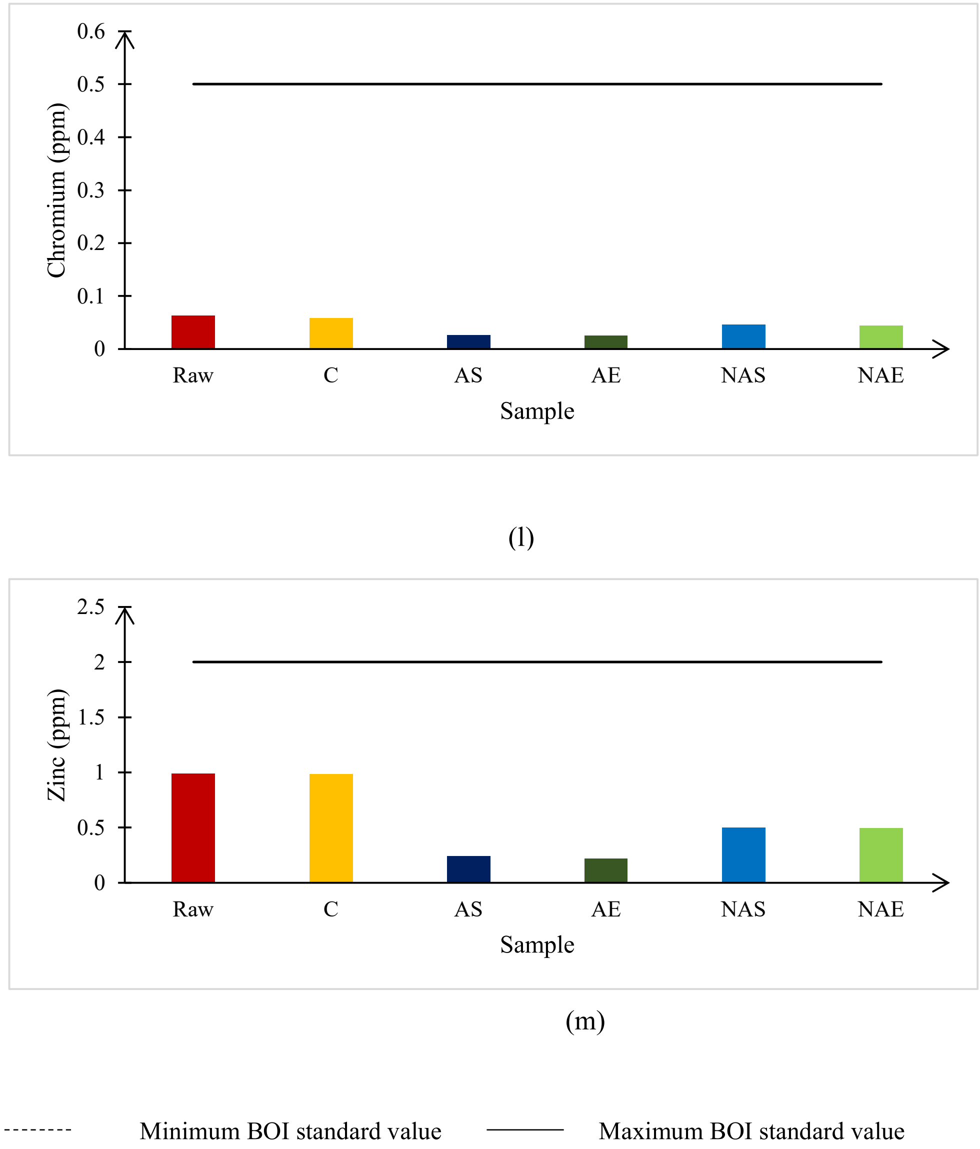

(l)

(m)

Fig. 3: Readings of measured water quality parameters of raw sample and treated samples (a) pH (b) Total Kjeldahl Nitrogen (TKN) (c) Total Suspended Solids (TSS) (d) Biological Oxygen Demand (BOD_5) (e) Chemical Oxygen Demand (COD) (f) Electrical Conductivity (EC) (g) Ammoniacal Nitrogen (NH_3-N) (h) Total Dissolved Solids (TDS) (i) Turbidity (j) Total Phosphates (TP) (k) Nitrate (l) Chromium (m) Zinc.

