Research Square

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Cassava Peel Biosorbent for Sustainable Wastewater Treatment: Implications for Achieving SDG-6 in Low-Resource Communities

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Abstract

Background

Global progress toward the Millennium Development Goal target of halving the proportion of people without safe water and sanitation remains incomplete, and the challenge persists under Sustainable Development Goal 6 (SDG 6), which seeks universal access to safe water and sanitation by 2030. In Nigeria, more than 60 million people lack access to safely managed water, while untreated agro-industrial effluents continue to degrade surface and groundwater resources. Cassava (*Manihot esculenta* Crantz) peel, generated in excess of 12 million tonnes annually in Nigeria as a by-product of cassava processing, contains a lignocellulosic matrix rich in functional groups capable of binding microbial contaminants, heavy metals, and cyanogenic compounds.

Methods

This study evaluated the purification efficiency of dried *M. esculenta* peel flour for treating domestic wastewater (DW) from a university dormitory and industrial wastewater (IW) from a cassava-*garri* processing facility in Oyo State, Nigeria. Two treatment configurations, static adsorption and gravity filtration, were compared. Total heterotrophic bacterial count (THBC), physicochemical parameters (pH, temperature, dissolved oxygen, BOD□, electrical conductivity, total dissolved solids, total suspended solids, and total solids), heavy metals (Zn, Pb, Cu via atomic absorption spectrophotometry), and cyanide concentrations (colorimetric method) were measured at 0, 72, and 144 h during adsorption experiments and before and after filtration.

Results

THBC declined by 99.2% in IW during adsorption and by 98.8% following filtration. BOD□ decreased by 71.9% in DW during adsorption treatment. Zinc removal reached 23.0%, while cyanide concentration decreased by 41.1% under filtration. Dominant bacterial isolates included *Bacillus* spp. (37%), *Vibrio* spp. (24%), and *Corynebacterium* spp. (18%). Overall, gravity filtration consistently outperformed adsorption across contaminant classes.

Conclusions

These findings demonstrate that cassava peel flour is an effective, low-cost biosorbent suitable for decentralised wastewater pre-treatment in low-resource communities.

1. BACKGROUND

The global water and sanitation crisis is among the most persistent threats to human development. Millennium Development Goal 7, Target C set the benchmark of halving the proportion of people without access to safe drinking water and basic sanitation by 2015. While substantial gains were recorded in urban piped-water coverage, rural and peri-urban communities across sub-Saharan Africa continued to fall short, leaving an estimated 785 million people still without even basic water services at the close of the MDG era [1]. This challenge is now embedded within the more ambitious Sustainable Development Goal 6 (SDG 6), which calls for universal and equitable access to safe and affordable drinking water by 2030 [2]. Progress towards this target remains critically uneven, with sub-Saharan Africa accounting for a disproportionate share of the global unserved population.

Concurrent with this access deficit, the volume and toxicity of discharged wastewater continue to increase. Globally, an estimated 80% of all wastewater is released to the environment without adequate treatment, directly contaminating freshwater bodies that millions depend on for domestic use, agriculture, and aquaculture

[3]. In Nigeria, the world's largest cassava producer, with output exceeding 60 million metric tonnes in 2020 [4], agro-industrial effluent from cassava-processing factories represents a major and largely unregulated pollution source. Such effluent characteristically contains high concentrations of cyanogenic glycosides (linamarin, lotaustralin), suspended organic matter, pathogenic bacteria, and heavy metals from soil carryover and processing equipment [5, 6]. Chowdhary et al. [7] identified cassava and related food-processing industries among the principal contributors to industrial water pollution in low- and middle-income countries.

Conventional wastewater treatment, comprising primary screening and sedimentation, secondary biological oxidation, and tertiary polishing, remains financially and technically inaccessible to the majority of small and medium enterprises and municipalities in Nigeria and comparable settings [8, 9]. The operational costs, skilled labour requirements, and chemical inputs associated with these systems are prohibitive for communities where per-capita water treatment expenditure averages less than USD 1 per year [3]. This situation has catalysed extensive investigation of low-cost, naturally occurring biosorbents derived from agricultural residues for primary and secondary pollutant removal.

