Water and Environment Journal
Promoting Sustainable Solutions
CIWEM

Water and Environment Journal. Print ISSN 1747-6585

Development of maize cob-based biochar filter for water purification

Isaac Oluk[1], Christine Betty Nagawa[2], Noble Banadda[1], Peter Tumutegyereize [1] & Prosper Achaw Owusu[3]

[1]Department of Agricultural and Biosystems Engineering, Makerere University, Kampala, Uganda; [2]Department of Forestry, Biodiversity, and Tourism, Makerere University, Kampala, Uganda; and [3]Department of Mechanical and Manufacturing Engineering, University of Energy and Natural Resources, Sunyani, Ghana

Keywords
biochar; maize cobs; pyrolysis; water filter; water quality.

Correspondence
Peter Tumutegyereize, Department of Agricultural and Biosystems Engineering, Makerere University, P.O. Box 7062, Kampala, Uganda.
Email: pierretumutegye@gmail.com

doi:10.1111/wej.12631

Abstract

The study aimed at biochar production from maize cob and its performance in improving water physiochemical attributes. Three feedstock masses (2, 2.5, 3 kg) were used for biochar production. Nine treatment combinations of T1L1, T1L2, T1L3, T2L1, T2L2, T2L3, T3L1, T3L2 and T3L3 in triplicate were used for biochar performance. Biochar yield of 50% was averagely achieved at slow pyrolysis conditions (300 to 600°C) and 120 min residence time. Biochar had 4.13% moisture content, 6.86% ash, 17.70% volatile matter, 71.28% fixed carbon, and a pH of 10.27. Odour, colour, and total hardness of the wastewater improved after filtration using biochar to acceptable levels for potable water use. Total hardness reduced by 51.9% in T2L2 and 44.4% in T3L2. Findings front maize cob biochar as a purification technology for domestic potable water use. There is need for maize cob biochar performance on heavy metals and when it is sandwiched with other materials.

Introduction

The burden of limited water resources and waterborne diseases in Low- and Middle-Income Countries (LMICs) arising from domestic use of water contaminated with toxins, and pathogens to morbidity, mortality, economic productivity, and global development cannot be underrated. Globally, an estimate of 2·39 billion diarrhoea cases was reported in 2015, of which 957·5 million occurred in children below five years (Troeger *et al*., 2017). Diarrhoeal cases annually contribute to an estimated 1.3 million global deaths, the majority of which are children under five in Sub-Saharan Africa (Troeger *et al*., 2017; Mokomane *et al*., 2018). In Uganda, the situation is not any different; domestic use of dirty water is correlated to similar waterborne disease outbreaks and atrocities, with border districts and urban slums zoned as high-risk areas (Bwire *et al*., 2013; Kabwama *et al*., 2017; Murphy *et al*., 2017). This threat of water-borne diseases and deaths is largely preventable with continued efforts to improve and deliver access to sanitation and safe domestic water at point-of-use. Therefore, satisfying the need for research, development, awareness, and the use of biochar-based point-of-use water purification technologies would not only increase gains in health but also accelerate ecological sustainability, sanitation and productivity in LMICs. Double desirable goals are accomplished by such technologies including (i) decent quality of water, reduced waterborne disease-death burden and advancement of public health since they have a strong capacity to decontaminate pollutants including pathogens, organic and inorganic substances, and (ii) frugality and eco-friendliness since production is optimised to accommodate abundant agricultural wastes such as maize-cobs, a conundrum to the environment (Kaetzl *et al*., 2020). In Uganda; maize which is a widely produced and preferred staple food generates huge quantities of agricultural wastes including maize stover and cobs; with less financial returns and environmental benefits attached (Okoboi, 2010; Nsubuga *et al*., 2019). Maize wastes usually end up as litter in the environment or landfill, or they are burnt off as fuel which expedites air pollution and accumulation of greenhouse gases (Nsubuga *et al*., 2019). On an annually quantified basis, 1 000 000 hectares of maize are cultivated in Uganda leading to about 2.9 million tonnes of maize produced (MAAIF, 2017). Kanengoni *et al* (2015) approximate 20% of maize cobs generation from each tonne of maize that is field harvested (Kanengoni *et al*., 2015). Therefore, this revelation not only translates to 580 000 metric tonnes of maize cobs generated as wastes but also indicates a potential sustainable raw material base for thermochemical conversion of maize cobs into biochar water filters to extend access to clean water and solve the prevailing dirty water-related mayhems in LMICs.