Water Quality Parameters of Treated and Non-Treated Water

The present study forwards a BC-incorporated laboratory sand filter as a treatment option for wastewater. The filter unit was developed using fine, coarse sand, gravel layers, and BC layers (activated and nonactivated BC). The BC layer was placed in between fine and coarse sand layers. The raw water was passed through different filter units to select the best filter media for the effective treatment process. In addition, the control setup was developed incorporating only sand and gravel layers, excluding any form of BC. The measured water quality parameters before and after treatment through control setup activated BC and nonactivated BC filter units are presented in Fig. 3.

The raw water had a higher pH value (8.72±0.01) than the neutral pH (pH = 7). The recorded pH value of raw water exceeded the national recommended water quality criteria (6.0-8.5). The pH values observed in the treated water obtained from activated and nonactivated BC-containing filter units were close to the neutral pH.

The two traditionally most common oxygen demand measures are the BOD and the COD. The BOD determines the biodegradable fraction in the wastewater, and the COD measures both the biodegradable and non-biodegradable organic content by oxidizing them in acidic conditions. Previous studies have demonstrated that large specific surfaces and high porosity of BC provide better absorption capacity, which is reasoned for the greater reduction of organic matter than sand. After the initial period dominated by physical and chemical filtration processes, biological activities gradually take over due to the development of a biofilm in BC (Rolland et al. 2009).

In this study, BOD_5 values of raw water (57±1.73) and raw water treated with nonactivated BC samples (37-44 ppm) and control setup (52.67±0.58) exceeded the national recommended water quality criteria. However, BOD_5 values of raw water treated with activated BC samples (14-24 ppm) were lower than the national recommended water quality criteria (30 ppm).

The organic matter removal efficiency is also measured as COD throughout the experiment. Gwenzi et al. (2017) have reported that BC produced from biomaterials has a favorable removal ability for organic contaminants that cause COD. In general, pore-filling, hydrophobic effect, electrostatic interaction, and π–π bond interactions are the main mechanisms of organic contaminants sorption by BC (Gupta et al. 2016; Wang et al. 2020). Pore-filling is an important mechanism for the sorption of organic contaminants in BC. The sorption capacity is directly related to the micropores' surface area (Han et al. 2013). The SEM images of all BC samples have a porous structure, which is one reason for the reduction of COD values in this study. In this study, both activated and nonactivated BC samples have C=C aromatic stretching at 1400-1660 cm^{-1}. It represents BC's π–π bond interactions and is reasoned for proper COD removal compared with raw water.

The COD value of water obtained from the AE filter unit (224 ppm) was close to the national recommended water quality criteria (250 ppm). The COD value of water treated with AS filter (256 ppm) exceeded the national recommended water quality criteria. COD values (320-416 ppm) of water obtained from nonactivated filter units were more significant than the national recommended water quality criteria.

The recorded TKN value (158.67±2.89 ppm) in the raw water sample also exceeded the national recommended water quality criteria (150pm). However, TKN values of water treated with activated BC filter units (33-45 ppm) showed a clear difference. However, the TKN values of water treated with nonactivated BC (134-147 ppm) were slightly higher than water treated with activated BC. The TKN values (151 ppm) of water obtained from the control setup did not show rapid reduction compared with raw water. Gupta et al. (2016) reported that the wastewater TKN showed a 58.3% reduction after passing through the BC-containing filter.

The EC value (1578.33±1.53 µS) of water obtained from the control setup has shown little change when compared with raw water (1694±1.73 µS). EC values in water treated with activated and nonactivated filter units ranged from 1220-1460 µS. The EC variation among filter units was quite low compared to raw water's EC value.