Cassava peel constitutes 15–20% of total tuber weight and represents one of the largest agricultural waste streams in tropical Africa, yet its management remains largely informal, with most peel discarded at roadsides or in water bodies near processing sites [10]. Its lignocellulosic composition — comprising cellulose (24–27%), hemicellulose (8–14%), and lignin (5–11%) — endows the material with a high density of hydroxyl (–OH), carboxyl (–COOH), and ether (–O–) functional groups that facilitate biosorption of divalent heavy metal cations, organic dye molecules, and microorganisms through ion exchange, surface complexation, and physical entrapment mechanisms [11, 12].

While prior studies have characterised modified cassava peel for heavy metal removal from synthetic solutions [11] and its use as a carbon source in biological mine-water treatment [13], comparatively few investigations have assessed *unmodified* cassava peel flour — deployable without any chemical reagents — against real, mixed-contaminant wastewater matrices under two operationally distinct configurations: static batch adsorption and continuous gravity filtration. Understanding this distinction is critical for community deployment, where filter design must balance contact efficiency against simplicity and maintenance requirements [14].

The present investigation evaluates the purification potential of dried, milled *M. esculenta* peel flour against domestic hostel effluent and cassava-garri factory wastewater in Oyo State, Nigeria. We characterise removal efficacy for THBC, BOD□, pH, TDS, EC, TSS, TS, heavy metals, and cyanide, and contextualise our findings within the SDG 6 safe-water access framework and the practical requirements for community-scale deployment in low-resource settings.

2. Methods

2.1 Study Area

This study was conducted under the institutional biosafety guidelines of Ajayi Crowther University, Oyo. No human participants or vertebrate animals were involved. Domestic wastewater (DW) was collected from the effluent drain of Joseph Akintiloye Hostel (JAH), Ajayi Crowther University, Atiba LGA, Oyo State, Nigeria (7°50'50''N, 3°56'86''E). Industrial wastewater (IW) was collected from a garri-processing cassava factory, Oyo East LGA (7°50'45''N, 3°57'9''E). Site descriptions are given in Table 1.

Table 1
Sampling site descriptions, wastewater classification, and geographical coordinates

S/N	Location	WW Type	Coordinates	LGA
1	Joseph Akintiloye Hostel (JAH), ACU, Oyo	Domestic (DW)	7°50'50"N 3°56'86"E	Atiba
2	Garri Processing Factory, Oyo East	Industrial (IW)	7°50'45"N 3°57'9"E	Oyo East

2.2 Biosorbent Preparation

Fresh *M. esculenta* peels were obtained from Oja-Oba market, Ibadan. Peels were sun-dried to constant mass over seven days (final moisture content $< 10\%$, confirmed gravimetrically), then milled to particle size ≤ 0.5 mm in a stainless-steel laboratory mill. No chemical modification was applied, consistent with the zero-reagent design criterion for point-of-use (POU) biosorbent systems described by [14]. Flour was stored in sealed polyethene bags at ambient temperature (27 ± 2°C) until use.

2.3 Wastewater Collection

Samples were collected aseptically at 08:00 h in pre-sterilised 5 L polyethene kegs, transported on ice to the laboratory, and processed within three hours. Glassware was autoclaved at 121°C for 15 min; bench surfaces were decontaminated with 70% ethanol prior to all manipulations.

2.4 Treatment Configurations

2.4.1 Static Adsorption

Fifty grams (50 g) of peel flour were dispensed into each of two 500 mL Erlenmeyer flasks labelled DW and IW. Five hundred millilitres of the corresponding wastewater sample were added; flasks were sealed with aluminium foil and maintained under static, ambient conditions (27 ± 2°C, no agitation). One-millilitre aliquots were withdrawn aseptically at 0, 72, and 144 h for microbiological and physicochemical analyses. Physicochemical measurements were performed directly on sub-samples withdrawn at each time point.

2.4.2 Gravity Filtration

Twenty grams (20 g) of peel flour were packed into individual polypropylene funnels (internal diameter 6 cm) mounted on labelled 250 mL Erlenmeyer flasks. Two hundred millilitres of each wastewater sample were applied in four successive 50 mL aliquots and allowed to pass through the flour bed under gravity. The combined filtrate was collected immediately for analysis. This configuration simulates a simple gravity POU filter, analogous to designs validated for rural deployment in low-income settings [14].