Access and use of conventional water treatment and purification technologies including; chlorination, boiling, clarification, sand and granular activated carbon filtration (Gadgil, 1998), etc, is limited due to complexity of use, high-energy demand, expertise and high initial or progressive financial requirements. For example, clarification involves chemical treatment of dirty water to subvert colloidal particles (coagulation) and support flocculation and settling, however, Its efficiency is dependent on complex technical factors including the dosage of the coagulant, water speed and mixing energy, temperature, and pH (Stackelberg *et al*., 2007; Mirbagheri *et al*., 2016). Boiling is effective in water treatment however; it has a competitive disadvantage of fuel required to disinfect water. A technique such as chlorination is ineffective on a small scale and can potentially combine with organic compounds to produce harmful carcinogenic substances (Yang and Shang, 2004). Filtration techniques using activated carbon filters require frequent replacement since they are prone to growth and colonisation of bacteria overtime of use (Gadgil, 1998) while sand filters require larger areas and are susceptible to physical clogging which is mainly caused by the suspension and sedimentation of insoluble matter hence reducing water filtration and purification efficiency (Gadgil, 1998; Segismundo *et al*., 2017). Since its discovery in 1972 (Fujishima and Honda, 1972), heterogenous photocatalysis backed by its environmental friendliness is a promising and rapidly growing technological alternative of interest in wastewater treatment and water purification (Dong *et al*., 2015). This photocatalysis process is a perfect fit for the removal of trace metals and the destruction of pathogenic bacteria and viruses, degrading organic and inorganic contaminants, eventually mineralising them into carbon dioxide (CO_2) and water (H_2O) (Di Mauro *et al*., 2017; Ahmed and Haider, 2018). Heterogeneous photocatalysis utilises photon energy to stimulate photochemical splitting of water (Teoh *et al*., 2012) into hydrogen and oxygen under ambient conditions and surface environment of inorganic semiconductors mainly titanium dioxide (TiO_2) (Ahmed and Haider, 2018). Upon light irradiation, the semiconductor transfers light energy to charge carriers followed by the generation of OH– free radicals; which triggers further reactions to form CO_2 and H_2O (Trapalis *et al*., 2016). Unlike other semiconductors, TiO_2 can absorb photon energy across a broad spectrum, it has lower toxicity, a reusability advantage and it is stable under highly oxidative, reductive, acidic or basic harsh reaction conditions hence qualifying it as a good fit for photocatalysis. For this reason, heterogenous photocatalysis research has expanded to explore advances in nanotechnology and more photocatalytic nanomaterials including; nickel oxide (NiO) (Motahari *et al*., 2014), magnetite (Fe_3O_4), zinc oxide (ZnO) and graphitic carbon nitride (g-C3N4) and optimisation of photocatalytic reactors (Ahmed and Haider, 2018) to boost photocatalytic water purification and wastewater treatment. Nonetheless, the practical evidence of heterogeneous photocatalysis in water purification applications is still limited to laboratory experiments compared to industrial-scale use and impact. This is due to the overall associated cost, human health risk, technical knowledge requirements, the need for high precision and efficient photocatalytic reactor designs, Its relative slowness compared to conventional methods, and the need for a comprehensive life cycle assessment (LCA) to understand and support large scale implementation (Dong *et al*., 2015; Ahmed and Haider, 2018). As a standalone in real water purification, heterogeneous photocatalysis is still far from satisfactory and it is largely dependent on hardly achievable operating parameters under normal circumstances (Dong *et al*., 2015). The known recent successful efforts of heterogeneous photocatalysis in wastewater treatment are reported in studies where it was combined with biological oxidation, coagulation-flocculation or heterogeneous photo-Fenton (Ayekoe *et al*., 2017; Ahmed and Haider, 2018). Therefore, such existing constraints limit the applicability of this method in LMICs hence creating room for further research on other feasible alternative water purification technologies like biochar to advance the United Nations SDG6 and SDG3 agenda.

Numerous studies have evaluated biochar as a sustainable product with untapped and prospective multiple benefits to the environment. The reported benefits of this black carbon include carbon sequestration, provision of clean energy for household heating and cooking, water retention and soil enrichment to improve soil fertility and crop yields (Maraseni, 2010; Gwenzi *et al*., 2017). Biochar is carbon-rich; produced by pyrolysis or thermochemical conversion of biomass feedstock such as wood, forest residues and agricultural crop straws under limited or no oxygen conditions. Slow pyrolysis at a temperature range of 300–700°C and a relatively longer vapour residence time (Manyà, 2012) is the commonly used process for biochar production. Slow pyrolysis allows the feedstock to fully pyrolyse and gives a high product yield of about 35–50% biochar, 35% bio-oil, and syngas (Park *et al*., 2013) while fast pyrolysis (temperatures >700°C) yields about 60% bio-oil, 20% biochar and 20% syngas (Maraseni, 2010). The physicochemical properties of the resulting biochar produced are generally dependent on the nature and composition of feedstock used (Van Hien *et al*., 2018). Additionally, production factors such as pyrolysis temperature greatly influence the biochar physiochemical and structural characteristics. A high pyrolysis temperature accelerates the degree of carbonisation and thus develops a more stable form biochar (Rafiq *et al*., 2016). Generally, biochar is porous, has a low bulk density, high stability, high cation exchange capacity (CEC), high surface area, high carbon content, contains hydroxyl, carboxyl, carbonyl functional groups and it is alkaline with a high pH (around

10) (Shackley *et al*., 2012; Wang *et al*., 2017; Van Hien *et al*., 2018). These properties make biochar a good sorption medium of pollutants, organic compounds, and heavy metals (Nartey and Zhao, 2014; Santos *et al*., 2019; Van Hien *et al*., 2020). As a result, biochar application and research have extended intensively to wastewater treatment and water purification. Kaetzl *et al*. (2020) evaluated the performance of miscanthus-based biochar filters as better compared to sand in the improvement of physicochemical and microbial parameters of wastewater treatment (Kaetzl *et al*., 2020). Olive husks and forest waste biochar as a component mixture in green roof substrates demonstrated better performance in the retention of phenanthrene and heavy metals compared to traditional green roofs (Piscitelli *et al*., 2018). According to Gupta *et al*. (2018), pre-treated maize cob-based biochar was highly efficient in the removal of chromium(VI) and showed good repeatability upon reuse (Gupta *et al*., 2018). These findings provide a stepping stone to explore more and maximise the production and performance of maize cob-based biochar in water purification. Maize cobs are composed of 45.88% cellulose, 39.40% hemicelluloses and 11.32% lignin, 7.14 mf wt% moisture content, 1.05 mf wt% ash content, 87.76 mf wt% volatile matter, have high fixed carbon, low percentages of nitrogen and sulphur, and they start to degrade at 250°C (Shariff *et al*., 2016a). Based on these findings, Shariff *et al* (2016a) concluded that maize cobs are suitable feedstock for slow pyrolysis and production of high-quality biochar. In this research study, the authors report a slow pyrolysis of maize cob agricultural wastes using appropriate technology to produce biochar for water purification. Great adsorption performance of the maize cob-based biochar in improving water quality attributes including pH, EC, TDS, Chloride, Odour, Colour, and Total Hardness were observed and assessed in the process.

