Heliyon 8 (2022) e12386

Contents lists available at ScienceDirect

Heliyon

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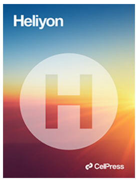

Research article

Exploitation of indigenous bamboo macrophyte species and bamboo biochar for faecal sludge treatment with constructed wetland technology in the Sudano-Sahelian ecological zone

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ARTICLE INFO

Keywords:
Faecal sludge
Constructed wetland
Bamboo species
Biochar
Effluent quality

ABSTRACT

Treatment of faecal sludge (FS) has been a major challenge in most developing countries of Sub-Saharan Africa due to the difficulties in finding appropriate technology. Previous studies have however highlighted the potentials of the vertical flow constructed wetland for FS treatment, yet efforts in the identification of potential indigenous plant species as macrophyte for the Sudano-Sahelian ecological zone have been unsuccessful due to toxic levels of FS quality. This research studied the macrophyte potentials of indigenous bamboo species and bamboo biochar as a conditioner for FS treatment in a vertical flow constructed wetland (VFCW). Typical yard scale experiment consisting of filter media of sand supported at the base with gravels and planted with Bamboo shoots was used. Treatments were Bamboo Constructed Wetland (CW) and Faecal Sludge (FS) load only (CW-FS), Bamboo CW with a mixture of FS and Bamboo biochar (CW–BCH), unplanted drying bed with a mixture of FS and bamboo biochar (UDB-BCH) and an unplanted drying bed with FS (UDB-FS), and in triplicates. Control setup (CTR) consisted of Bamboo CW irrigated with wastewater. Morphological development (plant height, number of plants, number of leaves and culm diameter) of indigenous Bamboo species and reduction of faecal contaminants were monitored. Loading of FS was carried out in a single batch twice per week with a hydraulic loading rate of 56.47/mm/d with an annual Total Solid loading rate of 155.6 and 233.2 kg TS/m^2/year for CW-FS and CW-BCH respectively. The bamboo species adapted to the complex wetland conditions, observed by a progressive increase in morphological development for all the treatments. Removal efficiencies of effluent quality parameters generally ranged from 70 to 99%, except for PO_4^{3-}, TOC and TDS and indicator micro-organisms which were found below 50%. A strong positive linear relationship was determined among species growth parameter with coefficient (r) ranging between 0.83 – 0.99. Except for pH and TSS, all the effluent quality parameters exceeded the national allowable limits for safe discharge. Nonetheless, the study demonstrated positive potentials for adopting indigenous bamboo species as emergent macrophytes for FS treatment using VFCW. Further treatment to reduce contaminant levels in a second to a third series of a connected constructed is recommended wetland prior to reuse for agriculture.

1. Introduction

Excreta management is a major environmental challenge in most developing countries across the globe. Due to the high water demand and installation cost of the centralised sewerage system, developing countries in Sub-Saharan Africa mainly resort to onsite sanitation system (OSS) which includes, unsewered public and private latrines or toilets, aqua privies, septic tanks among others to guarantee total separation of excreta from human contact (Strande et al., 2014).

Eventually, the pits and vaults of the OSS are filled up with FS which generally constitutes raw or partially digested, slurry or semi-solid, of combinations of excreta, blackwater, greywater, etc. (Tilley et al., 2009; Strande, 2014) and thus demands critical management strategies for final disposal or reuse.

Vertical Flow Constructed Wetland (VFCW) is an engineered eco-technology (Rizzo and Langergraber, 2016) with positive potentials for faecal sludge treatment. The system stands out from other existing technologies due to the synergy of processes from the presence of an

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https://doi.org/10.1016/j.heliyon.2022.e12386
Received 7 October 2022; Received in revised form 19 November 2022; Accepted 8 December 2022

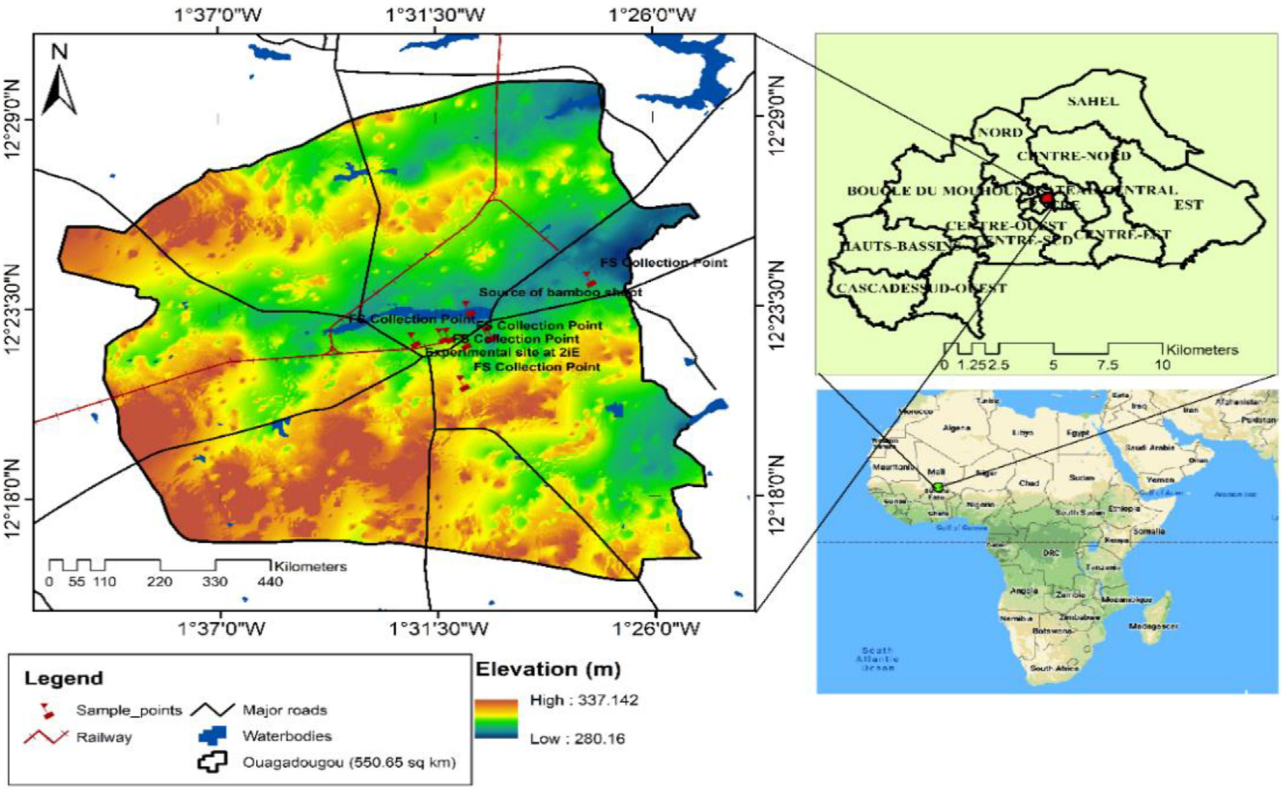


Figure 1. Map showing location of study area and source of faecal sludge.

emergent macrophyte, micro-organisms and environmental interaction for the improvement of sludge quality (Jain et al., 2022). It thus functions as a naturally occurring wetland with enhanced processes of dewatering, filtration, mineralisation and phytoremediation for contaminant removal and allows for long term accumulation of potentially useable biosolids for agricultural soil amelioration.

However, previous studies have shown the difficulties for identification of potential indigenous macrophyte species specifically for the Sudano-Sahelian ecological zone. Two different species of *Oryza longistaminata* and *Sporobolus pyramidalis,* were selected for a typical yard scale experiment which wilted off completely due to toxic levels of FS quality parameters (Kouawa et al., 2015). In another study, Osei et al. (2019) subjected two different species of *Bambusa vulgaris* and *Cymbopogon nardus* to faecal polluted wetland conditions in a pot experiment and found satisfactory resistance of the species to CW conditions. It is thus essential to develop an innovative approach that might help reduce the high sludge contamination for the survival of macrophytes species in the wetland system. Over the years, sludge conditioning with chemical or physical products is known to have a significant influence on sludge dewatering processes. By definition, sludge conditioning is a process whereby sludge solids are treated with chemicals or various other means to prepare the sludge for dewatering and to improve the quality of the sludge. In a pilot-scale unplanted drying bed experiment, Kuffour (2010) found that conditioning of faecal sludge with sawdust improved sludge dewatering but had an insignificant effect on contaminant load removal. This study, thus introduced biochar produced using bamboo feedstock as a potential FS conditioner for treatment in the VFCW.

Design configuration of the VFCW should however allow for the harvesting of the macrophyte species for sludge removal. Over the years, uses of the macrophyte are noted to include ornamental arrangements, compost and as fodder (Kengne et al., 2014a). The introduction of bamboo biochar in this study might thus, serve as an additional form of resource recovery where the biochar feedstock is recycled from the VFCW to aid in the sludge treatment process.

Biochar is significantly gaining much attention as a multifunctional material for agricultural and environmental applications (Chen et al., 2011). Extensive studies have over the years highlighted the potentials of biochar as a very important bioresource for pollution remediation. This is due to the enhanced properties of carbon-richness, high specfic surface area and cation exchange capacity (CEC), alkaline pH among others, attained by the process of pyrolysis, which involves heating of biomass in a complete absence or minimal amount of oxygen. Biochar is thus recognised as an efficient and cost-effective adsorbent which affects the fate, transport and outmost removal of various environmental pollutants (Rawat et al., 2019; Tomczyk et al., 2020; Ji et al., 2022). The adsorptive properties of biochar, as introduced in this study for FS conditioning, might aid in macrophyte establishment by reducing the levels of FS intoxication in the constructed wetland. The current study thus assessed the performance of the indigenous bamboo species and biochar conditioning for faecal sludge treatment in a typical yard-scale VFCW experiment.

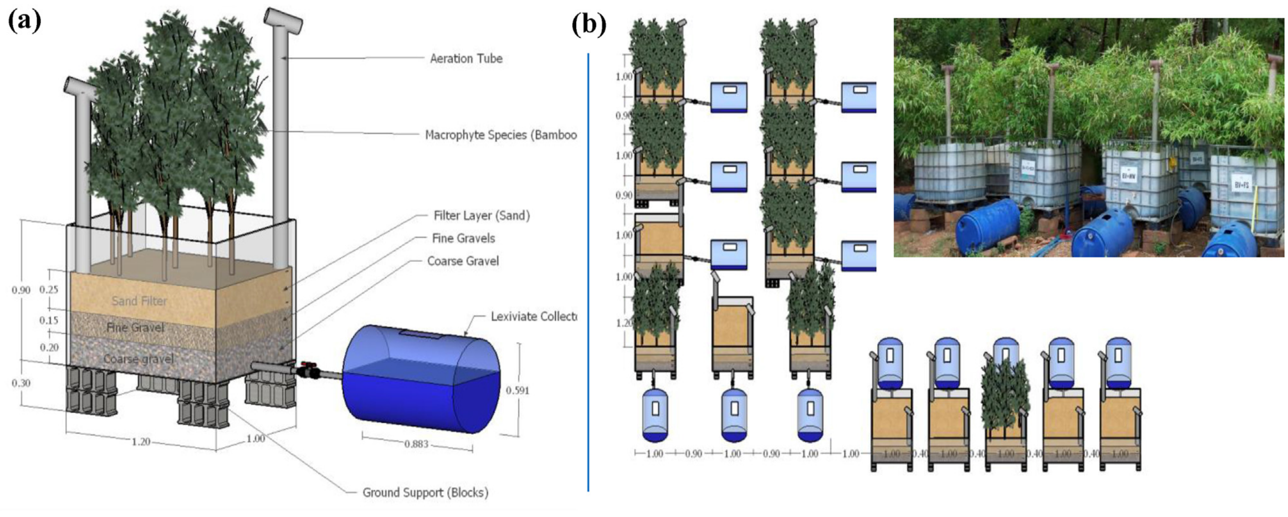
2. Materials and methods

2.1. Study area

This study was carried out in the International Institute of Water and Environmental Engineering (2iE), Ouagadougou, Burkina Faso, which is located in the Sudano-Sahelian ecological zone (Figure 1). The zone is characterised by a long dry season from November to April and with a mean annual rainfall of 600–900 mm for the period of May to October. Average temperatures range from 25 to 28 °C and to a maximum of 42°–43 °C at the hottest season of the Harmattan (Ibrahim et al., 2012). The maximum evapotranspiration 7.7 mm/day is attained in March. The study was conducted between the period of August 2018 and December 2019.

