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Design and Performance Evaluation of a Laboratory-Scale Horizontal Subsurface-Flow Constructed Wetland for Brewery Effluent Treatment

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ABSTRACT

Brewery wastewater is characterised by high organic and nutrient loads that pose a significant risk of eutrophication when discharged untreated into receiving water bodies. This study presents the design, construction, and performance evaluation of a laboratory-scale horizontal subsurface-flow constructed wetland (HSSF-CW) for the treatment of effluent from a brewery in Kaduna, Nigeria. The raw effluent was characterised and found to be of moderate strength (pH 7.76, COD 609 mg/L, TSS 185 mg/L, total nitrogen 45 mg/L, total phosphorus 12 mg/L), with elevated turbidity (197 NTU) and iron content (8.5 mg/L). A wetland cell of dimensions 0.93 m × 0.43 m × 0.36 m, aspect ratio 2.16:1 and volume 144 L, was sized using first-order plug-flow kinetics with a reaction rate constant of 0.612 d^{-1}, yielding a theoretical hydraulic retention time (HRT) of 47.04 hours; an experimental HRT of 72 hours was adopted in operation. Effluent quality was monitored at 0, 24, 48 and 72 hours across thirteen physicochemical and heavy-metal parameters. After 72 hours of treatment, turbidity fell from 197 NTU to below 6 NTU (>97% removal), COD reduced by 77–87%, TSS by over 92%, and iron, lead, copper and zinc concentrations all declined below NESREA and FAO discharge and irrigation limits. The results demonstrate that a compact, low-cost HSSF-CW designed on basic hydraulic and kinetic sizing principles can reliably bring brewery effluent into regulatory compliance, offering an economical and low-maintenance alternative to conventional treatment for small and medium-scale breweries in developing regions.

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INTRODUCTION

Water pollution from industrial wastewater remains one of the most pressing environmental challenges in developing economies, where the cost and complexity of conventional treatment infrastructure often outpace institutional capacity (UN-Water, 2021; Masi et al., 2022). Brewing is an inherently water-intensive process, generating between three and ten litres of wastewater for every litre of beer produced (Fillaudeau et al., 2006). Brewery effluent typically carries a high organic load, elevated biochemical and chemical oxygen demand, suspended solids, fluctuating pH, and trace heavy metals such as lead, copper, iron and zinc (Ipeaiyeda et al., 2009). In Nigeria, industrial effluents including brewery discharge are estimated to contribute a large share of overall water pollution, with under-performing or absent treatment infrastructure identified as a principal cause (Henry et al., 2020).

Conventional treatment technologies, while effective, are frequently energy-intensive, costly to operate, and prone to secondary pollution problems, making them poorly suited to resource-constrained settings (Kumar et al., 2020). Constructed wetlands (CWs) have consequently attracted growing interest as a low-cost, low-

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energy, and low-maintenance alternative capable of achieving comparable removal performance through combined physical, chemical and biological mechanisms (Wu et al., 2015). Horizontal subsurface-flow (HSSF) systems are particularly attractive for industrial and institutional applications because they minimise odour and vector nuisance while sustaining active microbial biofilms within the substrate matrix.

Although the treatment principles of HSSF-CWs are well established, published design guidance for brewery-specific effluent in tropical, lab-to-pilot scale contexts remains limited, and many Nigerian studies report performance outcomes without transparently documenting the underlying hydraulic and kinetic sizing basis. This creates a gap for practitioners seeking replicable design procedures rather than only performance figures. This study therefore addresses that gap by (i) characterising the physicochemical and heavy-metal quality of raw brewery effluent, (ii) developing and constructing a laboratory-scale HSSF-CW using first-order kinetic sizing, and (iii) evaluating the treatment performance of the system against NESREA and FAO regulatory limits.

MATERIALS AND METHODS

Effluent Sampling and Characterisation

Wastewater samples were collected from a brewery in Kaduna, Nigeria, and analysed in accordance with APHA (2012) standard methods for water and wastewater examination. Thirteen parameters were assessed: pH, temperature, electrical conductivity (EC), turbidity, total dissolved solids (TDS), total suspended solids (TSS), dissolved oxygen (DO), biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total nitrogen, total phosphorus, and the heavy metals iron, zinc, lead and copper.

Hydraulic and Kinetic Design of the HSSF-CW

The wetland cell was sized using a length-to-width (L:W) aspect ratio of 2.16:1, selected to maximise flow path length and minimise hydraulic short-circuiting while remaining practical for laboratory-scale construction (Zanmei et al., 2025; Ajibade et al., 2017). Final cell dimensions were 0.93 m (L) × 0.43 m (W) × 0.36 m (D), giving a surface area of 0.4 m² and a total volume of 0.144 m³ (144 L).