Materials and methods

Maize cobs and biochar production

Maize cobs were selected as a raw material feedstock to produce biochar. Dry maize cobs were collected from the farm store at Makerere University Agricultural Research Institute Kabanyolo (MUARIK), north of Kampala City. Tomczyk *et al*. (2020) show that dry feedstock with minimum moisture content is frugal for biochar production due to a substantial reduction in the fuel-heat energy and time required during pyrolysis (Tomczyk *et al*., 2020). The cobs were broken into smaller pieces of average length 3 cm to fit into the 60 L cylindrical batch bio-reactor. The corncobs in double replicates of 2, 2. and 3 kg batches were pyrolysed in the tight-fitted bio-reactor under recommended slow pyrolysis temperature conditions of 300–600°C (Manyà, 2012; Liu *et al*., 2015; Shariff *et al*., 2016b) and a constant residence time of 120 min to obtain biochar of good quality and uniform physiochemical and structural characteristics (Wang *et al*., 2019). After natural cooling to room temperature, the resultant biochar products were weighed to obtain the biochar yield using Equation (1) (Gupta *et al*., 2018).

$$\text{Biochar yield} = \frac{\text{Weight of biochar}}{\text{Weight of moisture} - \text{free sample}} \times 100 \tag{1}$$

Biochar physical characterization

The biochar was characterised for proximate analysis at the Animal Science Laboratory, College of Agricultural and Environmental Sciences, Makerere University. The biochar moisture content was analysed according to the standard method outlined by the American Society for Testing and Materials (ASTM D4442). Biochar samples in porcelain crucibles were weighed to determine the mass of the initial sample (M_0). The samples were oven-dried for 24 hours to constant weight. The oven-dry mass (M_1) was determined and moisture content (Mc) calculated using Equation (2) (ASTM, 2006).

$$\text{Moisture content (Mc)} = \frac{M_0 - M_1}{M_1} \times 100 \tag{2}$$

Ash content (Ac) was analysed following a laboratory analytical procedure similar to the standard method outlined by the American Society for Testing and Materials (ASTM, E1755-01). Porcelain crucibles with identifiers were preheated in a muffle furnace at 600°C for four hours, cooled to room temperature and weighed (M_f). The samples were then placed in the crucibles, weighed (M_s), and placed in the furnace for heating at 105°C to constant weight for 1 hour and heated at a set temperature of 600°C to ash. The crucibles were stored in a desiccator for conditioning until use. The weight (Ma) was determined and the ash content was calculated using Equation (3) (Sluiter *et al*., 2008):

$$\text{Ash content (Ac)} = \frac{M_a - M_f}{M_s - M_f} \times 100 \tag{3}$$

ASTM E872-82 was used to analyse the volatile matter (Vm) of the biochar. The weight of the crucible with a cover (Mc) and weight of the sample in the crucible with cover (Msc) were determined. The sample was then placed in a furnace and maintained at a temperature of 950°C for about to allow discharge of volatile matter. After cooling, the final weight of the sample with crucible (Mfc) covered recorded and percentage weight loss (W_L)

computed. The volatile matter was calculated using Equation (4) (ASTM, 2011)

$$\text{Volatile matter } (\text{Vm}) = \text{WL} - \text{Mc} \quad (4)$$

The fixed carbon (Fc) content was computed using Equation (5) (Gupta *et al*., 2018).

$$\text{Fixed carbon } (\text{Fc}) = 100 - (\text{Mc} + \text{Ac} + \text{Vm}) \quad (5)$$

Biochar filter design

The experimental setup consisted of open-end glass cylinder columns with an inner diameter of 40 mm and a total height of 200 mm. The columns were fitted with cotton wool at one open end to support the biochar material. Biochar was crushed and sieved to three distinct particles sizes of 0.5, 2.0, and 4 mm identified as T1, T2 and T3 respectively. These sizes are in the range of the effective particle sizes of sand filters. The glass cylinder columns were filled with biochar to different lengths: 150, 100 and 50 mm denoted as L1, L2 and L3, respectively. The setup had nine treatment combinations of T1L1, T1L2, T1L3, T2L1, T2L2, T2L3, T3L1, T3L2 and T3L3 in triplicate. The control group (T1L1c) in triplicate was also set aside. The purpose of the control group was to provide a valid basis for any possibility of maize cob biochar interference on the water quality parameters during filtration.

Sampling and filtration

Before sampling the experimental and control group setup filter columns, samples of industrial wastewater and refined lab water in triplicate were taken for physicochemical analysis of the parameters namely pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), Chloride and Total hardness. For filtration, each biochar filter column in the experimental setup was fed with a constant volume of 150 mL of industrial wastewater. The control group columns were fed with 150 mL of refined lab water. The filtrate that passed through each of the columns was collected in identified clean plastic bottles for further analysis of the physicochemical parameters.

Physiochemical analysis

Analysis of the collected samples was performed at the Uganda Industrial Research Institute (UIRI) at grid coordinates of 0° 20′ 10.0′ N, 32° 37′ 31.0′E Nakawa Industrial Area, Kampala District. Parameters analysed were pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), Chloride, and Total hardness in the water samples. The aesthetic parameters observed were Odour and colour. The pH was analysed using a Mettler Toledo's Seven Compact™ pH meter S220-kit. The EC (µs/cm) and TDS (ppm) were analysed using a Palin test Waterproof EC/TDS 800 meter (rated IP67). The results of pH, EC, and TDS were directly read from the digital display screens of the respective testing meters. The determination of chloride involves the use of silver nitrate in the presence of potassium chromate as an indicator (Shukla and Arya, 2018). Three drops of potassium chromate (K_2CrO_4) indicator was added in a conical flask containing 20 mL of the sample. The solution was titrated against standard silver nitrate ($AgNO_3$) until it turned to reddish yellow (Tea colour). Chloride was then calculated using Equation (6).

$$\text{Chloride (mg/L)} = \frac{\text{Volume of AgNO}_3 \times \text{Normality of AgNO}_3 \times 35.5 \times 1000}{\text{Volume of sample}} \quad (6)$$

Total hardness was determined by buffering a volume of 20 mL of the sample with 2 mL buffer of 16.9 g Ammonium chloride (NH_4Cl) & 250 mL concentrated Ammonium hydroxide (NH_4OH) titrated against Ethylenediaminetetraacetic Acid (EDTA) using the erichome black T indicator; 0.5 g in 100 mL triethanolamine until the solution turned from wine red to blue (Chawla and Parashar, 2015). Total hardness was calculated using Equation (7).

$$\text{Total hardness (mg/L)} = \frac{\text{Volume of EDTA} \times \text{Normality of EDTA} \times 50 \times 1000}{\text{Volume of sample}} \quad (7)$$

The efficiency of reduction of the water filtrate parameters was measured using Equation (8) (Huggins *et al*., 2016); where A_e is the adsorbent efficiency, C_{in} is the inflow concentration and C_{out} is the outflow parameter concentration (mg/L).

$$A_e = \frac{(C_{in} - C_{out})}{C_{in}} \times 100 \quad (8)$$

Data analysis

IBM SPSS statistics version 20 software was used to compute variance analysis, compare means, test for significance, and generate standard deviations. The general linear model was used to generate the Tukey's honesty significant difference (HSD) with univariate statistics for the water parameters as dependent variables within categories of the independent variables (Treatments). All statistical tests were done at a 0.05 probability level.