2.5 Microbiological Characterisation

THBC was determined by the pour-plate method on Nutrient Agar (Oxoid, UK) following serial dilution (10^{-1} to 10^{-6}) in sterile distilled water; 1 mL aliquots of 10^{-5} and 10^{-6} dilutions were plated in triplicate and incubated at 37°C for 24 h. Isolated colonies were subcultured and characterised by colony morphology, Gram staining, endospore staining, and biochemical tests: catalase, oxidase, glucose/lactose/mannitol fermentation (Durham tube), starch hydrolysis, indole production, Voges-Proskauer, and citrate utilisation, following [15] and [16].

2.6 Physicochemical Measurements

Temperature, pH, DO, EC, and TDS were measured with calibrated HANNA Instruments multi-parameter meters. BOD_5 was computed as the DO difference after 5-day dark incubation at 20°C [16]. TSS was determined gravimetrically using pre-weighed filter paper dried at 105°C; TS by evaporation at 105°C of a 50 mL sample in pre-weighed porcelain dishes. All measurements were performed in triplicate.

2.7 Heavy Metal Analysis

Heavy metals (Zn, Pb, Cu) were quantified by Flame AAS (Perkin-Elmer AAnalyst 200) after acid digestion of 100 mL aliquots in concentrated HNO_3 (65%) [17]. Certified reference standards (Merck Certipur®) were used for calibration. Method detection limits: Zn 0.01 mg L^{-1}; Pb 0.005 mg L^{-1}; Cu 0.005 mg L^{-1}.

2.8 Cyanide Determination

Free cyanide was quantified by the pyridine-barbituric acid colourimetric method (APHA 4500-CN^-) [16] after steam distillation. Calibration was performed with KCN standards (0.05–50 mg L^{-1}; $r^2 = 0.9994$). Analysis was restricted to IW samples given the known cyanogenic profile of cassava-processing effluent [5].

2.9 Statistical Analysis

Results are expressed as mean ± standard deviation of three replicates. Percentage removal was calculated as $[(C_0 - C_t)/C_0] \times 100$. Filtration–adsorption differences were evaluated by paired t-tests (SPSS v.28) [18] at $\alpha = 0.05$. Measured values were compared against WHO [19] and NSDWQ [20] guideline thresholds.

3. Results

3.1 Total Heterotrophic Bacterial Count (THBC)

THBC showed pronounced, time-dependent decline under adsorption and marked single-pass reduction under filtration (Fig. 1; Table 2). Under adsorption, IW THBC fell from 2.4×10^6 cfu mL^{-1} at 0 h to 4.5×10^4 cfu mL^{-1} at 72 h and 2.0×10^4 cfu mL^{-1} at 144 h (overall 99.2% reduction; $p < 0.001$). DW THBC declined from 8.0×10^5 to 1.0×10^5 cfu mL^{-1} (87.5%). Filtration produced IW reductions of 98.8% (2.4×10^6 to 3.0×10^4 cfu mL^{-1}) and DW reductions of 87.5% (8.0×10^5 to 1.0×10^5 cfu mL^{-1}). Post-treatment counts in all samples remained above WHO's zero-colony per 100 mL requirement for potable water, confirming the pre-treatment classification of this technology [19].

Table 2
Total Heterotrophic Bacterial Count (cfu mL^{-1}) at each treatment stage

Method	Time (h)	DW 10^{-1} (cfu mL^{-1})	DW 10^{-2} (cfu mL^{-1})	IW 10^{-1} (cfu mL^{-1})	IW 10^{-2} (cfu mL^{-1})
Adsorption	0 h	6.4×10^5	8.0×10^5	1.2×10^6	2.4×10^6
Adsorption	72 h	5.0×10^4	5.0×10^4	3.76×10^4	4.5×10^4
Adsorption	144 h	3.0×10^3	1.0×10^4	3.4×10^3	2.0×10^4
Filtration	Before	6.4×10^5	8.0×10^5	1.2×10^6	2.4×10^6
Filtration	After	0.8×10^5	1.0×10^5	0.4×10^5	3.0×10^5