The TDS values of water obtained from activated BC filter units showed a two-fold reduction to raw water (1197.33±1.15 ppm). TDS values of water obtained from nonactivated filter units (870-940 ppm) were lower than raw water. However, EC and TDS values of water obtained from the control setup (1076.67±2.31 ppm) did not show clear variation when compared with raw water. Delavernhe et al. (2018) have reported that functional groups like C-H and C-O-C on the BC surface can potentially interact with TDS-causing pollutants, resulting in enhanced removal (Delavernhe et al. 2018). In this study, C-O-C stretching was observed in AS and NAE samples, which is one of the reasons for removing TDS-causing pollutants in these samples.

This study observed higher turbidity (63.67±1.15 NTU) and TSS (75.33±1.15 ppm) in raw water. The recorded TSS value of raw water exceeded the national recommended water quality criteria (50 ppm). However, turbidity and TSS of water treated with activated BC (8-13 ppm) were reduced than water treated with nonactivated BC samples (15-21 ppm). The possibility of TSS concentration reduction upon using BC as an adsorbent was reported by De Rozari et al. (2016) when sewage was treated using BC as the filter media.

BC is also popular in inorganic contaminants removal, which targets the removal of nutrient elements nitrogen and phosphorus that exist in the form of inorganic ions in wastewater (Wang et al. 2020).

This study recorded a higher TP concentration (61.91±0.06) in raw water. But recorded nitrate concentration (7.62 ppm) of raw water is very low. Also, the recorded ammoniacal nitrogen concentration (22.63 ppm) of raw water was lower than the national recommended water quality criteria (50 ppm). However, there are no national recommended water quality criteria for nitrate and TP to discharge industrial effluents into inland surface waters. A clear difference was not observed in ammoniacal nitrogen (21.9 ppm), TP (54.01±0.06 ppm), and nitrate (7.04 ppm) concentrations of raw water treated with the sand and gravel filter unit.

Lou et al. (2016) have reported that BC's high surface area and oxygen functionality are rarely effective for removing phosphate forms and other anions. TP was not detected in raw water treated with activated BC. The TP concentration of raw water treated with nonactivated BC samples (NAS = 16.86±0.06 ppm, and NAE = 15.63±0.06 ppm) is low comparatively TP concentration of raw water.

Ajmal et al. (2020) have reported the removal efficiency of phosphate from wastewater by BC before and after magnetic modification. Results showed that magnetic BC's sorption efficiency was twice that of unmodified BC. Also, in this study, activated BC was shown to proper removal contaminants compared with nonactivated BC. Ajmal et al. (2020) have shown that phosphate sorption of activated BC occurs due to simultaneous mechanisms like electrostatic attraction, surface precipitation, and complexation, while the phosphate sorption of nonactivated BC is dependent on electrostatic attraction. SEM images obtained in this study showed the porous structure of BC. These porous structures might be the reason for the precipitation mechanisms.

Also, nitrate was not detected in water treated with activated AE BC. Low nitrate concentration (1.01±0.03 ppm) was recorded in raw water treated with AS BC. The nitrate concentration of raw water treated with nonactivated samples is low comparatively nitrate concentration of raw water (NAS = 2.38±0.03 ppm, and NAE = 2.09±0.03 ppm). Viglašová et al. (2018) have demonstrated that multiple interactions, primarily electrostatic attraction and ionic bonds with exchangeable cations from the BC, are reasoned for the nitrate sorption mechanisms based on the sorption study of nitrate by bamboo BC.