Results and discussion

Biochar yield

Our results for the biochar yield (Table 1) showed a 50% solid biochar recovery from maize cob pyrolysis in experiments 1 and 2, with the balance recovered as syngas and bio-oil. A fairly high biochar yield (>30, <50%) from corncob pyrolysis was reported by Gupta *et al*. (2018), Intani *et al*. (2016), and Shariff *et al*. (2016). However, even biochar yields >50% with maize cob as feedstock has been reported before (Rafiq *et al*., 2016). When comparing our results to those in previous studies, it must be pointed out that the variation in biochar yields could be resulting from a combination of factors including the difference in feedstock varieties and physicochemical characteristics, the difference in pyrolysis conditions or appropriate pyrolysis technology used (Liu *et al*., 2015). Because of the lack of equipment; we could not investigate the physiochemical characterisation of the corncob feedstock used during the study, which limits us to give a better feedstock comparison with other studies. However, based on our findings and reviewed literature; it can be argued that the corncob feedstock we used for pyrolysis had a high lignin content (Intani *et al*., 2016) hence producing a higher biochar yield than that reported in the previous studies (Shariff *et al*., 2016a).

The decrease in the yield in experiment 3 is due to the rapid temperature rise to the peak temperature of 600°C during pyrolysis hence causing the prime breakdown of feedstock or minor breakdown of the biochar residue (Shariff *et al*., 2016b). Shariff *et al*. (2016b) similarly reported a decrease in biochar yield by 19.74% with an increase in temperature from 400 to 600°C. Together, the present findings confirm findings that argue that an increase in pyrolysis temperature decreases biochar yield and increases volatile yield (Manyà, 2012; Ceranic *et al*., 2016; Intani *et al*., 2016; Rafiq *et al*., 2016). As discussed above, the authors agree that maize cobs are a reliable feedstock for higher biochar yield at slow pyrolysis and thus can provide a win-win scenario when it comes to waste management and biochar-based applications.

Proximate analysis of biochar

Table 2 summarised the results for the proximate analysis of biochar. The study results show a significant impact on the percentage of fixed carbon, volatile matter compared to moisture content, and ash content of the resulting biochar. The fixed carbon in the biochar increased, which corroborates with related literature that revealed an exponential rise of fixed carbon content as pyrolysis temperature increased (Shariff *et al*., 2016b). At higher temperatures, the more volatile matter is ejected leading to a reduced amount of volatile matter but with an additional fixed carbon in the resulting biochar. Contrary to the feedstock ash content reported in literature (Shariff *et al*., 2016a), the relative ash content of the resulting biochar in our study significantly increased. This finding is consistent with previous studies and it is attributed to mineral matter presence and destructive volatilisation of lignocellulosic matter with a rise in pyrolysis temperature (Rafiq *et al*., 2016). The pH values of biochar from the maize cob feedstock showed that the product was alkaline hence corroborating with the true nature of biochar. The alkaline pH is most likely attributed to inorganic constituents present in the feedstock especially alkaline earth metals such as K, Ca, and Mg (Liu *et al*., 2015).

Concentration of samples

The average concentration of pH, TDS, EC, chloride and Total hardness in the wastewater and control inflow samples are presented in Table 3. The pH and chloride values of both samples were within the acceptable limits of WHO (WHO, 1971; Meride and Ayenew, 2016). The high electroconductivity in the wastewater suggests the presence of harmful dissolved chemicals or ions in the water while the high TDS indicates that the water is highly mineralized which could be detrimental to kidney and heart patients at high concentration (Meride and Ayenew, 2016). Based

Table 1 Effect of feedstock quantity on biochar yield

Experiment	Maize cobs (kg)	Biochar (kg)	Biochar yield (%)
1	2.0	1.00	50
2	2.5	1.25	50
3	3.0	1.47	49

Table 2 Biochar proximate composition

% Moisture content	% Ash content	% Volatile matter	% Fixed carbon	pH
4.13	6.86	17.70	71.28	10.27

Table 3 Concentration of parameters in wastewater and control water

	pH	Total dissolved solids (ppm)	Electroconductivity (µs/cm)	Chloride (mg/L)	Total hardness (mg/L)
Wastewater (WW)	7.28	640.00	982.00	95.85	90.00
Control inflow (CI)	6.95	190.00	12.85	21.30	50.00

on aesthetic observation, the odour and colour of the wastewater indicate contamination of the water with organic pollutants which could be hazards to human health and environment upon use without treatment (Zheng *et al*., 2013).

Concentration of filtrate water parameters

The analysis of variance (ANOVA) at an alpha value of 0.05 revealed significant effects of treatments on pH, TDS, EC and Cl and a statistically significant difference between their groups as determined by a one-way ANOVA ($F(9, 20) = 7.179$, $P = 0.000$), ($F(9, 20) = 4.586$, $P = 0.002$), ($F(9, 20) = 6.064$, $P = 0.000$), and ($F(9, 20) = 4.101$, $P = 0.004$). For total hardness, there was no statistically significant difference between groups ($F(9, 20) = 1.623$, $P = 0.176$). The Tukey HSD post hoc test revealed the filtrate mean values of the pH, TDS, EC and Cl that were significantly different from each other across the treatments as summarised in Table 4.

During the study, clogging of filter columns was highly observed in treatments T1L1, T1L2, T1L3 compared to other treatments. Biochar particles were also detected in filtrates that passed through thickness T1. Clogging and possible mixture of biochar particles during filtration pose a disadvantage to wastewater treatment using biochar filters hence affecting the efficiency of performance. The water filtrates from all the experimental treatments were more visible and transparent compared to the wastewater except the control treatment. Generally, this trend showed that the aesthetic parameters in the wastewater mainly odour and colour for the water filtrates improved upon filtration with the maize cob biochar. In most scenarios, colour in wastewater may be due to the presence of coloured organic matter, metals, or highly coloured industrial wastes while odour indicates a possible presence of organic substances, biological activity or industrial pollution (Zheng *et al*., 2013).