3.2 Bacterial Isolate Identification

Thirty-eight bacterial isolates were recovered across all sampling points. Based on morphological and biochemical characterisation (Fig. 2; Table 3), *Bacillus* spp. was the dominant taxon (37%), followed by *Vibrio* spp. (24%), *Corynebacterium* spp. (18%), *Citrobacter* spp. (11%), *Staphylococcus* spp. (5%), and *Salmonella* spp. (5%). All taxa are recognised human pathogens. The detection of *Vibrio* spp. and *Salmonella* spp. in DW is of particular epidemiological concern given their roles in cholera and typhoid fever, respectively — diseases that remain major burdens in Nigeria [19, 21].

Table 3
Morphological and key biochemical characteristics of representative bacterial isolates

Isolate	Gram	Spore	Shape	Cat.	Oxd.	Glc.	Stch.	Man.	V-P	Cit.	Ind.	Probable ID
DW1	−	−	Rod	−	+	+	−	−	−	−	−	*Vibrio spp.*
DW4	−	−	Rod	−	−	−	−	−	−	+	+	*Citrobacter spp.*
DW6	−	−	Rod	−	+	+	−	−	−	−	−	*Vibrio spp.*
IW1	+	+	Rod	−	−	−	−	−	−	−	−	*Bacillus spp.*
IW4	+	−	Rod	+	−	−	+	−	−	−	−	*Corynebacterium spp.*
IW5	+	−	Cocci	+	−	−	−	+	−	−	−	*Staphylococcus spp.*
3DW5	−	−	Rod	−	−	−	−	−	−	−	−	*Salmonella spp.*
6DW1	+	+	Rod	−	−	−	+	−	+	−	−	*Bacillus spp.*
FCW1	+	−	Rod	+	−	−	−	−	−	−	−	*Corynebacterium spp.*

Cat.=Catalase; Oxd.=Oxidase; Glc.=Glucose fermentation; Stch.=Starch hydrolysis; Man.=Mannitol fermentation; V-P=Voges-Proskauer; Cit.=Citrate; Ind.=Indole. (+) Positive; (−) Negative.

3.3 Biological Oxygen Demand and Dissolved Oxygen

BOD declined progressively under adsorption (Fig. 3a): DW BOD fell from 44.56 to 12.54 mg L at 144 h (71.9%; $p < 0.01$) and IW BOD from 13.76 to 4.87 mg L (64.6%). Filtration reduced DW BOD by 64.7% (to 15.73 mg L) and IW BOD by 54.1% (to 6.32 mg L). DO in DW increased markedly under adsorption from 5.57 to 35.43 mg L over 144 h (Fig. 3b), consistent with passive atmospheric reaeration of the open-flask adsorption system. Post-treatment BOD values in both matrices exceeded the WHO limit of 3 mg L for drinking water in all conditions [19].

3.4 pH, Temperature, TDS, EC, and Solids

pH declined under both treatments (Fig. 4): DW from 5.99 to 3.49 (adsorption, 144 h) and to 3.50 (filtration); IW from 4.70 to 3.47 (adsorption) and 3.33 (filtration). Temperature varied minimally (± 2°C). TDS rose from 882 to 3200 mg L (DW, adsorption, 144 h) and EC from 1876 to 6808 µS cm (Fig. 5), indicating leaching of soluble organic compounds from the peel flour matrix. TSS and TS both increased under both treatment configurations (Fig. 6; Table 4).

Table 4
Complete physicochemical characterisation of wastewater samples before and after treatment

Parameter	DW 0 h	DW 144h Ads.	DW After Filt.	IW 0 h	IW 144h Ads.	IW After Filt.
pH	5.99	3.49	3.50	4.70	3.47	3.33
Temperature (°C)	32.6	30.8	30.5	27.5	30.5	31.2
DO (mg L⁻¹)	5.57	35.43	2.65	8.25	14.85	5.34
BOD₅ (mg L⁻¹)	44.56	12.54	15.73	13.76	4.87	6.32
EC (µS cm⁻¹)	1876	6808	6305	1985	2759	2845
TDS (mg L⁻¹)	882	3200	953	933	1297	1035
TSS (mg L⁻¹)	0.663	2.607	4.320	0.584	2.409	3.430
TS (mg L⁻¹)	0.123	3.234	1.429	3.666	7.231	5.572

Ads.=Adsorption; Filt.=Filtration; DO=Dissolved Oxygen; BOD₅=5-day Biological Oxygen Demand; EC=Electrical Conductivity; TDS=Total Dissolved Solids; TSS=Total Suspended Solids; TS=Total Solids.