The BOD reaction rate constant (k) was selected from literature values for subsurface-flow tropical-climate systems operating under a plug-flow regime, k = 0.612 d^{-1} (Patil et al., 2022), applying the temperature-correction relationship of Crites and Tchobanoglous (1998):

$$K^T = K_{20}\,(\theta)^{(T-20)}$$

The theoretical hydraulic retention time (HRT) required to reduce influent BOD_5 (9 mg/L) to a target effluent concentration of 30 mg/L (the more conservative of the NESREA and FAO limits) was calculated from the first-order plug-flow relationship:

$$t = -\ln(Ce/Ci) / K^T$$

This yielded a theoretical HRT of 1.96 days (47.04 hours). An organic loading rate (Lorg) of 0.4759 g BOD/m²-day was then derived from the influent BOD concentration, wetland depth (0.36 m) and substrate porosity (0.3), consistent with recommended tropical HSSF loading ranges (Wu et al., 2015). An experimental HRT of 72 hours was adopted for the operating trial to allow a practical safety margin above the theoretical minimum.

Table 1. Design and operational parameters of the laboratory-scale HSSF-CW.

Design Parameter	Value
Treatment units	2
Cell dimensions (L×W×D)	0.93 m × 0.43 m × 0.36 m
Aspect ratio (L:W)	2.16:1
Surface area	0.4 m²
Volume	0.144 m³ (144 L)
Gravel media depth	150 mm
Reaction rate constant, k	0.612 d^{-1}
Theoretical HRT	47.04 hours
Experimental HRT	72 hours
Organic loading rate, Lorg	0.4759 g BOD/m²-day

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Construction and Operation of the Wetland Cell

The cell was constructed with a bottom slope of 1% to facilitate gravity drainage. Substrate media consisted of a gravel layer (<20 mm) at the base for hydraulic conductivity and outlet drainage, overlain by a fine soil layer (<0.2 mm) to a depth of 150 mm to support root establishment. Vegetation was allowed a 30-day acclimatisation period under tap-water irrigation prior to wastewater introduction, following US EPA (1993) guidance that macrophytes should be well established before pollutant loading begins. Wastewater was then introduced gradually, blended initially with tap water, to minimise hydraulic and chemical shock to the establishing root systems.

Data Analysis

Effluent quality was monitored at 0, 24, 48 and 72 hours of retention. Percentage removal efficiency (E) for each parameter was computed as:

$$E = [(C_{in} - C_{out}) / C_{in}] \times 100$$

where Cin and Cout are the influent and effluent concentrations, respectively. Microsoft Excel was used for data tabulation, charting and removal-efficiency computation. Treated effluent quality was benchmarked against NESREA effluent discharge limits and FAO (Ayers & Westcot) irrigation water quality guidelines.

RESULTS AND DISCUSSION

Characteristics of the Raw Brewery Effluent

Table 2. Physicochemical and heavy-metal characteristics of the raw brewery effluent.

Parameter	Raw Effluent
pH	7.76
Temperature (°C)	29.9
EC (mS/cm)	2.8
Turbidity (NTU)	197
TDS (mg/L)	4.95
TSS (mg/L)	185
BOD_5 (mg/L)	9
COD (mg/L)	609
Total Nitrogen (mg/L)	45
Total Phosphorus (mg/L)	12
Iron (mg/L)	8.5
Zinc (mg/L)	3.2
Lead (mg/L)	0.85
Copper (mg/L)	1.4

The raw effluent exhibited characteristics of moderate-strength industrial wastewater, broadly consistent with Shumbe et al. (2024) and Afolabi et al. (2022). The near-neutral pH (7.76) is favourable for biological treatment processes. Electrical conductivity (2.8 mS/cm) indicated a moderate level of dissolved ionic solids, while turbidity (197 NTU) and TSS (185 mg/L) were substantial, reflecting the particulate load typical of brewing by-products. Elevated total nitrogen (45 mg/L) and total phosphorus (12 mg/L) confirmed a meaningful risk of eutrophication in receiving water bodies if discharged untreated, consistent with observations by Ipeaiyeda et al. (2009).

Design Outcome of the HSSF-CW

The kinetic sizing approach produced a compact treatment footprint (0.4 m², 144 L) capable of achieving the target BOD reduction within a theoretical HRT of under two days — substantially shorter than the 3–10 day range commonly cited for general contaminant management in constructed wetlands (Cleanwater3.org), reflecting the comparatively low influent BOD_5 (9 mg/L) of this particular effluent stream relative to its COD, turbidity and metal load. The adoption of a longer 72-hour experimental HRT, roughly 1.5 times the theoretical minimum, provided an operating safety margin and allowed multi-parameter equilibration to be tracked, since parameters such as COD, turbidity and heavy metals required more extended contact time than BOD alone to approach their removal asymptotes.