2.2. Selection of macrophyte species

The indigenous bamboo species was selected based on the results of a pot experiment by Osei et al. (2019) and the multipurpose uses and



a: Yard Scale VFCW

b: Experimental Layout of VFCW

Figure 2. Experimental setup: (a) Annotation of the Typical Yard scale VFCW and (b) Schematic Field Experimental Layout.

benefits of the bamboo plant in general. Bamboo is taxonomically classified as Eukaryota, Plantae, Tracheobionta, Spermatophyta, Angiospermae, Monocotyledonae, Commelinidae, Cyperales and Poaceae for the respective hierarchy of Domain, Kingdom, Sub-kingdom, Phylum, Sub-phylum, Class, Sub-class, Order and Family. The general species is *Bambusa vulgaris* Schrad. ex J. C. Wendl. The bamboo species used for the experiment were a year old indigenous seedling obtained from a local gardener in the capital city of Ouagadougou.

2.3. Experimental design

The experimental design was a simple complete randomised design (CRD) with four treatments in triplicates and a control in duplicate. The treatments were composed of Bamboo CW and FS load only (CW-FS), Bamboo CW with a mixture of FS and bamboo biochar (CW-BCH), an unplanted drying bed with a mixture of FS and bamboo biochar (UDB-BCH) and an unplanted drying bed with FS only (UDB-FS). The control setup (CTR) consisted of Bamboo CW irrigated with wastewater from maturation ponds of the International Institute of Water and Environmental Engineering (2iE) Ouagadougou Campus wastewater treatment system. The experimental setup and the field layout are presented in Figure 2(a)–(b). Six tufts of bamboo shoots were planted per pilot with an average of 15 bamboo shoots at a density of 12 shoots/m^2.

2.4. Characteristics of CW bedding material

The particle size distribution of the CW bedding materials determined by using the ASTM D6913-04 (2004) standard test methods is presented in Table 1.

2.5. Production and characteristics of bamboo biochar

Bamboo biochar was produced by slow pyrolysis using a locally fabricated reactor from a 200-litre capacity steel drum (Figure 5). The bamboo feedstock was sun dried to reduce moisture before pyrolysis. The optimum temperature for the pyrolysis was determined to range from 400 to 600 °C by thermal degradation analysis (TGA) using the 8 SETSYS 1750 (TGA-DSC 1500) CS EVOLUTION. The proximate analysis of biochar was in accordance with ASTM standards for moisture content (% MC), Ash (%) and Volatile Matter (%VM). Fixed carbon (%FC) was determined using Eq. (1) (García et al., 2013). pH and EC (μS/cm) were measured in a dilution 1:10 (w/v) biochar:distilled water using HANNA instrument (HI 9828) (Singh et al., 2017).

$$\%FC = 100 - (\%Ash + \%VM) \tag{1}$$

2.6. Source of faecal sludge

Faecal sludge was supplied by a contracted cesspit emptier from six different sectors (three, four, ten, twenty-three, forty-two and forty-three) of the capital city of Ouagadougou (Figure 1). Out of the six trips, three (ten, twenty-three and forty-two) were from a traditional pit latrine and the remaining (Three, four and forty-three) from septic tanks.

2.7. Determination of sludge loading rate

The VFCW were pre-acclimatised with wastewater from a maturation pond of 2iE Ouagadougou Campus wastewater treatment system for seven months (August 2018 to March 2019) and followed by FS load for six months (March to September 2019). Finally, a three-month rest period (September to December 2019) was allowed for sludge dewatering. The FS load was gradually introduced in lower concentrations with diluted wastewater at increasing proportions of 1:20, 5:10 and 8:10 per

Table 1. Material used for VFCW Construction.

	Construction Materials		
	Materials	Composition	Properties
Wetland	CW	Plastic reactor	1:1.2:1 m
	Ground Support	Blocks	0.3:0.4:0.2 m
	Aeration Tube	PVC pipe	Ø: 0.1 m
	Lixiviate Collector	Plastic drum	0.9:0.6 m
Bedding Media	Filter media	Sand	*ES* = 0.28
			UC = 2.2
			P (%) = 43.8
			BD (g/cm^3) = 1.46
			K (cm/s) = 5×10^{-3}
	Middle layer	Fine Gravel	Ø: 3.3–16 mm
	Base layer	Coarse Gravel	Ø: 10–20 mm

ES – effective size (d_{10}); *UC* – uniformity coefficient; *K* – Hydraulic conductivity; *P* – Porosity; *BD* – Bulk density.

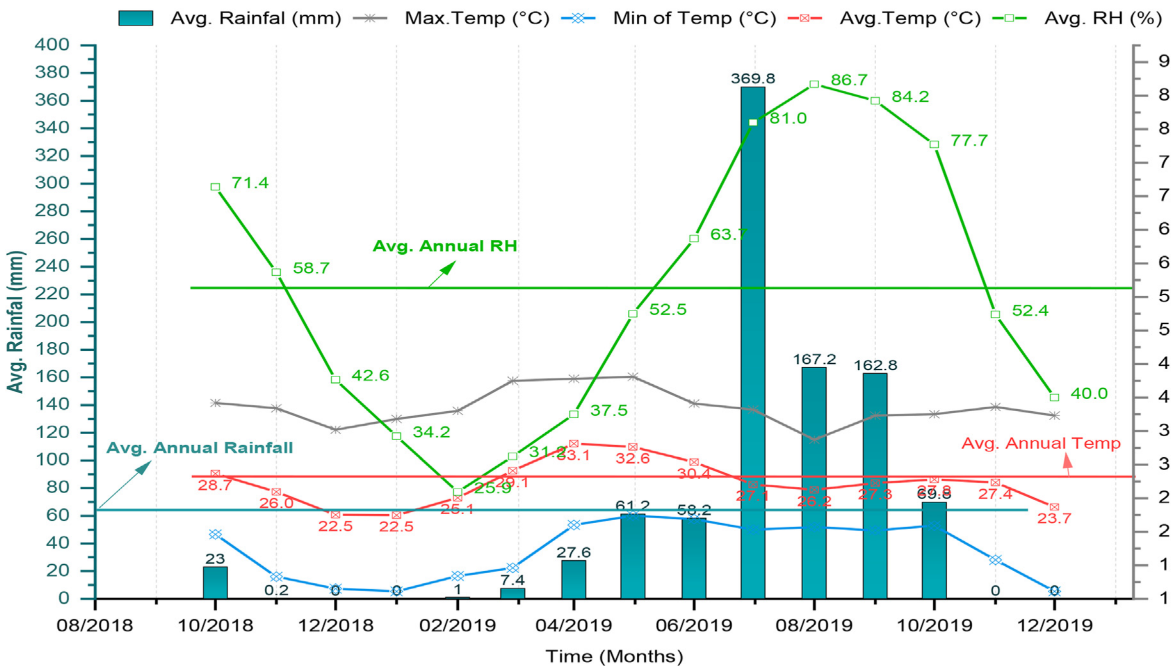


Figure 3. Weather conditions of the study period.

volume for one month. Loading was applied in a single batch at a frequency of trice per week and reduced to twice per week at the peak of the raining season (July to September 2019). The quantity of biochar added to FS was fixed at 50% of the Total Solid content of the raw FS to be loaded (Eq. (2)). The annual sludge loading rate for the different treatments was determined using Eq. (3) (Kengne et al., 2008).

$$BCH\ Load = 0.5 \times DM\ (g/l) \tag{2}$$

$$SLR = (HLR \times DM) \times 52 \tag{3}$$

where; BCH = Biochar, SLR = Annual sludge loading rate (kg TS/m^2/year), HRL = Sludge hydraulic loading Rate (mm/d), DM = Dry Matter content of fresh FS to be applied (kg/l).

2.8. Monitoring of species adaptation to the VFCW

Species adaptation was monitored for physiological growth parameters of number of plants and leaves by count and plant height using standard tape measure (10 m) on a monthly basis. Culm was measured for four basal internodes using a digital calliper.

2.9. Dynamics of internal and external wetland conditions

The weather condition for the period of study was monitored for average monthly rainfall, temperature and relative humidity, which was obtained from the 2iE Ouaga campus weather station (mounted at a distance of 20 m away from the experimental units).

Internal wetland conditions were monitored with METER TEROS 12 Advanced Soil Moisture, Temperature, and Electrical Conductivity Sensor coupled with a remote-download EM60G data logger. Six (6) sensors (2 and 1 each for CW and UDB treatments respectively) were configured for 1 h measurement time interval.

2.10. Laboratory analysis of FS and effluent quality

Laboratory analysis of FS and effluent quality (COD, BOD_5, TOC, NO_3^-, NH_4^+, PO_4^{3-}, TP, TSS, DM, TVS, *E.* coli, Faecal *Streptococcus* (*FS*), Total coliform (TC) and Faecal coliform (FC) was strictly by the APHA standard methods for the examination of raw sludge and wastewater quality parameters while HANNA instrument (HI 9828) was used for in situ measurement of Physico-chemical parameters (pH, ORP, EC and TDS). Percent (%) removal efficiency of effluent quality parameters was estimated for treatment performance.

2.11. Data analysis

Morphological development of bamboo macrophyte in VFCW was subjected to growth trend analysis on a monthly basis. The performance of the various treatments was subjected to analysis of variance (ANOVA) for the various parameters analysed for the study while the relationship among bamboo species development, weather conditions, internal wetland conditions and effluent quality was analysed using Pearson correlation matrix at 5% significance level. Data analysis and graphical representations of the results were aided by OriginPro (2022) and GraphPad Prism 8.

3. Results and discussion

3.1. Dynamics of weather conditions of VFCW

The weather was characterised by a total annual rainfall of 948.2 mm (at 63.21 mm/month), while the rainiest month was August 2019 with a peak of 369.8 mm. The average monthly temperature of 27.9 °C varied between 22.47 to 33.13 °C. However, monthly minimum and maximum temperatures varied from 11.1 to 22.4 °C and 33.7–43.1 °C respectively. The monthly relative humidity ranged between 29.91 and 86.71%, with an average of 55.98% (Figure 3) Coulibaly et al. (2020) reported an average daily minimum and maximum temperature of 16 and 40 °C respectively, and a relatively lower mean annual precipitation of 788 mm Ibrahim et al. (2012), however noted mean annual rainfall and temperature range of 600–900 mm and 25–43 °C respectively for the study area.