Our findings in Table 4 make known of the noticeable influence of treatments on water filtrate parameters. All the pH, TDS, EC, chloride mean values in the water filtrates were reported least in treatment T3L3 but were all above the respective concentrations in the wastewater. Total hardness was least in both treatment T2L2 and T1L1c. Furthermore, the pH, TDS, EC, chloride and total hardness mean values were greater in treatments T1L2, T2L2, T1L2, T1L2 and T1L2 respectively. The pH in the treatments (Table 4) increased compared to the one in the wastewater and control inflow (Table 3). The pH value of treatment T3L3 was minimum while T1L2 had a maximum pH. This may be due to more contact and adsorption time in T1L2 between the wastewater and biochar. Analysis of variance indicated a 3-unit average significant increase in pH among treatments T1L2, T1L3, T2L1, T2L2, T3L1, T3L2, T1L1c, and T3L3 correspondingly. An increase in the pH of water filtrates was similarly reported in granular activated carbon filters (Siong *et al*., 2013). The fact that the pH values generally increased in the water filtrates proposes that there was a pH buffering effect of the alkaline nature of the maize cob biochar. Furthermore, the pH results suggest that the water filtrates were alkaline or most likely had a soda-like taste hence possibly contain an excess of negative hydroxide ions (Islam *et al*., 2017). As per the Ugandan and WHO guidelines for portable water, the pH of the portable water ranges between 6.5 and 8.5 (WHO, 1971; UNBS, 2017). Although the obtained water filtrate pH results from both the experimental and control group were higher than the permissible limits, there is no substantial evidence about the health benefits or dangers of taking or using such water domestically (Islam *et al*., 2017). TDS values (Table 4) varied increasingly from 1336.67 to 4953.33 ppm. There was a significant increase in the TDS mean filtrate values in treatments T3L3, T1L1c, and T2L2. Similar to this study, an increase in TDS filtrate values were reported in absorption and adsorption

Table 4 Mean variation of water filtrate parameters with treatments

Treatment	pH	Total dissolved solids (ppm)	Electroconductivity (µs/cm)	Chloride (mg/L)	Total hardness (mg/L)
T1L1	10.16 ± 0.34^{ab}	3873.33 ± 2005.10^{ab}	6200.00 ± 2137.76^{ab}	1709.92 ± 1132.80^{ab}	70.00 ± 30.00^{a}
T1L2	10.49 ± 0.06^{a}	3070.00 ± 10.00^{ab}	10786.66 ± 1765.00^{a}	2797.40 ± 1431.72^{a}	90.00 ± 36.06^{a}
T1L3	10.31 ± 0.10^{a}	2453.33 ± 722.31^{ab}	5353.33 ± 1176.87^{b}	745.50 ± 140.62^{ab}	73.33 ± 23.09^{a}
T2L1	10.38 ± 0.12^{a}	3886.67 ± 872.31^{ab}	7480.00 ± 973.70^{ab}	2750.06 ± 1464.74^{a}	60.00 ± 30.00^{a}
T2L2	10.36 ± 0.14^{a}	4953.33 ± 1086.48^{a}	7216.67 ± 2909.99^{ab}	1810.50 ± 839.63^{ab}	43.33 ± 5.77^{a}
T2L3	10.15 ± 0.10^{ab}	2613.33 ± 614.03^{ab}	3923.33 ± 1281.46^{b}	588.12 ± 65.87^{ab}	56.67 ± 5.77^{a}
T3L1	10.27 ± 0.05^{a}	2520.00 ± 420.36^{ab}	4770.00 ± 962.70^{b}	934.83 ± 225.57^{ab}	53.33 ± 11.55^{a}
T3L2	10.20 ± 0.12^{a}	2480.00 ± 484.97^{ab}	6380.00 ± 1126.23^{ab}	665.03 ± 16.01^{ab}	50.00 ± 0.00^{a}
T3L3	10.06 ± 0.12^{b}	1336.67 ± 179.54^{b}	2866.67 ± 928.57^{b}	382.22 ± 51.97^{b}	56.67 ± 5.77^{a}
T1L1c	10.26 ± 0.04^{a}	1606.67 ± 777.45^{b}	9780.00 ± 2639.56^{a}	2541.80 ± 593.90^{ab}	43.33 ± 5.77^{a}

Note: Mean values ± SD in a column suffixed with different letters are significantly different from each other (Tukey's HSD, $P < 0.05$). ^{ab}Mean values ± SD are not significantly different to both ^{a} and ^{b} mean values.

experiments using water hyacinth (Islam and Guha, 2013). The high TDS values indicate a higher presence of inorganic salts or perhaps minor volumes of organic matter soluble in water that may be originating from the maize cob biochar. The suspected elements include sodium and potassium cations which were reported present in a previous cob biochar study (Dume *et al*., 2015). The obtained TDS results in T3L3 unlike other treatments are beyond the standard limits (700 ppm) for treated potable water but within the standard limits (1500 ppm) for natural potable water (UNBS, 2017). When benchmarked with other studies, the filtrate TDS results were beyond those reported (100 and 500 ppm) using clarification in a water treatment plant hence making it desirable for drinking (Mirbagheri *et al*., 2016). Similar to the TDS mean values, the EC values increased significantly with the highest and lowest values recorded in treatments T1L2 and T3L3 respectively; however, they were beyond the permissible limits for both treated and natural portable water (UNBS, 2017). There was a significant difference in the EC mean values in the treatments T1L2, T1L1c, T1L3, T2L3, T3L1 and T3L3 (Table 4). EC is directly related to TDS. The high EC values indicate the presence and interaction of high conductive ions from the dissolved salts, inorganic materials present in the adsorption sites, and porous structure of the maize cob biochar as reported by Dume *et al*. (2015). Chloride mean values increased significantly to least and greater values in treatments T3L3 and T1L2 respectively; however, they were below the required standards (WHO, 1971; UNBS, 2017). The general increase in chloride values in all treatments suggests a possible high presence of soluble salts of sodium (NaCl), calcium (CaCl2), magnesium (MgCl2) and potassium (KCl) (WHO, 1971). In comparison with wastewater concentrations (Table 1), total hardness in the water filtrates reduced comparatively in the treatments T1L1, T1L3, T2L1, T2L2, T2L3, T3L1, T3L2, T3L3 and T1L1c by 22.2, 18.5, 33.3, 51.9, 37.0, 40.7, 44.4, 37.0 and 13.3% respectively, however, there was no change in total hardness in treatment T1L2. From the results, the minimum and maximum reduction were observed in the experimental treatment groups of T1L3 and T2L2 respectively; though, there was no significant difference based on the observed mean values. The results suggest possible adsorption of magnesium and calcium cations that were in the wastewater. The obtained results of total hardness were within the maximum acceptable standard levels of 300 and 600 ppm for both treated and natural potable water respectively (WHO, 1971; Islam and Guha, 2013).