Ammoniacal nitrogen concentration in raw water treated with both activated BC samples (AS = 3.82±0.01 ppm and AE = 3.28±0.01 ppm) and nonactivated BC samples (NAS = 9.11±0.02 ppm, and NAE = 6.66 ppm) has very low concentrations comparatively ammoniacal nitrogen concentration of raw water sample (22.63 ppm). Ammoniacal nitrogen concentrations of raw water treated with activated BC samples have low concentrations compared with raw water treated with nonactivated BC. Xiang et al. (2020) have mentioned that precipitation on the surface of BC is the dominant mechanism for the removal of ammonium. Moreover, previous studies have demonstrated that the BC surface is usually negatively charged due to the dissociation of oxygen-containing functional groups like carboxylic, hydroxyl, phenolic(hydroxyl), and carbonyl, which causes electrostatic attraction between BC and positively charged molecules (Ahmad et al. 2014; Qambrani et al. 2017). In this study, FT-IR spectra showed oxygen-containing functional groups like hydroxyl and phenolic in all activated and nonactivated BC samples. These electrostatic interactions due to oxygen-containing functional groups might be involved as a mechanism for ammoniacal nitrogen removal.

BC has been suggested to be used for heavy metal removal from contaminated water. Wang et al. (2020) have shown that removal mechanisms of heavy metals vary depending on the valence state of the target metal at different solution pH. In this study, raw water's concentration of Zinc (Zn) and Chromium (Cr) was high. Lead (Pb) and Copper (Cu) were not recorded in raw water and also treated water because their concentrations were smaller than the minimum detection level (Pb = 0.01 ppm, Cu = 0.01 ppm). These minimum detection level values are even lower than the national recommended water quality criteria values. There is no clear variation in Zinc concentration (0.9867 ppm) of treated water obtained from the control setup compared with raw water samples (0.9886 ppm). Also, there is no clear variation in chromium (0.0585 ppm) concentration of treated water obtained from the control setup compared with raw water samples (0.0625 ppm).

However, after the BC treatment, the initial concentration was decreased in treated water samples of all filter units compared with the raw water sample. This means BC is a suitable material for the sorption of Zinc and Chromium in wastewater. Previous studies have demonstrated that mainly four mechanisms are involved in removing heavy metals from water by BC. Electrostatic attraction between heavy metals and BC surface, ion exchange between heavy metals and alkali or alkaline earth metals or protons on BC surface, complexation with π electron-rich domain or surface functional groups, and co-precipitation to form insoluble compounds (Qian et al. 2015; Tan et al. 2015; Li et al. 2017). Precipitation and electrostatic interactions have been commonly cited as one of the main mechanisms responsible for the immobilization of heavy metals by BC sorbents due to their highest porous structure. According to the FTIR results in this study, all FTIR spectra have shown a peak at 1400-1660 cm^{-1} range representing the C=C stretching. According to previous studies, it might be a reason for the removal of heavy metals. Pan et al. (2013) reported that the abundance of functional groups in several crop straws BC has been reasoned for the Cr (III) sorption. Previous studies have demonstrated that the Zn (II) sorption mechanism by the BC derived from apple tree branch samples includes surface precipitation, ion exchange, and minor contribution by cation–π interaction (Zhao et al. 2020).

Results of Statistical Analysis

The findings showed no significant difference in pH (P = 0.708) between water treated with the control setup and the raw water sample. Significant differences were observed ($P < 0.05$) between the rest of the water quality parameters in the raw water sample and water treated with the control setup. Moreover, significant differences were also obtained for the water quality parameters ($P < 0.05$) analyzed using one-way ANOVA between the raw water sample and the BC-incorporated filter units (AS, AE, NAS, and NAE). The Turkey HSD, multiple comparison test shows that AE BC is the most effective filter medium for the treatment process.

According to the P values obtained during the statistical analysis, it is clear that treatment of raw water has taken place in all the filter units since during the treatment processes of BC incorporating filter units, all the measured water quality parameters have changed and, in the sand and gravel containing filter treatment process, except for the pH value rest of the parameters have changed. However, most of the measured water quality parameters in the sample treated with sand and gravel were closer to the values of the raw water sample. Interestingly, activated and nonactivated BC-containing sand and gravel filter units (AS, AE, NAS, and NAE) showed higher efficiency than those containing only sand and gravel. Kaetzl et al. (2018) have also shown that over the entire experiment, the removal efficiency of the gravel filter is comparatively low or equal compared with used treated water from BC.