3.1.1. Characteristics of bamboo biochar

The characteristics of the biochar are presented in Table 2 and the results as compared to a similar study by Hernandez-Mena et al. (2014) for the same bamboo feedstock revealed relatively higher%FC and%Ash contents and a lower%MC and%VM. In another study, Chen et al. (2016),

Table 2. Characteristics of bamboo biochar.

Parameters	Experimental Data				(Hernandez-Mena et al., 2014) Temperature – 500 °C	
	Mean	Min	Max	St. dev (±)	Mean	St. dev (±)
pH	8.15	8.08	8.24	0.07	–	–
EC (μS/cm)	306.33	239	367	52.47	–	–
MC (%)	1.9	1.37	2.75	0.59	6.5	1
Ash (%)	6	5.89	6.09	0.09	3.9	0.4
VM (%)	2.6	2.4	2.77	0.15	8.1	1.7
FC (%)	91.5	91.34	91.67	0.16	81.5	0.4

also recorded relatively lower FC (64.38–86.34%) and Ash (3.31–4.15%) contents for bamboo biochar produced between a temperature range of 300–700 °C.

The pH of the biochar was moderately alkaline and similar to the results (pH 8.2) of Cruz-Méndez et al. (2021) while EC was relatively higher (1021 μS/cm) for the same feedstock produced at 450–500 °C. The usual alkaline nature of biochar has been attributed to the temperature of pyrolysis (Singh et al., 2017; Cruz-Méndez et al., 2021). The low EC of the biochar might be ideal to preserve salinity levels in the VFCW.

The dynamics of the Thermogravimetric (TG) and Difference Thermo Analysis (DTG) are presented in Figure 4 whiles the Pyrolysis of Bamboo feedstock to biochar are presented in Figure 5(a)–(c) respectively. The results of the ATG indicated that the thermal degradation of bamboo was almost completed at 500 °C with the initial mass lost at 40–110 °C, explained by moisture loss and evaporation of some extractives compounds. The second event of mass loss at 200–300 °C is attributed to the degradation of hemicelluloses and cellulose to volatile organic products. The subsequent degradation beyond 300–500 °C is explained by the decomposition of lignin due to the high level of stability (Hernandez--Mena et al., 2014; Chen et al., 2019).

3.2. *Quality of faecal sludge load*

According to Niwagaba et al. (2014), appropriate characterisation of FS should encompass essential parameters such as solids concentration, chemical oxygen demand (COD), biochemical oxygen demand (BOD), nutrients, pathogens, and metals. The study generally showed varied characteristics for all the quality parameters, as presented in Table 3.

The raw FS was moderately alkaline, with anti-oxidising condition. EC and TDS were relatively lower than that of Kouawa et al. (2015) but higher than Osei et al. (2019). According to Corwin and Yemoto (2017), EC might indicate salinity levels and cause toxicity, reduced osmotic potential and negatively affect plant water relationship and nutritional balance. Except for pH, all quality parameters showed a high level of inconsistency with a coefficient of viability (CV) ranging from 29.5 to 130.9% (Table 3). In a related study, Kengne et al. (2011) described the quality of raw FS in Yaoundé as highly concentrated with great variability (for CV range of 21–102%) except for pH.

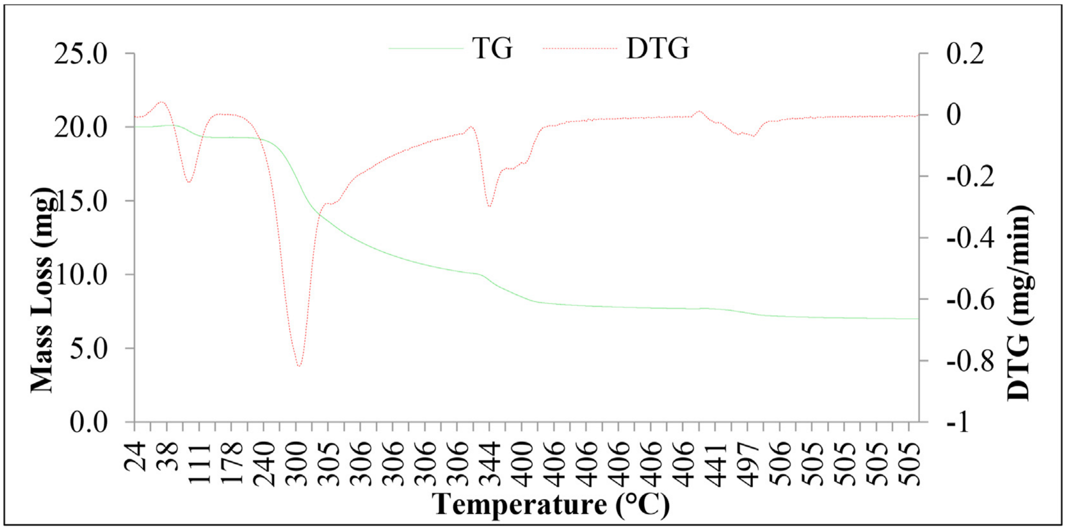


Figure 4. ATG analysis of bamboo biochar.

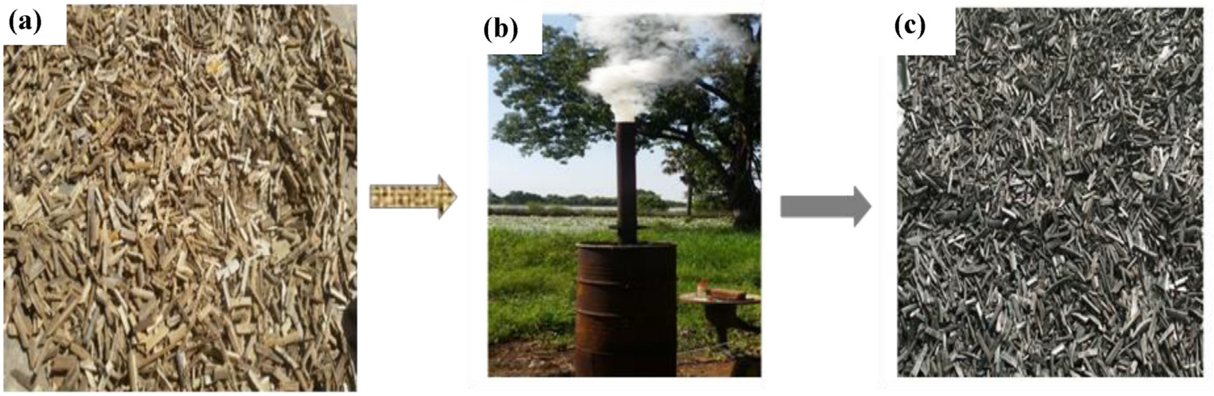


Figure 5. Pyrolysis of Bamboo Biochar: (a) Bamboo feedstock, (b) Bio carbonization (400–600 °C) and (c) Bamboo Biochar.

Table 3. Characteristics of faecal sludge applied to VFCW.

Parameter	Mean	St. Dev (±)	n	CV (%)	Results from Previous Studies			
					Burkina Faso (Ouagadougou)			Cameroon (Yaoundé)
					Osei et al. (2019)	Kouawa et al. (2015)	Bassan et al. (2013)	Kengne et al. (2011)
pH	7.91	0.28	81	3.51	8.6 ± 0.8	9.1 ± 0.7	NA	7.50
ORP (mV)	−69.36	20.45	69	29.5	−54.9 ± 28.08	−139.4 ± 32.5	NA	−54.2
EC (µS/cm)	4973.68	2929.38	81	58.9	2723.6 ± 2289.3	6600 ± 2200	NA	2790
COD (g/l)	13.45	62.79	108	106	19.63 ± 20.28	4.672 ± 3.72	10.73 ± 9.51	31.1
BOD_5 (g/l)	1.13	1.07	87	103.3	NA	NA	1.902 ± 1.33	NA
NO_3^- (mg/l)	0.1	0.13	66	124.3	NA	NA	NA	
NH_4^+ (g/l)	0.39	0.31	72	81.21	3.06 ± 2.43	0.328 ± 0.20	1.23 ± 0.73	0.6
PO_4^{3-} (g/l)	0.06	0.03	69	36.7	0.71 ± 0.88	0.0519 ± 0.06	NA	NA
TP (g/l)	3.93	8.68	59	201.5	NA	0.172 ± 0.18	NA	NA
TDS (g/l)	2.48	1427.04	89	57.60	2.41 ± 2.25	5.4 ± 9.8	NA	NA
TSS (g/l)	18.28	27.75	81	151.8	50.45 ± 43.73	1.533 ± 2.5	9.014 ± 8.48	27.6
DM (g/l)	21.19	26.67	66	125.9	52.86 ± 45.59	6.4 ± 10	11.82	NA
DM (%)	2.12	2.67	66	125.9	NA	NA	NA	3.7
TVS (g/l)	12.58	16.47	66	130.9	33.24 ± 38.37	5.8 ± 10.2	NA	NA
TVS (%DM)	54.58	12.79	66	130.9	NA	65 ± 21	58	65.4
E. coli (CFU/g)	1.49E+10	3.87E+10	50	66.81	NA	NA	NA	NA
FC (UFC/g)	1.28E+10	3.62E+10	58	61.82	NA	NA	NA	NA
FS (CFU/g)	2.55E+04	8.16E+04	58	36.13	NA	NA	NA	NA
TC (CFU/g)	6.36E+10	1.74E+11	52	48.36	NA	NA	NA	NA

St. dev – Standard deviation; CV – coefficient of variation; n – number of samples.

3.3. Sludge loading rate (SLR)

Raw FS was loaded at a hydraulic loading rate of 56.47 mm/d, which resulted to an average annual SLR of 155.6 and 233.3 kg DM/m^2/year for the treatment with FS only (CW-FS/UDB-FS) and that of Biochar (CW-BCH/UDB-BCH), respectively (Table 4). The difference was mainly due to the addition of the 50% DM of biochar to the latter treatment scenario. In a similar experiment, Kengne et al. (2011) studied the effect of different SLR (100, 200 and 300) on the performance of a typical yard-scale VFCW and found a high incidence of clogging for SLR above 200 kg DM/m^2/year. Nonetheless, the optimum annual SLR for FS treatment in a tropical climate was found to be 250 kg DM/m^2/year by Koottatep et al. (2005). The annual SLR for the different treatment scenarios in this study are thus, within the recommended rate for FS treatment.

3.4. Development of indigenous bamboo species in VFCW

3.4.1. Number of plants

Throughout the study period, new bamboo developed from buds into elongated shoots and culms. The number of plants generally increased for all the treatments as well as the control. The number of bamboo plants progressively increased from initial averages of 14 ± 4, 14 ± 1, and 15 ± 3 plant/pilot, to 25 ± 3, 24 ± 3 and 22 ± 4 plant/pilot for CW-FS, CW-BCH and CTR respectively (Figure 6). The observed variation was primarily due to the sprouting of shoots and wilting of old plants, during the rest period, which resulted to a marginal reduction for CW-BCH and CTR. The results of ANOVA showed no significant difference at a *p*-value of 0.985. This suggests that the various treatments had an insignificant influence on the number of bamboo plants. According to Das (2019), new bamboo shoots usually emerge as tightly clasped with overlapping sheaths.

Table 4. Annual sludge and hydraulic loading rates.

Treatment	DM (kg/l)	HLR (mm/d)	SLR (kg DM/m^2/year)
CW-FS/UDB-FS	0.021	56.47	155.6
CW-BCH/UDB-BCH	0.032	56.47	233.3

HRL – Hydraulic Loading Rate; SLR – Sludge loading Rate.