Conclusions

(1) It can be concluded that the slow pyrolysis of maize cobs at different feedstock masses averagely gives a 50% yield of the maize cob feedstock as biochar. The study ties with previous findings that point out a decrease in biochar yield resulting from pyrolysis temperature rise. In this study, the resulting biochar was evaluated in the improvement of wastewater physicochemical parameters.

(2) Filtration with biochar resulted in improvement of; odour, colour, and total hardness of the water. Total hardness reduced in all the treatments with a 51.9% reduction reported in experimental treatment of 2 mm biochar particle size and 100 mm column length and a 44.4% reduction through the 4 mm biochar particle size and 100 mm column length.

(3) This finding shows a promising aspect of using maize cob biochar in applications where reduction of total hardness and improvement of aesthetic parameters in wastewater is paramount. The maize cob biochar did not perform well in the improvement and reduction of pH, TDS, EC, and chloride in the wastewater.

(4) Averagely, the pH values in the filtrates increased by three units while EC, chloride, and TDS concentrations increased correspondingly above acceptable levels, therefore, showing a possible effect of leached constituents from the maize cob biochar during filtration. Therefore, from this study, the maize cob biochar of 2 mm particle size and 100 mm filter length performed better.

(5) Although some of the results obtained exceeded the acceptable WHO limit for drinking, the filtrates qualify for domestic potable water use including washing or backyard irrigation and gardening. This promising finding should guide the design of relatively simple, cheap, and sustainable pyrolysis technologies to support household production of the biochar filters and their emerging use.

(6) Our study was limited to a few water parameters, and therefore investigating the maize cob-based biochar's performance in the reduction of heavy metals and other water quality parameters like COD, Tot-N, NO3-N, NH4-N, Tot-P, BOD & PO4-P from wastewater is another aspect for further research.

(7) Similarly, the performance of maize cob biochar when sandwiched with other filter mediums and materials should be investigated to enhance its suitability as a prospective point-of-use technology at the household level.

Conflict of interest

The authors declare that they have no conflict of interest.

To submit a comment on this article please go to http://mc.manuscriptcentral.com/wej. For further information please see the Author Guidelines at wileyonlinelibrary.com

References

Ahmed, S.N. and Haider, W. (2018) Heterogeneous photocatalysis and its potential applications in water and wastewater treatment: a review. *Nanotechnology*, **29**(34), 342001. https://doi.org/10.1088/1361-6528/aac6ea.

ASTM. (1997) Standard test method for determination of moisture content of particulate wood fuels using a microwave oven E 1358–97 (Reapproved 2006). *ASTM International*, **11**(10), 1–2. https://doi.org/10.1520/E1358-97R13.2.

ASTM. (2011) Standard test method for volatile matter in the analysis of particulate wood fuels E872–82 (Reapproved 2006). *ASTM International*, **82**, 14–16. https://doi.org/10.1520/E0872-82R06.2.

Ayekoe, C.Y.P., Robert, D. and Lanciné, D.G. (2017) Combination of coagulation-flocculation and heterogeneous photocatalysis for improving the removal of humic substances in real treated water from the Agbô River (Ivory-Coast). *Catalysis Today*, **281**, 2–13. https://doi.org/10.1016/j.cattod.2016.09.024.

Bwire, G., Malimbo, M., Maskery, B., Kim, Y.E., Mogasale, V. and Levin, A. (2013) The burden of cholera in Uganda. *PLoS Neglected Tropical Diseases*, **7**(12), e2545. https://doi.org/10.1371/journal.pntd.0002545.

Ceranic, M., Kosanic, T., Djuranovic, D., Kaludjerovic, Z., Djuric, S., Gojkovic, P., *et al*. (2016) Experimental investigation of corn cob pyrolysis. *Journal of Renewable and Sustainable Energy*, **8**(6), 63102. https://doi.org/10.1063/1.4966695.

Chawla, S. and Parashar, R.K. (2015) Environmentally benign method for estimation of hardness in water. *International Journal of Chemical and Pharmaceutical Review and Research*, **1**(2), 49–54. Available at: https://www.semanticscholar.org/paper/Environmentally-Benign-Method-for-Estimation-of-in-Chawla/94089e40dd7cece8b102ddff299657359c478db8. [Accessed 22 June 2020].

Di Mauro, A., Cantarella, M., Nicotra, G., Pellegrino, G., Gulino, A., Brundo, M.V., *et al*. (2017) Novel synthesis of ZnO/PMMA nanocomposites for photocatalytic applications. *Scientific Reports*, **7**, 1–12. https://doi.org/10.1038/srep40895.

Dong, S., Feng, J., Fan, M., Pi, Y., Hu, L., Han, X., *et al*. (2015) Recent developments in heterogeneous photocatalytic water treatment using visible light-responsive photocatalysts: a review. *RSC Advances*, **5**(19), 14610–14630. https://doi.org/10.1039/c4ra13734e.

Dume, B., Berecha, G. and Tulu, S. (2015) Characterization of biochar produced at different temperatures and its effect on acidic nitosol of jimma, southwest Ethiopia. *International Journal of Soil Science*, **10**(2), 63–73. https://doi.org/10.3923/ijss.2015.63.73.

Fujishima, A. and Honda, K. (1972) Electrochemical photolysis of water at a semiconductor electrode. *Nature*, **238**(5358), 37–38. https://doi.org/10.1038/238038a0.

Gadgil, A. (1998) Drinking water in developing countries. *Annual Review of Energy and the Environment*, **23**(1), 253–286. https://doi.org/10.1146/annurev.energy.23.1.253.

Gupta, G.K., Ram, M., Bala, R., Kapur, M. and Mondal, M.K. (2018) Pyrolysis of chemically treated corncob for biochar production and its application in Cr(VI) removal. *Environmental Progress & Sustainable Energy*, **37**(5), 1606–1617. https://doi.org/10.1002/ep.12838.