Brine Shrimp Lethality Assay

Brine shrimp was applied as an indicator to assess the toxicity of the final treated water and raw water. Fig. 4 represents the brine shrimp mortalities during the toxicity assay of treated water samples obtained from the filter units composed of sand and gravel, activated and nonactivated BC.

In the brine shrimp toxicity assay, 100% mortality recorded in the non-treated raw water may indicate that the raw water contains higher amounts of chemicals. The treatment with the control setup does not significantly reduce the toxicity of the water as the sand and gravel were incapable of removing chemicals in the water. In the nonactivated BC-containing filter units, the mortality was lower than the water obtained from the control setup n indicating that some amounts of chemicals might be removed through the process. The samples, including nonactivated BC, NAS, and NAE, showed mortalities of 70% and 60%, respectively. There were no mortalities recorded in water samples treated through activated BC. This might be due to the efficient adsorbent of chemicals and toxic substances to the surface layers of the activated BC. Interestingly, Kaetzl et al. (2018) have shown that BC can remove organic and inorganic substances that are caused by the toxicity of wastewater due to the high adsorption capacity.

Among the BC-incorporating filter units, the AE filter unit was given comparatively better water quality parameters than AS, NAE, and NAS units. This was also proved during the Tukey HSD multiple comparison test. Activated BC produced from *Eichhornia* spp. is the most potential absorbent for industrial wastewater treatment. As a result, the current study has proposed a sustainable strategy for managing invasive aquatic plants and an efficient BC-based filter method to treat industrial wastewater.

CONCLUSION

The low cost of feedstock and physio-chemical properties of biochar (BC) make its application more feasible for wastewater treatment. Porosity, surface area, and functional groups are involved in the adsorption process. Tested activated BC filters suggest that they should have a higher capacity for treating wastewater than nonactivated BC filters, especially activated *Eichhornia* spp. Filter unit. Hence, activated BC is expected to be a highly suitable

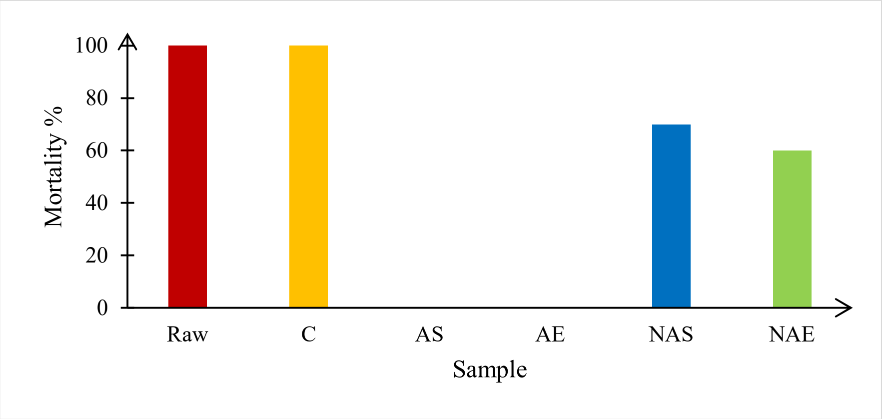

Fig. 4: Mortality of brine shrimp of raw water and treated water samples.

and sustainable material for the improvement of pH, Total Suspended Solids (TSS), Biological Oxygen Demand (BOD_5), Chemical Oxygen Demand (COD), Total Kjeldahl Nitrogen (TKN), ammoniacal nitrogen (NH_3-N), Electrical Conductivity (EC), Total Dissolved Solids (TDS), turbidity, Total Phosphates (TP), nitrate, and heavy metals (Zinc and Chromium). There is no apparent difference between the control setup and the raw water. In conclusion, BC, produced using *Eichhornia* spp., is a promising absorbent for industrial wastewater treatment. Hence, the present study has forwarded an effective BC-based filter method to treat industrial wastewater and a tangible solution for controlling aquatic invasive plants.

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