3.4.2. Plant height

The species as well increased in height from initial averages of 86.07 ± 7.02 cm, 71.66 ± 13.33, and 144.13 ± 80.43 cm to 366.67 ± 140.12, 410 ± 55.68 and 311.13 ± 37.11 cm for CW-FS, CW-BCH and CTR respectively for the study period (Figure 7). The monthly variation among the treatments showed to be statistically insignificant at a *p*-value of 0.654, indicating no significant influence from the various treatments on average plant height.

Kala et al. (2020) similarly recorded an increase in bamboo height, from an initial average of 50–60 cm to 205, 380, and 235 cm for the different planting techniques of earthen gully plugs, trenches and live check dams, respectively in a typical bamboo plantation within four years. Bamboo is generally described as the fastest-growing and highest-yielding plants species in the world with an average growth rate of 30–100 cm/day and can grow up to a height of 36 m (Gupta et al., 2018; Kala et al., 2020).

3.4.3. Development of leaves

The number of leaves also increased from initial averages of 427 ± 23, 492 ± 14 and 525 ± 78 leaves/pilot, to 14143 ± 476, 12600 ± 3784 and 7292 ± 1025 leaves/pilot for CW-FS, CW-BCH and CTR respectively at the end of the study period (Figure 8). Also, the monthly variation of the number of bamboo leaves showed to be statistically not significant at a *p*-value of 0.602 among the various treatments.

Leaves of bamboo typically grow from the nodes of culms, while regular defoliation was very characteristic of the species throughout the study period. There was an appreciable reduction during the fourth month of sludge (July 2019) due to a sudden wilting of leaves after the fourth batch of FS sludge from the cesspit emptier was loaded. The beds were swiftly irrigated with tap water, which helped leach out the toxic

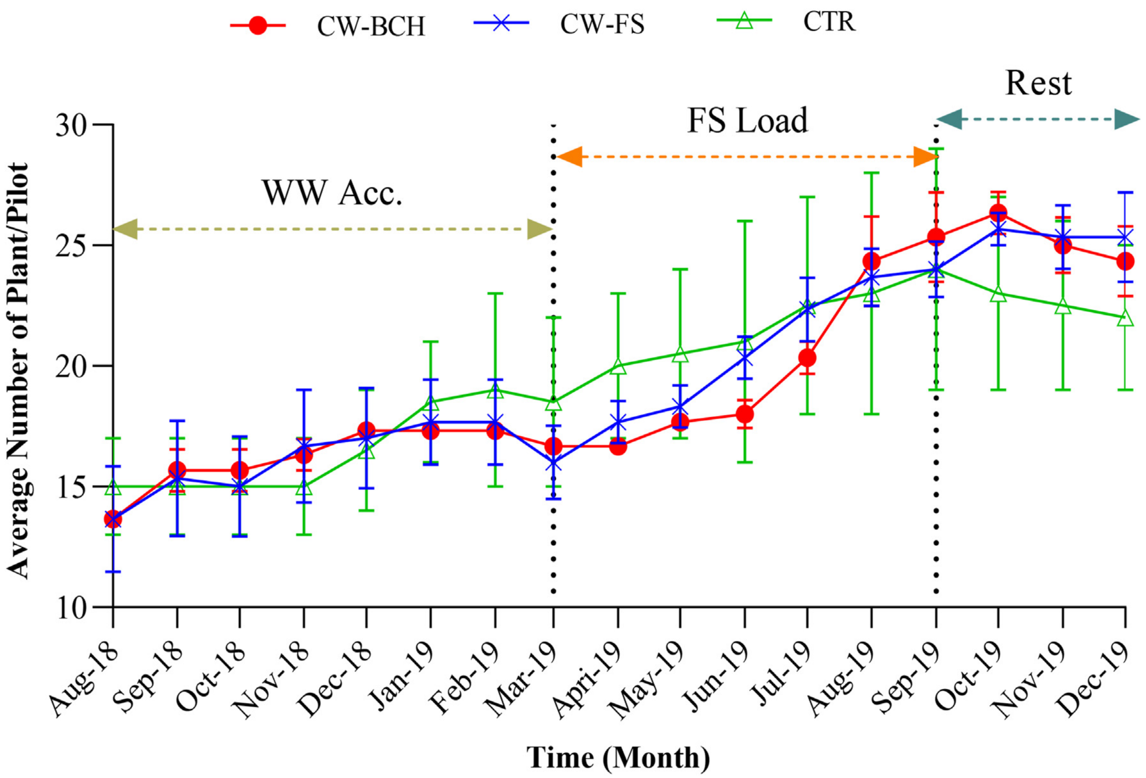


Figure 6. Number of bamboo plants per pilot.

contents of the load, after which a rapid leave recovery was observed. This observation was similar to the control setup of the preliminary experiment (Osei et al., 2019). Rapid wilting and dropping of leaves have been observed to be the first adaptative mechanism of the bamboo species to toxic wetland conditions and thus a very critical indicator for studying the species adaptability for the treatment of FS by the VFCW technology.

3.4.4. Development of culm

Bamboo culm is described as the aerial stems, which arises from a network of underground rhizomes in full diameter and develop branches and leaves from nodes and internodes (Das, 2019). Similar to the other parameters, the size of culm diameter increased from initial averages of 4.68 ± 0.71, 5.06 ± 6 and 6.67 ± 1.27 mm to 24.17 ± 3.16, 24.56 ± 2.31 and 21.46 ± 1.12 mm for CW-FS, CW-BCH and CTR respectively

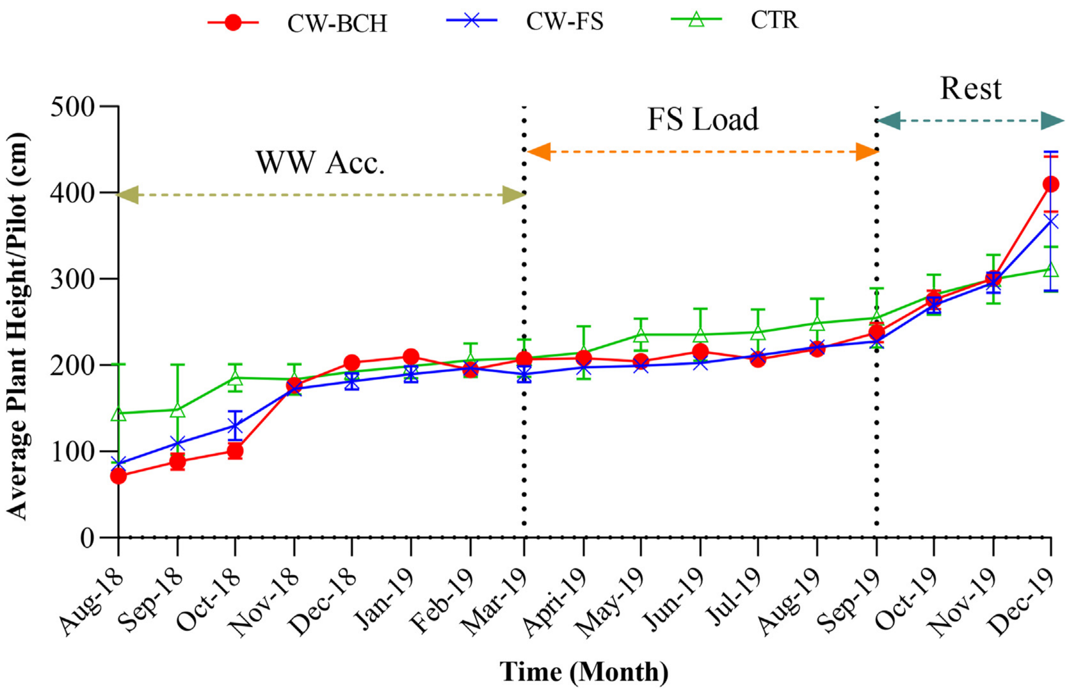


Figure 7. Average plant height per pilot.

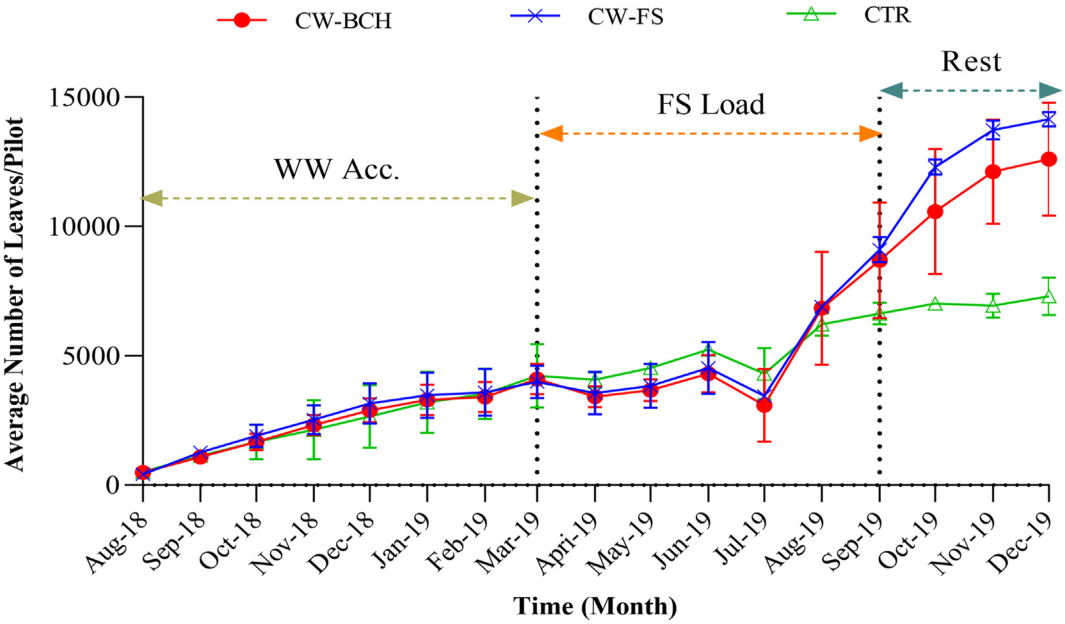


Figure 8. Number of bamboo plant per pilot.

(Figure 9). However, variation among treatment showed no significant variation at a *p*-value of 0.640. The study by Kala et al. (2020) averagely recorded between 9.80 and 22.50 mm of bamboo culm diameter for various treatments within a period of four years. The growth of bamboo culm was generally described as telescopic for which wider and taller shoots emerge each year. The new shoots sprout with a diameter which remains as the culm width at maturity. As a result, the culms of the older generation are usually smaller and shorter than new once. This growth dynamics are, therefore, related to the maturity of the underground rhizome system and its accessibility to nutrients (Ord-Hume, 2020).

On the whole, the selected indigenous bamboo species can be stated to have demonstrated superior resistance as a potential macrophyte for FS treatment in the vertical flow constructed wetland, compared to the species of *Oryza longistaminata* and *Sporobolus pyramidalis* which completely wilted out upon FS load in the premiere study by Kouawa et al. (2015). A study by Gueye et al. (2016) similarly observed an increase in plant density for the different species of Echinocloa colona, Echinochloa crus-galli, *Echinochloa pyramidalis*, Paspalidium geminatum, and *Paspalum vaginatum* at annual SRL loading rates of 100–300 DM/m^2/year.