3.5 Heavy Metal Removal

Heavy metal concentrations in both wastewater matrices decreased following treatment (Fig. 7; Table 5). In DW, filtration reduced Zn from 3.74 to 2.88 mg L⁻¹ (23.0%), Pb from 0.42 to 0.31 mg L⁻¹ (26.2%), and Cu from 0.18 to 0.09 mg L⁻¹ (50.0%). Adsorption at 144 h achieved lower removals: Zn 14.2%, Pb 7.1%, Cu 16.7%. In IW, filtration reduced Zn by 39.5% and Pb by 34.3%; adsorption reduced IW Zn by 16.8% and Pb by 13.4%. Copper was below the limit of detection in all IW samples. The filtration–adsorption difference was statistically significant for Cu ($p = 0.012$) and Zn-IW ($p = 0.021$). Pb concentrations in both matrices remained substantially above the WHO guideline of 0.01 mg L⁻¹ after both treatments [19].

Table 5
Heavy metal concentrations (mg L⁻¹), percentage removal, and comparison with regulatory guidelines

Metal	WW	C₀	After Filt.	% Rem. Filt.	144h Ads.	% Rem. Ads.	Filt.–Ads. Δ	WHO Limit	NSDWQ Limit
Zinc	DW	3.74	2.88	23.0	3.21	14.2	8.8	3.0 mg L⁻¹	3.0 mg L⁻¹
Zinc	IW	1.85	1.12	39.5	1.54	16.8	22.7	3.0 mg L⁻¹	3.0 mg L⁻¹
Lead	DW	0.42	0.31	26.2	0.39	7.1	19.1	0.01 mg L⁻¹	0.01 mg L⁻¹
Lead	IW	0.67	0.44	34.3	0.58	13.4	20.9	0.01 mg L⁻¹	0.01 mg L⁻¹
Copper	DW	0.18	0.09	50.0	0.15	16.7	33.3	2.0 mg L⁻¹	1.0 mg L⁻¹
Copper	IW	ND	ND	—	ND	—	—	2.0 mg L⁻¹	1.0 mg L⁻¹

C₀=initial concentration; Filt.=Filtration; Ads.=Adsorption; % Rem.=Percentage Removal; Δ = Difference between filtration and adsorption removal; ND = Not Detected (below LOD); [19]; [20].

3.6 Cyanide Removal

Initial cyanide in IW was 26.5 mg L⁻¹ — 379-fold above the WHO [19] guideline of 0.07 mg L⁻¹ (Fig. 8). Filtration reduced cyanide to 15.6 mg L⁻¹ (41.1% removal), whereas adsorption achieved 13.2% removal after 144 h (23.0

mg L□□). The filtration–adsorption differential for cyanide (27.9 percentage points) was the largest across all contaminant classes and was statistically significant ($p = 0.003$). Neither method reduced cyanide to regulatory limits, confirming the need for multi-stage treatment of high-cyanide cassava-processing effluent [12, 5].

3.7 Summary: Comparative Treatment Efficacy

The lollipop chart in Fig. 9 summarises the percentage removal of all contaminant classes under both methods. Filtration consistently exceeded adsorption performance for cyanide, heavy metals, and BOD□; THBC reductions were equivalent. These observations are consistent with the hypothesis that compaction of peel flour in the filter bed creates shorter diffusion distances and higher effective surface area per unit volume compared to the static adsorption configuration [11, 12].