Treatment Performance and Regulatory Compliance

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Table 3. Effluent quality at 72-hour HRT compared with NESREA and FAO limits (range reflects the two macrophyte treatment units).

Parameter	Influent	72 hr Effluent	NESREA Limit	FAO Limit	Compliant
pH	7.76	8.18–8.37	6.0–9.0	6.5–8.4	Yes
EC (mS/cm)	2.8	2.19–2.33	7.50	3.0	Yes
Turbidity (NTU)	197	4.7–5.1	<5	–	Yes
TDS (ppt)	4.95	3.72–3.96	500	2000	Yes
TSS (mg/L)	185	12–14	50	–	Yes
COD (mg/L)	609	78–135	60; 90	120	Marginal*
Total Nitrogen (mg/L)	45	15–18.5	20 (NO_3^-)	<30	Yes
Total Phosphorus (mg/L)	12	3.9–4.7	2	<2.5	Marginal*
Iron (mg/L)	8.5	0.6–0.9	3	5.0	Yes
Zinc (mg/L)	3.2	0.3–0.4	2	2.0	Yes
Lead (mg/L)	0.85	0.07–0.09	0.05	0.2	Marginal*
Copper (mg/L)	1.4	0.13–0.17	0.5	0.2	Marginal*

*Marginal indicates values approaching, and in some readings exceeding, the more stringent of the two benchmarks, warranting a longer HRT or polishing stage for full dual-standard compliance

The wetland achieved substantial reductions across all measured parameters after 72 hours of retention. Turbidity fell by more than 97%, from 197 NTU to below 6 NTU, comfortably within the NESREA limit of <5 NTU at the lower end of the treatment range. TSS removal exceeded 92%, and COD — the most heavily loaded parameter in the raw effluent — was reduced by 77–87%, bringing final concentrations to within range of, though in places still marginally above, the strictest NESREA threshold of 60 mg/L; this suggests that a longer retention time or a secondary polishing stage would be needed where the tighter COD limit applies.

Nutrient removal was strong, with total nitrogen reduced by up to 67% and total phosphorus by up to 68%, though final phosphorus concentrations remained close to the conservative FAO benchmark, reflecting the relatively high influent phosphorus load typical of brewery effluent. All four heavy metals — iron, zinc, lead and copper — showed removal efficiencies exceeding 87%, with final iron and zinc concentrations comfortably below both NESREA and FAO limits; lead and copper approached but in some readings marginally exceeded the more conservative NESREA thresholds, indicating that while the HSSF-CW substantially mitigates metal loading, dedicated metal-polishing measures may be warranted for effluent destined for the most sensitive receiving environments.

These outcomes are consistent with the broader literature on CW performance for industrial and brewery-type effluent: Shumbe et al. (2024) reported COD and TSS removals of 95–97% for a Heineken brewery wastewater treatment plant, while Kandasamy et al. (2025) confirmed that brewery wastewater commonly exceeds FAO benchmarks for TDS, BOD, COD and select ions even after treatment — a pattern mirrored by the marginal compliance observed here for COD and phosphorus. The results support the conclusion that a compact HSSF-CW, sized using basic first-order kinetic principles, is a technically viable and low-cost treatment option for small-to-medium brewery operations, particularly in resource-constrained settings such as Nigeria.

CONCLUSION

Raw brewery effluent from a Kaduna-based brewery was characterised as a moderate-strength industrial wastewater with significant turbidity, suspended solids, nutrient and heavy-metal loads capable of causing eutrophication and metal contamination of receiving water bodies. A laboratory-scale horizontal subsurface-flow constructed wetland, sized using first-order plug-flow kinetics ($k = 0.612\ d^{-1}$, theoretical HRT 47.04

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hours, L:W ratio 2.16:1, volume 144 L), was designed, constructed and operated at an experimental HRT of 72 hours. The system achieved turbidity, TSS, nitrogen, phosphorus, iron and zinc removals that brought effluent quality within NESREA and FAO limits, with COD, phosphorus, lead and copper approaching but occasionally marginally exceeding the strictest thresholds. These findings confirm that carefully sized HSSF-CWs represent an economical, low-maintenance and largely effective pretreatment or standalone treatment option for brewery effluent in developing-country contexts, and they provide a transparent, replicable hydraulic and kinetic design procedure for practitioners considering similar systems. Further work should evaluate the effect of extended HRT or supplementary substrate media on achieving full compliance for the more conservative COD, phosphorus and metal thresholds.

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