The prospects of bamboo as a potential macrophyte cannot be overlooked. Bamboo is widely used as a source of raw material for furniture, building, pulp, particle board, bioenergy, food, forage, medicine, among others. Its vital role in environmental and ecosystems restoration,

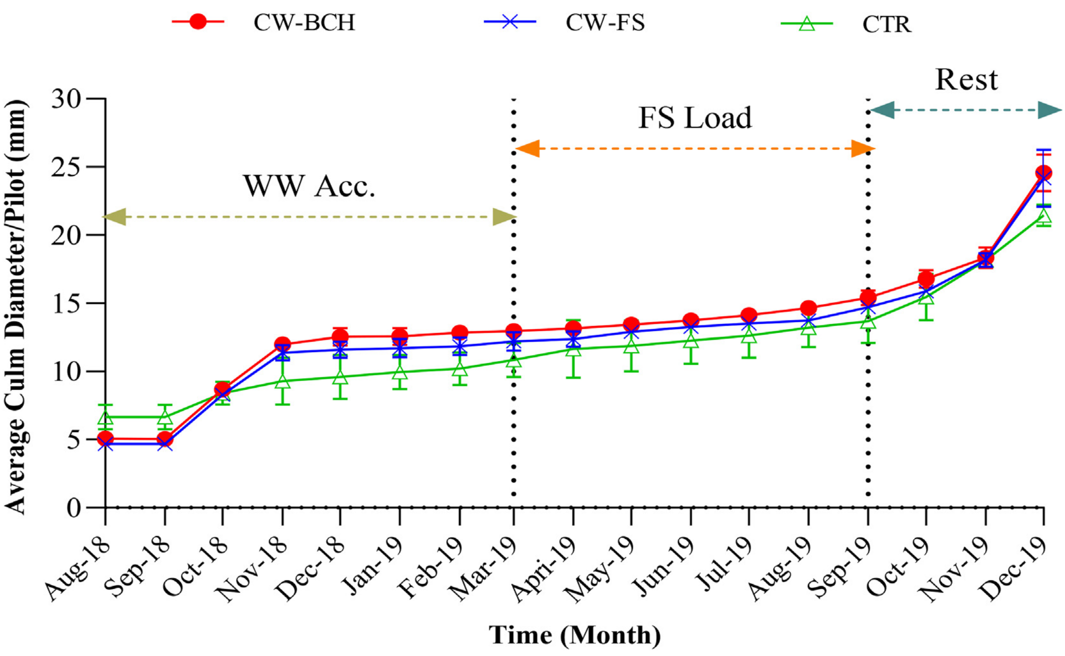


Figure 9. Number of bamboo plant per pilot.

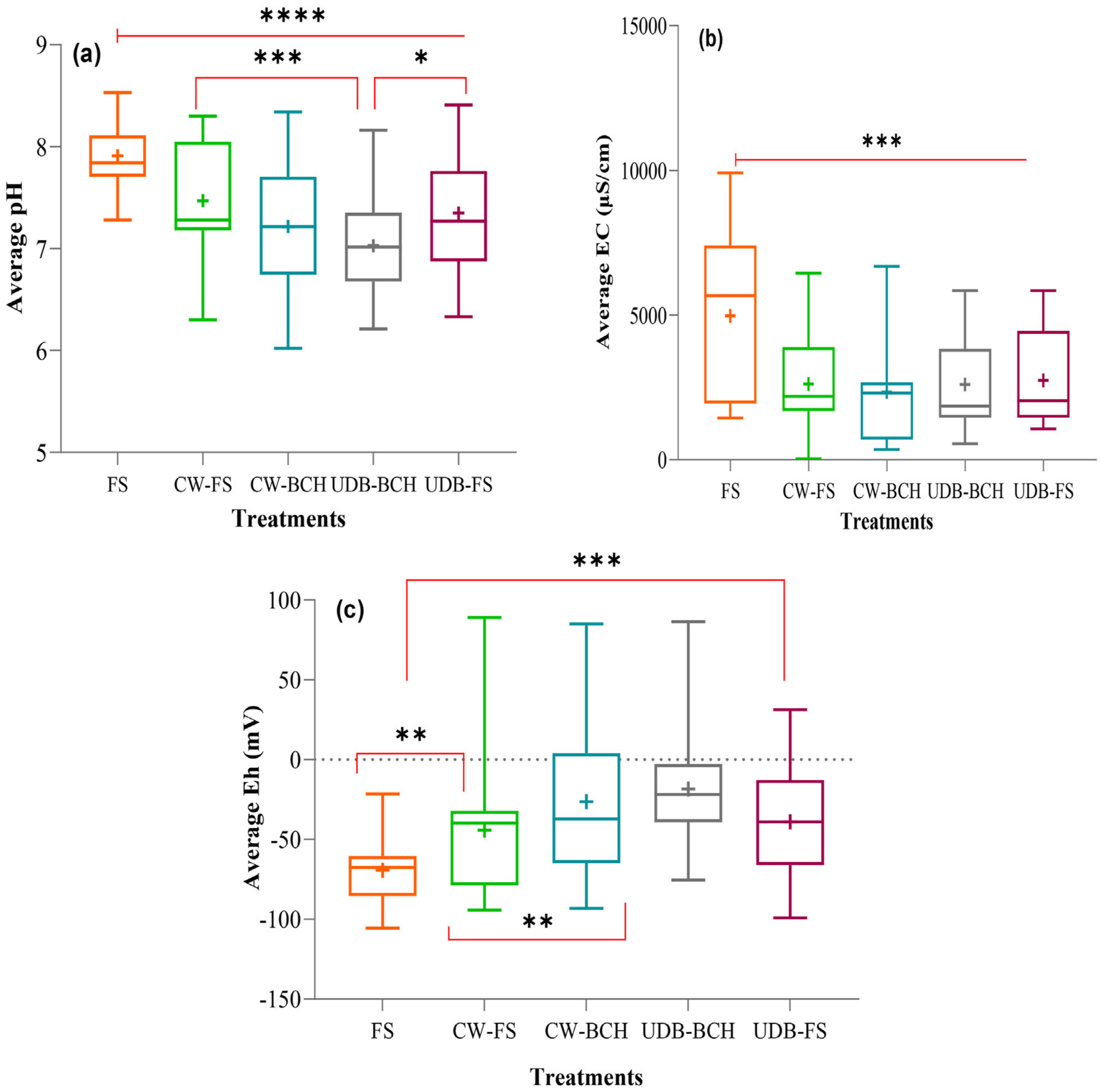


Figure 10. Average effluent levels: (a) pH, (b) Redox Potential and (c) Electrical Conductivity.

biodiversity preservation with high waste purification potential is broadly studied and discussed in different literature (Chen et al., 2015; Emamverdian et al., 2018; Das, 2019).

3.5. Effluent quality and pollutant removal

3.5.1. pH, redox potential and electrical conductivity

The pH of the faecal effluent showed a slight reduction from moderately alkaline in FS to slightly alkaline (7.35 ± 0.6 to 7.47 ± 0.5) for UDB-FS and CW-FS and neutral (7.21 ± 0.6 to 7.03 ± 0.5) for CW-BCH and UDB-BCH (Figure 10a). The range of effluent pH is very consistent with the results (pH 6.5 to 7.4) of the initial experiment by Osei et al. (2019). pH of 6.5–8.5 is noted to favour the process of ammonification in wetland systems (Stefanakis, 2018). The average effluent pH for the various treatment were within the Burkina Faso Ministry of Environment and Fisheries Resources (MEFR) (2015) allowable limit of 6.5–9 for safe discharge into the environment.

The effluent EC was within the range of 2344 ± 1648 µS/cm to 2744 ± 1620 µS/cm (Figure 10b). Treatments with BCH content were relatively lower than that of FS. Faecal effluent EC and pH levels of 121–1010 (µS/cm) and 6.4–7.6 respectively, were noted as favourable for biological processes by Kengne et al. (2014b) and are compatible with the WHO guidelines for safe reuse of wastewater in agriculture. However, the average range of effluent EC for the treatments was above the Burkina Faso MEFR (2015) allowable limit of 1000 µS/cm for safe discharge into the environment.

The effluent Eh exhibited lower anti-oxidising condition for the treatments with BCH composition and ranged between −18.4 ± 31.4 and −44.2 ± 35.3 mV (Figure 10c). According to Stefanakis (2018), the measure of Redox potential (Eh) is an indication of the electrochemical potential or electron availability in chemical and biological systems. In an aqueous system, the intensity of oxidation is limited by the electrochemical potential at which water becomes unstable and releases molecular oxygen. The oxidation-reduction potential of the aqueous system thus may affect the oxidation states of various elements such as hydrogen, carbon, nitrogen, oxygen, sulfur and several metals, among others. According to Tanaka et al. (2011), reaction rates of nitrification and denitrification in wetlands are significantly influenced by pH, redox potential and temperature.

3.5.2. Removal of organic constituents

The concentrations of COD and BOD_5 and TOC were reduced to a range of 455.27 ± 362.4 to 597.4 ± 524.6 mg/l (Figure 11a), 44.64 ±

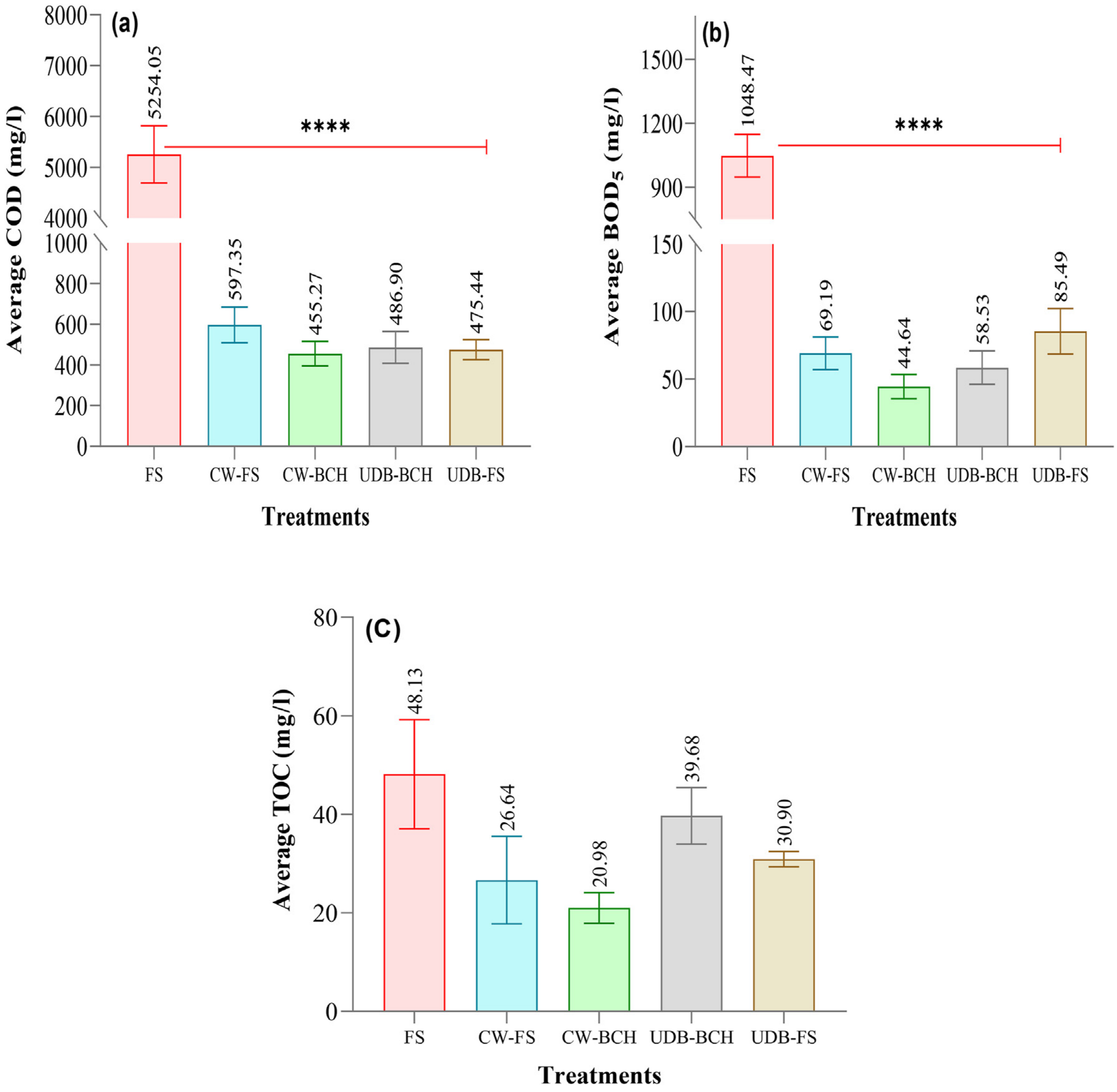


Figure 11. Average concentration of organic constituents: (a) COD, (b) BOD$_5$ and (C) TOC.