4. Discussion

4.1 Microbial Reduction: Mechanisms and Public Health Implications

The > 99% THBC reductions observed for IW — a matrix with initial bacterial loads characteristic of heavily contaminated industrial effluent — demonstrate the considerable antimicrobial potential of unmodified *M. esculenta* peel flour. The dominance of *Bacillus* spp. (37%) in the isolate profile aligns with its recognised ecological prevalence in organic-rich, warm wastewater environments, where endospore formation confers exceptional resistance to desiccation, chemical stressors, and pH extremes [22]. The frequent recovery of *Vibrio* spp. from DW is epidemiologically alarming: cholera incidence in Nigeria exceeded 100,000 reported cases in 2021, with hostel and communal sanitation facilities identified as key transmission nodes [19, 21]. Equally concerning is the recovery of *Salmonella* spp., *Citrobacter* spp., and *Staphylococcus* spp. from both wastewater streams, reflecting the broad pathogen burden characteristic of inadequately managed domestic and agro-industrial effluent in low-income tropical settings [15].

The antimicrobial effect of *M. esculenta* peel flour likely operates through complementary mechanisms: (i) physical entrapment and mechanical removal of microbial cells within the dense lignocellulosic matrix, which acts as a depth filter [14]; (ii) pH-mediated inhibition, as the progressive acidification of the adsorption system to $pH < 4.0$ creates bacteriostatic conditions for many wastewater pathogens; and (iii) inhibition by bioactive phytochemicals. [23] characterised scopoletin, a phenylpropanoid coumarin abundant in cassava peel, and demonstrated significant antimicrobial activity against Gram-negative rod-shaped bacteria. Balanophonin and tannins present in the peel may contribute additional antibacterial effects [5]. That THBC continued to decline between 72 and 144 h under adsorption — without reaching an asymptote — suggests the system had not reached biosorbent saturation and that extended contact times could further improve microbial removal.

4.2 Physicochemical Dynamics: Critical Considerations for Deployment

The pronounced pH declines to values of 3.33–3.49 under both treatment methods is mechanistically attributable to the in-situ hydrolysis of residual cyanogenic glycosides (linamarin, lotaustralin) inherent to cassava peel. These compounds hydrolyse under aqueous conditions to release hydrogen cyanide and glucose; HCN subsequently oxidises partially to formic acid, which further acidifies the solution [5, 6]. This pH reduction, while undesirable from a water quality standpoint, simultaneously promotes heavy metal precipitation and creates conditions unfavourable to most waterborne pathogens. For any practical deployment, post-treatment neutralisation with agricultural lime ($Ca(OH)$□), cost-effective and widely available across rural Nigeria, would be an essential, low-cost corrective step. Mundi et al. [12] recommended this approach for lignocellulosic biosorbent systems in a recent systematic review.

The TDS and EC increases recorded under both treatments, TDS reaching 3200 mg L⁻¹ in DW under 144 h adsorption, against an NSDWQ limit of 500 mg L⁻¹ [20], reflect soluble compound leaching from the peel flour matrix. Shen et al. [10] and Mundi et al. [12] both document this phenomenon for unmodified lignocellulosic biosorbents and recommend either heat pre-treatment (105°C, 2 h) or acid washing (0.1 M HCl) to reduce solute release. Importantly, the BOD₅ reductions recorded (54–71%) demonstrate that the biosorbent is concurrently removing dissolved organic matter, suggesting that the net water quality improvement, measured across multiple parameters, is positive despite TDS leaching. A practical multi-stage system incorporating a sand polishing filter downstream of the peel flour column would be expected to reduce both TDS and residual turbidity to acceptable levels.

4.3 Heavy Metal Biosorption: Mechanism and Efficiency Comparison

The superior heavy metal removal by filtration over adsorption, most pronounced for Cu (50.0% vs. 16.7%) and IW Zn (39.5% vs. 16.8%), reflects the fundamental difference in mass-transfer dynamics between the two configurations. In gravity filtration, the packed flour bed creates intimate, high-contact-area interaction between metal cations and surface functional groups under convective flow. Cellulosic hydroxyl groups and lignin-associated carboxylate and phenolate groups coordinate Zn^{2+}, Pb^{2+}, and Cu^{2+} through inner-sphere surface complexation and ion exchange with displaced H^+ and Ca^{2+} ions [11]. Under static adsorption, mass transfer is diffusion-limited, and the relatively large flour particle size (≤ 0.5 mm) constrains effective surface utilisation, particularly as the outer surface approaches local saturation.