Gwenzi, W., Chaukura, N., Noubactep, C. and Mukome, F.N.D. (2017) Biochar-based water treatment systems as a potential low-cost and sustainable technology for clean water provision. *Journal of Environmental Management*, **197**, 732–749. https://doi.org/10.1016/j.jenvman.2017.03.087.

Huggins, T.M., Haeger, A., Biffinger, J.C. and Ren, Z.J. (2016) Granular biochar compared with activated carbon for wastewater treatment and resource recovery. *Water Research*, **94**, 225–232. https://doi.org/10.1016/j.watres.2016.02.059.

Intani, K., Latif, S., Kabir, A.K.M.R. and Müller, J. (2016) Effect of self-purging pyrolysis on the yield of biochar from maize cobs, husks, and leaves. *Bioresource Technology*, **218**, 541–551. https://doi.org/10.1016/j.biortech.2016.06.114.

Islam, A. and Guha, A.K. (2013) Removal of pH, TDS, and colour from textile effluent by using coagulants and aquatic/non-aquatic plants as adsorbents. *Resources and Environment*, **3**(5), 101–114. https://doi.org/10.5923/j.re.20130305.01.

Islam, R., Faysal, S.M., Amin, R., Juliana, F.M., Islam, M.J., Alam, M.D.J., *et al*. (2017) Assessment of pH and total dissolved substances (TDS) in the commercially available bottled drinking water. *IOSR Journal of Nursing and Health Science Ver. IX*, **6**(5), 2320–1940. https://doi.org/10.9790/1959-0605093540.

Kabwama, S.N., Bulage, L., Nsubuga, F., Pande, G., Oguttu, D.W., Mafigiri, R., *et al*. (2017) A large and persistent outbreak of typhoid fever caused by consuming contaminated water and street-vended beverages: Kampala, Uganda, January - June 2015. *BMC Public Health*, **17**(1), 1–9. https://doi.org/10.1186/s12889-016-4002-0.

Kaetzl, K., Lübken, M., Nettmann, E., Krimmler, S. and Wichern, M. (2020) Slow sand filtration of raw wastewater using biochar as an alternative filtration media. *Scientific Reports*, **10**(1), 1–11. https://doi.org/10.1038/s41598-020-57981-0.

Kanengoni, A.T., Chimonyo, M., Ndimba, B.K. and Dzama, K. (2015) Potential of using maize cobs in pig diets – a review. *Asian-Australasian Journal of Animal Sciences*, **28**(12), 1669–1679. https://doi.org/10.5713/ajas.15.0053.

Liu, W.J., Jiang, H. and Yu, H.Q. (2015) Development of biochar-based functional materials: toward a sustainable platform carbon material. *Chemical Reviews*, **115**(22), 12251–12285. https://doi.org/10.1021/acs.chemrev.5b00195.

MAAIF. (2017) *The Republic of Uganda Ministry of Agriculture, Animal Industries and Fisheries: Performance Review Report*, p. **150**. Available at: https://www.agriculture.go.ug/ [Accessed 15 June 2020].

Manyà, J.J. (2012) Pyrolysis for biochar purposes: a review to establish current knowledge gaps and research needs. *Environmental Science and Technology*, **46**(15), 7939–7954. https://doi.org/10.1021/es301029g.

Maraseni, T.N. (2010) Biochar: maximising the benefits. *International Journal of Environmental Studies*, **67**(3), 319–327. https://doi.org/10.1080/00207231003612225.

Meride, Y. and Ayenew, B. (2016) Drinking water quality assessment and its effects on residents' health in Wondo genet campus, Ethiopia. *Environmental Systems Research*, **5**(1), 1–7. https://doi.org/10.1186/s40068-016-0053-6.

Mirbagheri, S., Sohrabi, S. and Abdolhashemi, L. (2016) Evaluation and comparison of water treatment plants efficiency and clarifiers performance in removing pollutants in water treatment plants of Tehran, Iran. *Desalination and Water Treatment*, **57**(8), 3503–3513. https://doi.org/10.1080/19443994.2014.987170.

Mokomane, M., Kasvosve, I., de Melo, E., Pernica, J.M. and Goldfarb, D.M. (2018) The global problem of childhood diarrhoeal diseases: emerging strategies in prevention and management. *Therapeutic Advances in Infectious Disease*, **5**(1), 29–43. https://doi.org/10.1177/2049936117744429.

Motahari, F., Mozdianfard, M.R., Soofivand, F. and Salavati-Niasari, M. (2014) NiO nanostructures: synthesis, characterization, and photocatalyst application in dye wastewater treatment. *RSC Advances*, **4**(53), 27654–27660. https://doi.org/10.1039/c4ra02697g.

Murphy, J.L., Kahler, A.M., Nansubuga, I., Nanyunja, E.M., Kaplan, B., Jothikumar, N., *et al*. (2017) Environmental survey of drinking water sources in Kampala, Uganda, during a typhoid fever outbreak. *Applied and Environmental Microbiology*, **83**(23), 1–11.

Nartey, O.D. and Zhao, B. (2014) Biochar preparation, characterization, and adsorptive capacity and its effect on the bioavailability of contaminants: an overview. *Advances in Materials Science and Engineering*, **2014**, 715398. https://doi.org/10.1155/2014/715398.

Nsubuga, D., Banadda, N. and Kiggundu, N. (2019) Innovations in value-addition of agricultural by-products in Uganda. *Journal of Environmental Protection*, **10**(11), 1493–1506. https://doi.org/10.4236/jep.2019.1011089.

Okoboi, G. (2010) *Improved Inputs Use and Productivity in Uganda's Maize Sub-Sector*, Vol. **69**. Economic Policy Research Center (EPRC), Kampala, Uganda.

Park, J., Hung, I., Gan, Z., Rojas, O.J., Lim, K.H. and Park, S. (2013) Activated carbon from biochar: influence of its physicochemical properties on the sorption characteristics of phenanthrene. *Bioresource Technology*, **149**, 383–389. https://doi.org/10.1016/j.biortech.2013.09.085.

Piscitelli, L., Rivier, P.A., Mondelli, D., Miano, T. and Joner, E.J. (2018) Assessment of the addition of biochar to filtering mixtures for potential water pollutant removal. *Environmental Science and Pollution Research*, **25**(3), 2167–2174. https://doi.org/10.1007/s11356-017-0650-6.