53.59 to 85.49 ± 101.0 mg/l (Figure 11b) and 20.98 ± 15.43 to 39.68 ± 9.929 mg/l (Figure 11c) respectively. The average COD concentration was relatively lower than that recorded for the effluents of the preliminary studies by Osei et al. (2019). The different studies of Tan et al. (2020) and Kim et al. (2018), found varied COD concentration of 213.77, 753 ± 39, respectively while a relatively higher BOD of 246 ± 433 and 200 ± 116 mg/l were noted by Andrade et al. (2017) and Karolinczak and Dabrowski (2017). The results of ANOVA for both COD and BOD$_5$ showed a highly significant difference between FS and the treatment concentrations at a *p*-value of 0.0001. However, the ANOVA for TOC was statistically insignificant at a *p*-value of 0.25. Though there were no significant differences among the treatments, CW-BCH recorded the lowest concentration for all the organic contents.

The observed reduction in organic concentration resulted to an appreciable removal efficiency with the range of 88.6–91.3 and 91.8–95.7% for COD and BOD$_5$ respectively with removal of TOC being less than 60% (Figure 15). Despite the appreciable removal efficiencies, the average effluent concentrations for COD and BOD$_5$ were higher than the Burkina Faso MEFR (2015) national acceptable limits of 150 and 40 mg/l, respectively for safe discharge into the environment.

Kengne et al. (2011) similarly recorded average removal efficiency of 92% for both COD and BOD$_5$ while, Kouawa (2016) recorded a relatively lower efficiency of 35–74% for COD.

Removal of organic matter is explained by the high oxygen transfer capacity of the VFCW, which creates a favourable aeration condition and allows for effective organic matter (BOD) and ammonia nitrogen removal (Stefanakis, 2018).

3.5.3. Removal of Nutrients Composition

The nutrients content of the effluent was monitored for the average concentrations of nitrogen compounds and phosphorus. There was a general reduction of ammonium (NH$_4^+$), Total phosphorus (TP), Phosphate (PO$_4^{3}$-) at average concentrations of 71.49 ± 61.89 to 110.4 ± 102.7 mg/l (Figure 12a), 40.04 ± 37.92 to 118.2 ± 172.9 mg/l (Figure 12b) and 39.16 ± 32.94 to 44.71 ± 51.44 mg/l (Figure 12c) respectively. The average concentrations of NH$_4^+$ and PO$_4^{3-}$ for the various treatments however, exceeded the national allowable limit of 35 and 0.8 mg/l (Kone et al., 2016) respectively, for safe discharge into the environment for potential reuse. Nutrient composition within the range of 4–1500, 6.3 to 19.2, and 0.7–7.1 mg/l was reported for NH$_4^+$, TP and PO$_4^{3-}$ respectively in similar studies by different authors (Tan et al., 2020, 2017; Kim et al., 2018; Bui et al., 2018; Karolinczak and

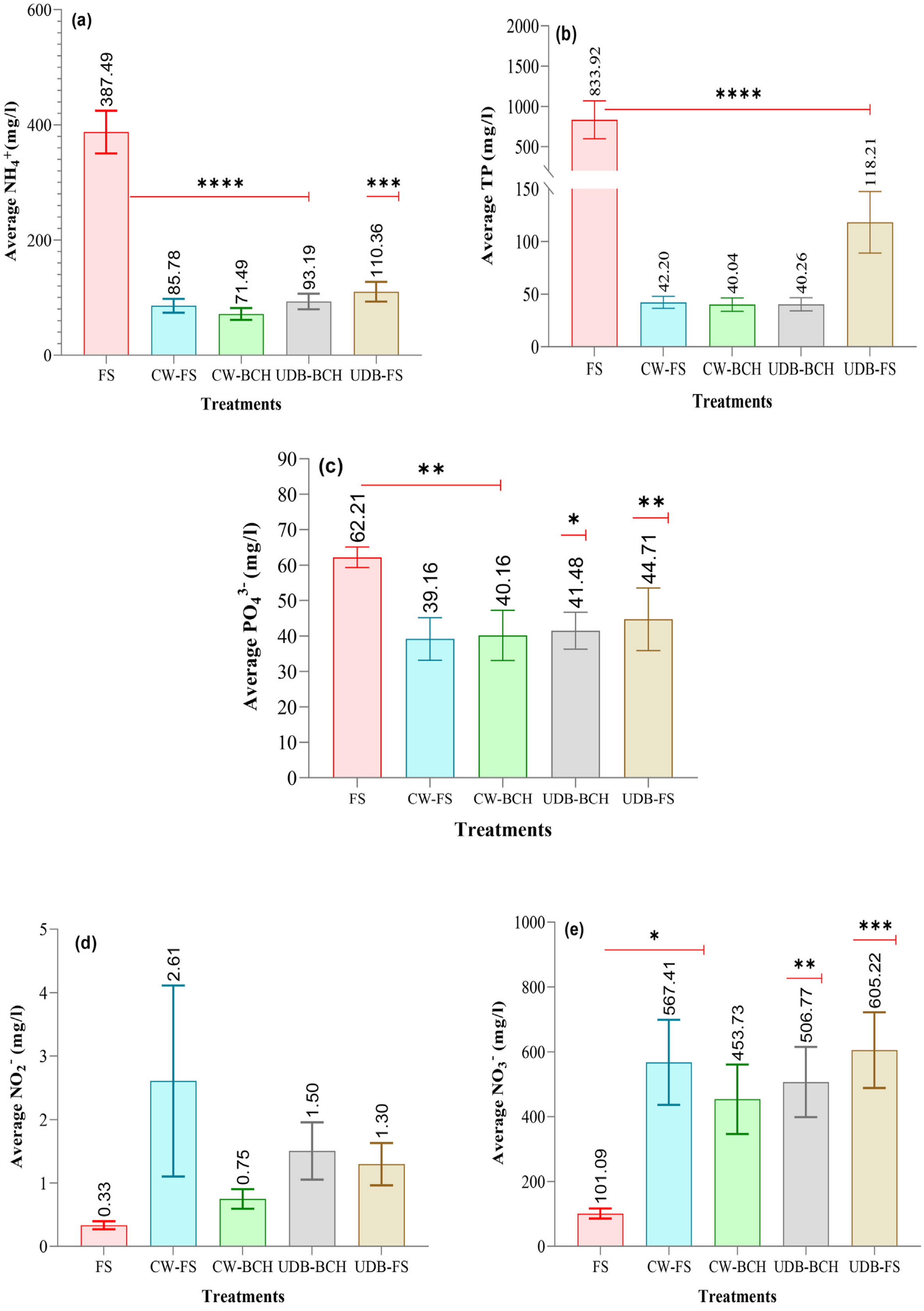


Figure 12. Concentrations of nutrient composition: (a) NH_4^+, (b) TP, (c) PO_4^{3-} (d) NO_2^- and (e) NO_3^-.

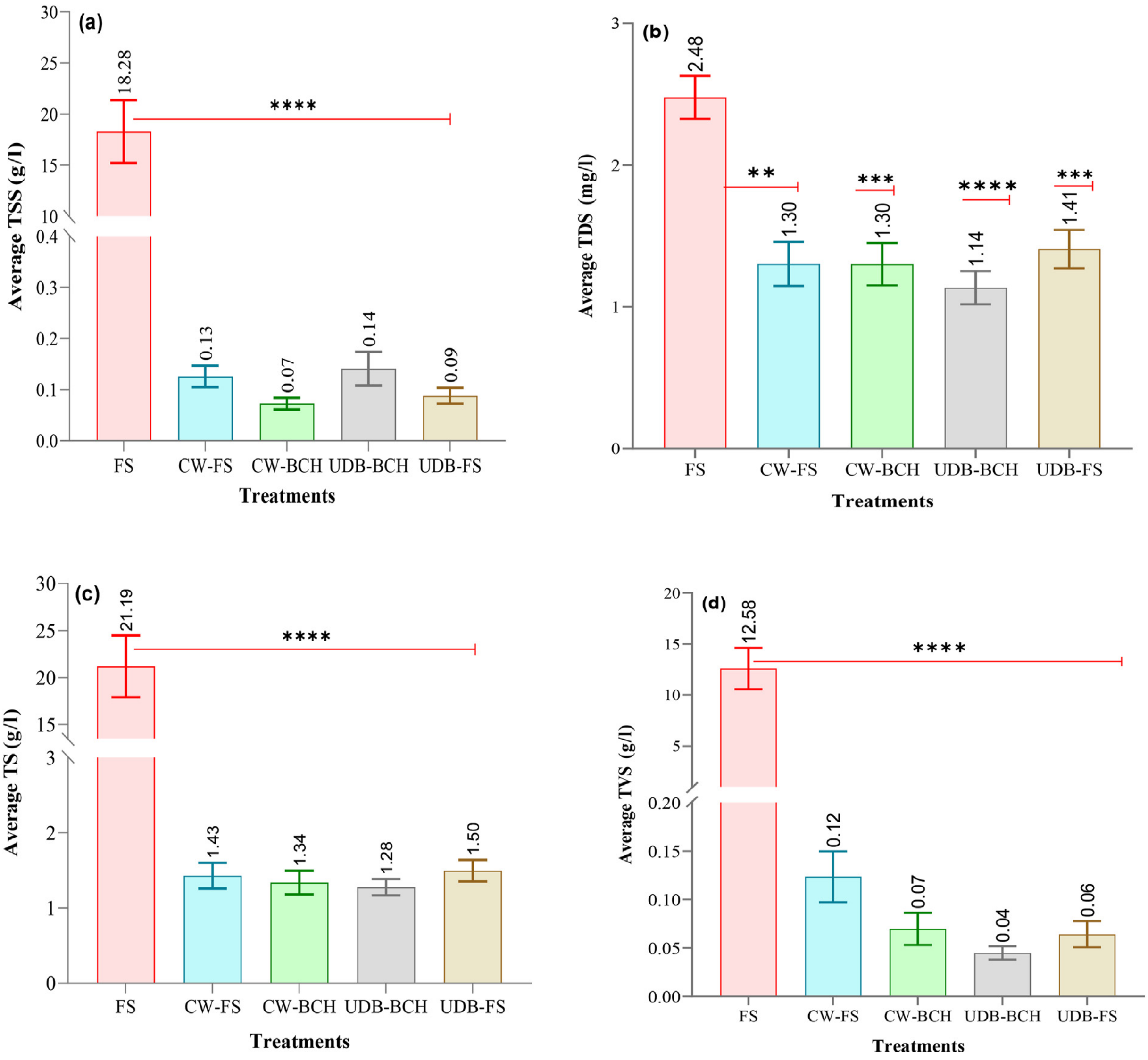


Figure 13. Average levels of solid content: (a) TSS, (b) TDS, (c) TS and (d) TVS.