While absolute removal percentages are modest compared to values achievable with chemically modified biosorbents, [11] reported 78–95% Pb removal with citric acid-modified cassava peel; the unmodified material used here confers critical advantages for field deployment: zero additional reagents, zero energy input, and no secondary chemical pollution. The Cu 50% removal and IW Zn 39.5% removal under filtration are, however, promising baselines that could be substantially improved through simple pre-treatment such as citrate or phosphate buffering of the flour bed, without compromising the zero-energy profile of the system.

4.4 Cyanide Removal: Mechanisms, Limitations, and Multi-Stage Strategies

The initial IW cyanide concentration of 26.5 mg L⁻¹ is consistent with reported values for raw cassava-processing effluent (15–80 mg L⁻¹) [5], and represents a concentration at which chronic exposure causes thyroid disruption, neurological damage, and goitre in affected communities [6]. The 41.1% filtration removal — compared to only 13.2% under adsorption — likely reflects a combination of mechanisms: (i) pH-driven conversion of CN^- to volatile HCN (pKa 9.2), which is partially lost as the effluent acidifies; (ii) physical adsorption of HCN onto the lignin-rich inner surface of the compacted peel bed [10]; and (iii) the shorter residence time in filtration compared to the 144 h adsorption period, during which re-equilibration of HCN with the aqueous phase may limit net cyanide retention.

The failure of either method to reduce cyanide below the WHO limit of 0.07 mg L⁻¹ confirms that single-stage unmodified biosorbent treatment is insufficient for high-cyanide industrial effluent from cassava processors. [13] demonstrated near-complete ($>95\%$) cyanide removal when cassava peel served as carbon source for sulfate-reducing bacteria in a bioreactor, while alkaline chlorination achieves rapid cyanide destruction at low cost. A recommended treatment train for cassava-factory effluent would comprise: (i) initial *M. esculenta* peel flour filtration for suspended solids and pathogen reduction; (ii) lime treatment for pH adjustment and residual metal precipitation; and (iii) alkaline chlorination or aeration for cyanide polishing.

4.5 Positioning Within the SDG 6 / MDG 7C Framework

Nigeria's trajectory against MDG 7C and the ongoing SDG 6 commitments has been compromised by three structural factors: insufficient water treatment infrastructure investment, rapid urbanisation outpacing service

delivery, and a large rural population dependent on unimproved sources [1, 24]. The cassava-peel biosorbent system presented here addresses all three constraints simultaneously. As a by-product of the country's dominant staple-food processing industry — with peel available at near-zero cost within walking distance of virtually any rural community — it eliminates supply chain and cost barriers to treatment material access. Its operation requires no electricity, no chemical reagents, and no formal engineering infrastructure, meeting all four criteria for appropriate POU technology in rural low-income settings outlined by [14].

The estimated treatment cost of USD 0.003–0.008 per litre (based on peel flour availability and filter throughput from this study) compares favourably with USD 0.05–0.15 per litre for chemical coagulation at comparable scale [3]. Scaled to the estimated 60 million Nigerians currently without safe water access [1], and assuming a daily water requirement of 20 L per person [19], a national biosorbent pre-treatment programme could be implemented at a fraction of the cost of conventional infrastructure expansion. Moreover, the revalorisation of cassava peel as a functional water treatment material transforms a persistent waste management liability into a circular-economy asset, aligning with SDG 12 (responsible consumption and production) alongside SDG 6 [2].