Rafiq, M.K., Bachmann, R.T., Rafiq, M.T., Shang, Z., Joseph, S. and Long, R.L. (2016) Influence of pyrolysis temperature on physicochemical properties of corn stover (Zea mays l.) biochar and feasibility for carbon capture and energy balance. *PLoS ONE*, **11**(6), 1–17. https://doi.org/10.1371/journal.pone.0156894.

dos Santos Martins, D.D., Serra, J.C.V., Zukowski Junior, J.C. and Pedroza, M.M. (2019) The efficiency of biochars in the removal of heavy metals. *Acta Brasiliensis*, **3**(3), 131. https://doi.org/10.22571/2526-4338242.

Segismundo, E.Q., Kim, L.H., Jeong, S.M. and Lee, B.S. (2017) A laboratory study on the filtration and clogging of the sand-bottom ash mixture for stormwater infiltration filter media. *Water*, **9**(1), 32. https://doi.org/10.3390/w9010032.

Shackley, S., Sohi, S., Ibarrola, R., Hammond, J., Mašek, O., Brownsort, P., *et al*. (2012) Biochar tool for climate change mitigation and soil management. *Encyclopedia of Sustainability Science and Technology of Food Industry*, **2012**, 845–893. https://doi.org/10.1007/978-1-4419-0851-3_386.

Shariff, A., Aziz, N.S.M., Ismail, N.I. and Abdullah, N. (2016) Corn cob as a potential feedstock for slow pyrolysis of biomass. *Journal of Physical Science*, **27**(2), 123–137. https://doi.org/10.21315/jps2016.27.2.9.

Shariff, A., Noor, N.M., Lau, A. and Ali, M.A.M. (2016) A comparative study on biochar from slow pyrolysis of corn cob and cassava wastes. *International Journal of Biotechnology and Bioengineering*, **10**(12), 767–771.

Shukla, M. and Arya, S. (2018) Determination of chloride ion(Cl-) concentration in ganga river water by Mohr method at Kanpur, India. *Green Chemistry & Technology Letters*, **4**(1), 6–8. https://doi.org/10.18510/Gctl.2018.412.

Siong, Y.K., Atabaki, M. & Idris, J. (2013) Performance of activated carbon in water filters. Department of Material Engineering. Faculty of Mechanical Engineering, University Teknologi, Malaysia.

, Sluiter, A., Hames, B., Ruiz, R., Scarlata, C., Sluiter, J. & Templeton, D. (2008) Determination of Ash in Biomass; Technical Report. National Renewable Energy Laboratory, Golden, CO. Tech Rep NREL/TP-510-42619, pp. 1–9.

Stackelberg, P.E., Gibs, J., Furlong, E.T., Meyer, M.T., Zaugg, S.D. and Lippincott, R.L. (2007) The efficiency of conventional drinking-water-treatment processes in the removal of pharmaceuticals and other organic compounds. *Science of the Total Environment*, **377**(2–3), 255–272. https://doi.org/10.1016/j.scitotenv.2007.01.095.

Teoh, W.Y., Scott, J.A. and Amal, R. (2012) Progress in heterogeneous photocatalysis: from classical radical chemistry to engineering nanomaterials and solar reactors. *The Journal of Physical Chemistry Letters*, **3**(5), 629–639. https://doi.org/10.1021/jz3000646.

Tomczyk, A., Sokołowska, Z. and Boguta, P. (2020) Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. *Reviews in Environmental Science and Bio/Technology*, **19**(1), 191–215. https://doi.org/10.1007/s11157-020-09523-3.

Trapalis, A., Todorova, N., Giannakopoulou, T., Boukos, N., Speliotis, T., Dimotikali, D., *et al*. (2016) TiO2/graphene composite photocatalysts for NOx removal: a comparison of surfactant-stabilized graphene and reduced graphene oxide. *Applied Catalysis B: Environmental*, **180**, 637–647. https://doi.org/10.1016/j.apcatb.2015.07.009.

Troeger, C., Forouzanfar, M., Rao, P.C. Khalil, I., Brown, A., Reiner, R.C., *et al*. (2017) Estimates of global, regional, and national morbidity, mortality, and aetiologies of diarrhoeal diseases: a systematic analysis for the Global Burden of Disease Study 2015. *The Lancet Infectious Diseases*, **17**(9), 909–948. https://doi.org/10.1016/S1473-3099(17)30276-1.

UNBS. (2017) *Portable Water Specification*. Uganda National Bureau of Standards, Kampala-Uganda

Van Hien, N., Valsami-Jones, E., Vinh, N.C., Phu, T.T., Tam, N.T.T. and Lynch, I. (2020) Effectiveness of different biochar in aqueous zinc removal: correlation with physicochemical characteristics. *Bioresource Technology Reports*, **11**, 100466. https://doi.org/10.1016/j.biteb.2020.100466.

Van Hien, N., Valsami-Jones, E., Vinh, N. and Phu, T. (2018) Physicochemical characterization of biomass residue-derived biochars in Vietnam. *Preprints*, **1**, 1–23. https://doi.org/10.20944/preprints201807.0403.v1.

Wang, B., Gao, B. and Fang, J. (2017) Recent advances in engineered biochar productions and applications. *Critical Reviews in Environment Science and Technology*, **47**(22), 2158–2207. https://doi.org/10.1080/10643389.2017.1418580.

Wang, Z., Liu, K., Xie, L., Zhu, H., Ji, S. and Shu, X. (2019) Effects of residence time on characteristics of biochars prepared via co-pyrolysis of sewage sludge and cotton stalks. *Journal of Analytical and Applied Pyrolysis*, **142**, 104659. https://doi.org/10.1016/j.jaap.2019.104659.

WHO. (1971) *International Standards for Drinking Water* (3rd edn). 1–70. WHO, Geneva-Switzerland.

Yang, X. and Shang, C. (2004) Chlorination byproduct formation in the presence of humic acid, model nitrogenous organic compounds, ammonia, and bromide. *Environmental Science and Technology*, **38**(19), 4995–5001. https://doi.org/10.1021/es049580g.

Zheng, C., Zhao, L., Zhou, X., Fu, Z. and Li, A. (2013) Treatment technologies for organic wastewater. *Water Treatment* **11**, 250–286. https://doi.org/10.5772/52665.