Dabrowski, 2017; Magri et al., 2016). The average effluent concentration of TP and PO_4^{3}- are thus relatively higher while NH_4 is within the reported range.

Concentrations of nitrite (NO_2^-) and nitrate (NO_3^-) rather increased in the effluent treatments (Figure 12d & e). The average concentrations of 0.75–2.61 mg/l and 453.73–605.22 mg/l were however, beyond the national discharge limit of 0.9 and 11.4 mg/l (Kone et al., 2016) for NO_2^- and (NO_3^-) respectively. Uggetti et al. (2009) similarly recorded higher effluent concentrations of NO_2^- and NO_3^- and explained the observation as a clear indication of the aerobic condition in constructed wetlands.

The observed trend resulted to average removal efficiencies of 71.5–81.6%, 85.8–95.2% and 28.1–37.1% for NH_4^+, TP and PO_4^{3-} respectively (Figure 15). The results of Kouawa (2016) comparatively presented a wider range of removal efficiencies for NH_3 (17–80%) and TP (21–73%). The efficiency of PO_4^{3-} presents an appreciable reduction from the preliminary study of >90% for the bamboo species (Osei et al., 2019). The removal efficiency of TP of wetlands was rated between 40 to 60% for typical domestic wastewater (Tanaka et al., 2011).

A review by Jain et al. (2022), on the treatment of septage and faecal sludge management with special emphasis on constructed wetlands similarly reported high average removal efficiencies of 84.3% and 84.4% for TP and PO_4^{3-} respectively.

According to Paing et al. (2015), the removal of nutrients initially begins with the retention of organic and particulate nitrogen and phosphorous in the sludge layer. Nitrogen transformations in wetland system are mainly attributed to the different processes of ammonification nitrification, denitrification and anaerobic ammonium oxidation (Stefanakis, 2018; Kadlec and Wallace, 2008). According to Paing et al. (2015), vertical filters allow for a favourable aerobic condition for high nitrification as against denitrification. Aside transformation of molecular nitrogen in wetlands, translocation has also been attributed to processes such as particulate settling and resuspension, diffusion of dissolved forms, plant translocation, litterfall, ammonia volatilization, and sorption of soluble nitrogen on substrates (Kadlec and Wallace, 2008).

TP in the wetland is consequently reduced due to the sorption of orthophosphate on the filtration media and saturation of the sorption site as the macrophyte ages (Paing et al., 2015). The general transformation of P in wetlands has been ascribed to the different processes of soil accretion, adsorption/desorption, precipitation/dissolution, plant/microbial uptake, fragmentation, leaching, mineralisation and burial (Tanaka et al., 2011).

3.5.4. Removal of solid content of faecal effluent

The solid content of faecal effluent apparently decreased for Total Suspended Solid (TSS), Total Dissolved Solid (TDS), Total Volatile Solid

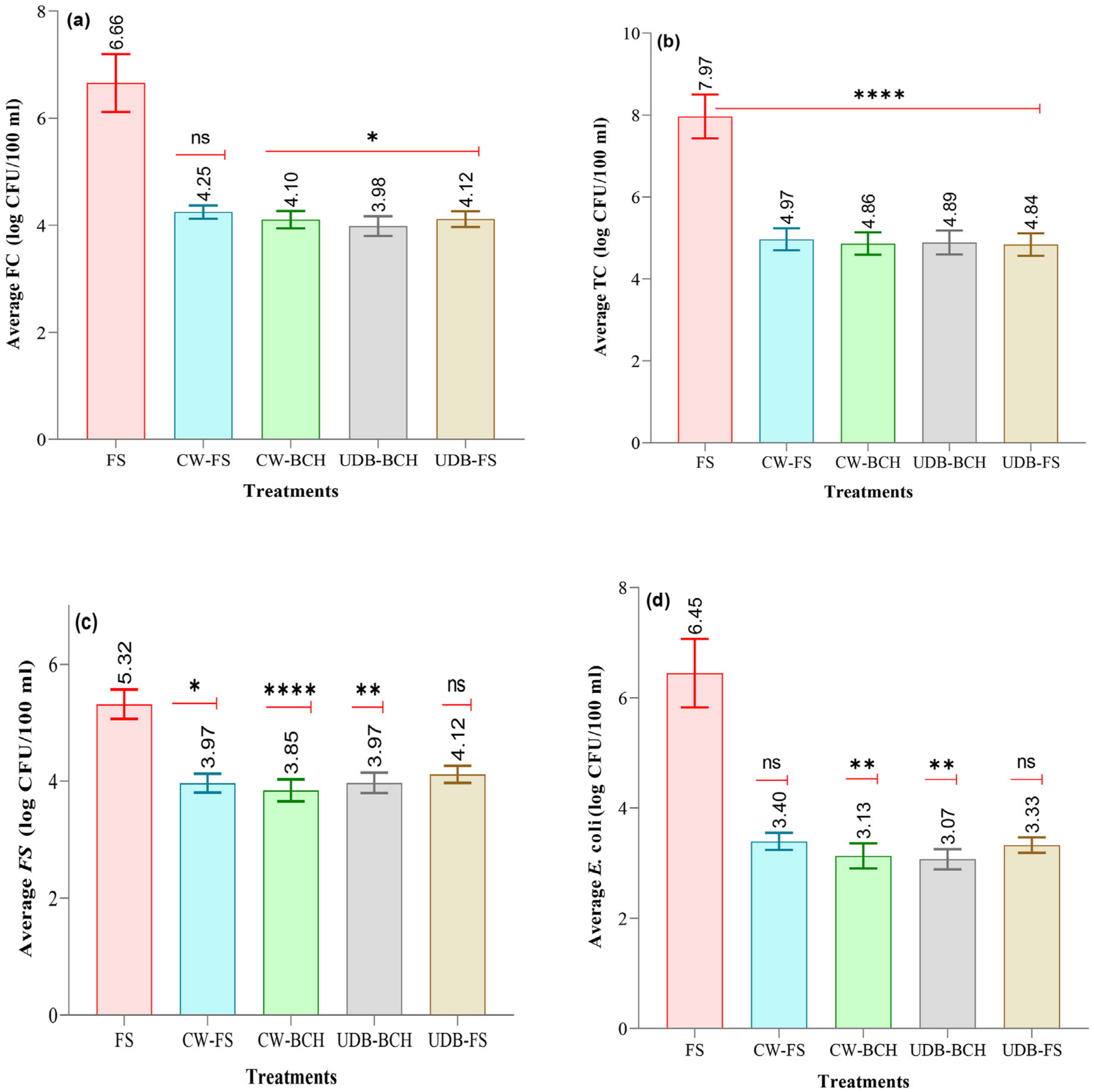


Figure 14. Average levels of faecal contaminants: (a) FC, (b) TC, (c) *FS* and (d) FC.

(TVS) and Total Solid (TS). Average levels were found within the ranges of 0.07–0.14 g/l, 1.14–1.41 g/l, 0.04–0.12 g/l and 1.28–1.50 g/l for TSS, TDS, TVS and TS (Figure 13a–c) respectively. All the treatments were significantly different from the FS at *p*-value of 0.0001. Despite the statistically insignificant difference among treatments for the various solid compositions, the overall TS concentration decreased in the order of UDB-BCH < CW-BCH < CW-FS < UDB. This might be a positive indicator of the effect of BCH for solid content removal in VFCW resulting from potential attraction between the solid particles and biochar. The average TVS and TSS contents of the effluent were within the range of 187–591 mg/l and 12–401 mg/l respectively from the results of previous studies while TS was relatively higher than 817.15–1,014 mg/l (Tan et al., 2020; Kim et al., 2018; Andrade et al., 2017; Karolinczak and Dabrowski, 2017; Magri et al., 2016; Afifi et al., 2015; Calder'on-Vallejo et al., 2015).

Reduction in solid content resulted to 99% removal efficiency for all the solid compositions with the exception of TDS which was apparently below 50% (Figure 15). High TSS removal efficiency of 80% was also recorded by Kouawa (2016). The study Jain et al. (2022), similarly reported high average removal efficiencies of 80 and 93% for TS and TSS respectively.

The result was thus a positive indication of effective solid–liquid separation. The Burkina Faso MEFR (2015) guideline for effluent discharge allows for a maximum TSS limit of 0.15 g/l, and thus the levels found for the study were within the safe range for discharge into the environment.

Wetland system facilitates the removal of solids by the different mechanisms of filtration in which particles are mechanically strained by flow constrictions, and sedimentation of heavier particles which settle into stagnant micro pockets (Kadlec and Wallace, 2008). Solid removal processes is as well aided by the aggregation or flocculation of suspended particles by attraction and results to the formation of larger and heavier particles. Also, the growth of biofilm on filter bed media serves as interceptors of the smaller particles (Tanaka et al., 2011).

3.5.5. Faecal contaminants load in effluent

The indicator organisms monitored for faecal contamination includes Total and Faecal coliform, *Escherichia coli* and Faecal *Streptococcus* (*FS*). The diverse strains were noted to pose severe risk to human health (Kadlec and Wallace, 2008). The average microbial load in effluent showed a significant reduction from the raw FS, while a

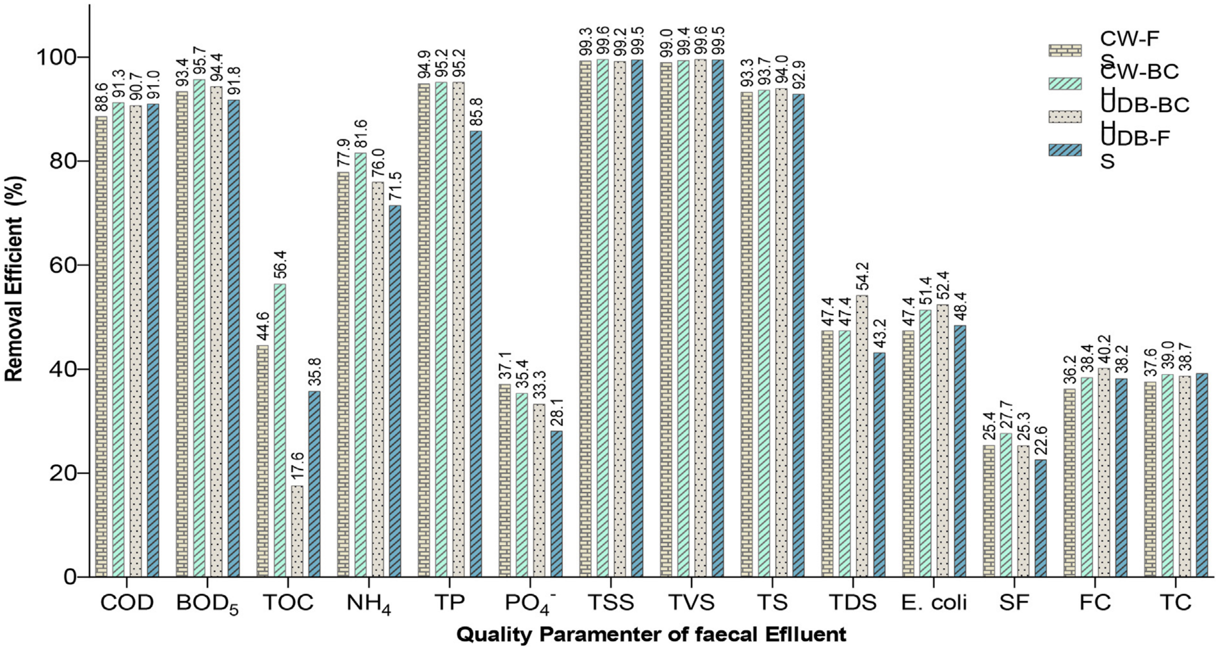


Figure 15. Removal efficiency of faecal contaminants.

slight variation was realised among the various treatments. Effluent concentrations ranged from 3.98 to 4.25 log CFU/100 ml for FC (Figure 14a), 4.84 to 4.97 log CFU/100 ml for TC (Figure 14b), 3.85 to 4.12 log CFU/100 ml for *FS* (Figure 14c) and 3.07 to 3.40 log CFU/100 ml for *E. coli* (Figure 14d). Accordingly, the results of ANOVA showed a significant difference between the raw FS and the various treatment with P values of 0.0001. However, FC and *E. coli* for CW-FS and SF and *E. coli* for UDB-FS were not statistically significant. The study of Kouawa (2016) recorded overall bacteria removal of <1 ULog. Lekeufack et al. (2012) however, recorded significantly higher faecal indicators reductions of 1.15–1.4 and 0.3 to 0.65 log units for CW and UDB respectively. Generally, low removal efficiency of <50% was recorded for the indicator micrograms (Figure 14). Coliform removal efficiency in wetland systems is reported to possibly range from 34 to 99.9% (Tunçsiper et al., 2012). Removal of enteric pathogens in natural wetland systems is primarily due to unfavourable wetland conditions or natural die-off rates (Kadlec and Wallace, 2008). Established removal mechanism are listed to include attachment, sedimentation, mechanical filtration and secretion of bactericidal substances by roots of macrophytes, plant-microbe interaction within biofilms, oxidation, ultraviolet radiations and exposure to biocides (Lekeufack et al., 2012; Alufasi et al., 2017).

3.6. Correlation matrix of bamboo species development, weather conditions, internal wetland conditions and effluent quality

The results from the Pearson correlation matrix generally revealed a statically significant ($p < 0.05$) relationship among parameters of bamboo development, weather condition, effluent quality and internal CW conditions (Figure 16). A strong positive linear relationship was determined among species growth parameter with coefficient (r) ranging between 0.83 and 0.99 (Figure 15). The average concentration of the different FS quality parameters generally recorded a moderate to strong positive ($r = 0.55$–0.94) linear relationship with the development of the bamboo species with the exception of NO^{3-} which was noted to be weak ($r = 0.14$–0.42). TS and TVS, however, recorded a moderate to weak ($r = -0.31$ to – 0.53) negative relationship with species development (Figure 16a). The relationship among FS quality parameters ranged from moderate to perfect positive ($r = 0.57$–1). Similarly, TS and TVS recorded a moderately negative to no ($r = -0.52$ to 0.076) relationship with all the different FS quality parameters. The results was statistically significant at $p < 0.05$. The results thus imply that the development of the bamboo species is influenced by almost 55–94% occurrence dynamics of the different FS quality parameters while the growth parameters are 83–99% interdependent. The occurrence of FS quality parameters is thus 57–100% interrelated. The study of Kouawa et al. (2015), contrarily found a strong negative to a weak ($r = -7.85$ to 0.307) correlation between important FS quality parameters and morphological development of the different species of *Oryza longistaminat*a and *Sporobolus pyramidalis* which was noted to have contributed to the continuous species deterioration at excessive threshold concentrations. Temperature and EC in the CW showed a moderate to strong negative ($r = -0.41$ to -0.950 correlation with bamboo development, while% MC recorded a weak positive (0.29–0.37) relationship. Rainfall, and RH however recorded a moderate to strong positive correlation ($r = 0.46$–0.72 and 0.43–0.62 respectively) whereas that of minimum temperature was noted to be weak (0.47–0.49.) as presented in Figure 16b. However, Gu et al. (2021), observed a weak positive to strong negative (0.28 to −0.03) relationship between the growth parameters (culm height and leaf length) and climatic factors (annual temperature and precipitation) while a strongly negative correlation (−0.04 to −0.12) was noted between the growth parameters and soil factors (OM, TP, K and pH). In another study, Fan et al. (2015) generally observed a negative relation between precipitation and Diameter at breast height (DBH) for five different species of bamboo, while Wang et al. (2016) similarly established a negative correlation between annual mean air temperature and elevation. The development of the bamboo species generally recorded no linear relationship with effluent quality aside Eh and NO^{3-} which exhibited a weak positive correlation ($r = 0.20$–0.38 and 0.31–0.47 respectively) with the different growth parameters. The results also show a strong positive relationship between the different effluent quality parameters of EC and TVS ($r = 0.8$), EC and TS ($r = 0.89$), EC and TSS ($r = 0.6$), COD and TVS ($r = 0.62$), BOD$_5$ and TVS ($r = 0.66$), TSS and TVS ($r = 0.91$) and TS and TVS ($r = 0.77$). There was however a perfect linear relationship between effluent TP and TDS (Figure 16c).

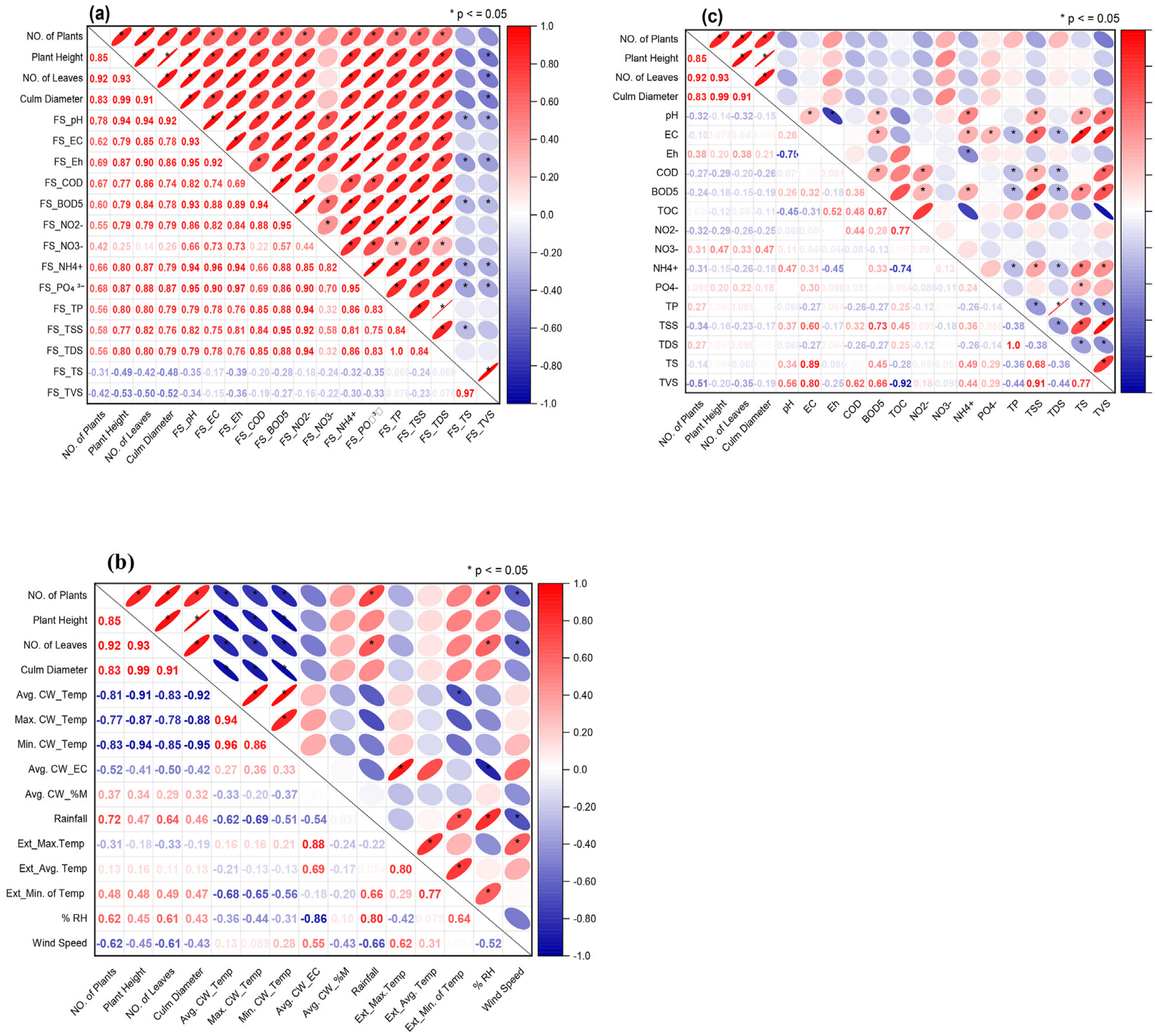


Figure 16. Correlation Matrix: (a): Bamboo Development and FS Quality Parameters, (b) Bamboo Development, Weather Parameters and Internal Wetland conditions (c): Bamboo Development and Effluent Quality Parameters.

3.7. Conclusion

Characteristics of raw faecal sludge showed a high level of inconsistency and variability for the various quality parameters except for pH. The annual sludge loading rate was within the recommended levels for faecal sludge treatment, as determined from previous studies.

The study observed positive adaptation of indigenous bamboo species to the VFCW conditions for faecal sludge treatment by demonstrating a progressive increase in morphological development for all the treatments throughout the study period (from acclimatisation to rest). Monthly growth of bamboo however, showed no significant difference among the various treatments. A strong positive linear relationship was realized between species growth parameters, while a moderate to strong positive relationship was determined between the different FS quality parameters. Satisfactory pollutant removal efficiencies of 70–99% were recorded for the various pollutants monitored for the study except for PO_4^{3-}, TOC and TDS and indicator micro-organisms which were found below 50%. Removal efficiencies especially for solid contents thus indicated a positive potential for solid-liquid separation. The introduction of bamboo biochar as a conditioner showed virtually no significant influence on species morphological development and contaminant removal in the effluent. Except for pH and TSS, all the effluent quality parameters monitored for the study exceeded the national allowable limits for safe discharge in Burkina Faso. There is thus the need for further treatment to reduce contaminant levels in a second or to the third series of a connected constructed wetland prior to reuse for agriculture. Nonetheless, the study demonstrated the positive potentials for adopting indigenous bamboo species as emergent macrophytes for faecal sludge treatment using the VFCW.

Declarations

Author contribution statement

Richard Agyemang Osei: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Felix Kofi Abagale; Yacouba Konate: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Funding statement

This work is supported by World Bank, Africa Centres of Excellence (ACE) Project.

Data availability statement

Data will be made available on request.

Declaration of interest's statement

The authors declare no competing interests.

Additional information

No additional information is available for this paper.

Acknowledgements

The authors express gratitude to the World Bank, Africa Centres of Excellence (ACE) Project, International Institute for Water and Environmental Engineering (2iE), University for Development Studies and the for their financial support for this study.

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