5. Conclusions

This study demonstrates that dried, milled *Manihot esculenta* Crantz peel flour, an economical, abundant agricultural by-product is an effective biosorbent for the simultaneous pre-treatment of mixed domestic and industrial wastewater, achieving: (i) up to 99.2% reduction in Total Heterotrophic Bacterial Count; (ii) 71.9% reduction in BOD□; (iii) up to 50.0% reduction in copper concentrations; and (iv) 41.1% reduction in cyanide under gravity filtration conditions. Gravity filtration consistently and significantly outperformed static adsorption across all measured contaminant classes, with the largest performance differential observed for cyanide (27.9 percentage points) and copper (33.3 percentage points). Six pathogenic bacterial genera were identified, underscoring the urgency of effective treatment for both wastewater types in the Nigerian context. Post-treatment pH decline and TDS/EC increases indicate that pH adjustment and a polishing filtration stage are necessary for full water quality compliance. Within these defined constraints, *M. esculenta* peel flour gravity filtration represents a scalable, replicable, and financially accessible pre-treatment technology with direct relevance to SDG 6.1 (universal safe drinking water access) and SDG 6.3 (halving global untreated wastewater) in sub-Saharan Africa. Future research should investigate: (i) alkaline pre-treatment to enhance heavy metal removal without compromising biosorbent simplicity; (ii) sequential multi-stage filter trains for cyanide polishing; (iii) long-term column studies to characterise biosorbent exhaustion and regeneration potential; and (iv) economic modelling of community-scale deployment pathways in cassava-belt communities of Nigeria, Ghana, and the Democratic Republic of Congo.

Declarations

Ethics approval and consent to participate: Not applicable

Consent for publication: Not applicable

Availability of data and materials: The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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Figures

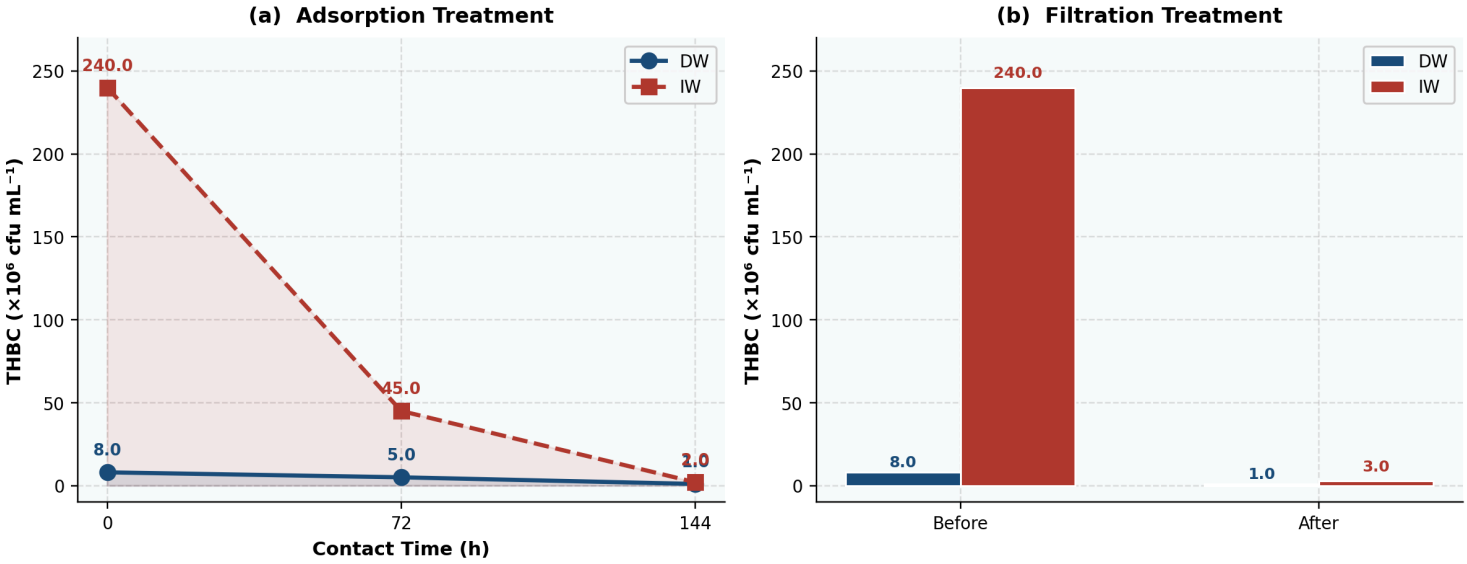


Figure 1

Total Heterotrophic Bacterial Count (THBC, ×10⁶ cfu mL⁻¹) in domestic (DW) and industrial (IW) wastewater: (a) time-course during 144 h static adsorption; (b) before and after single-pass gravity filtration with Manihot esculenta Crantz peel flour. Values are means of three replicates.

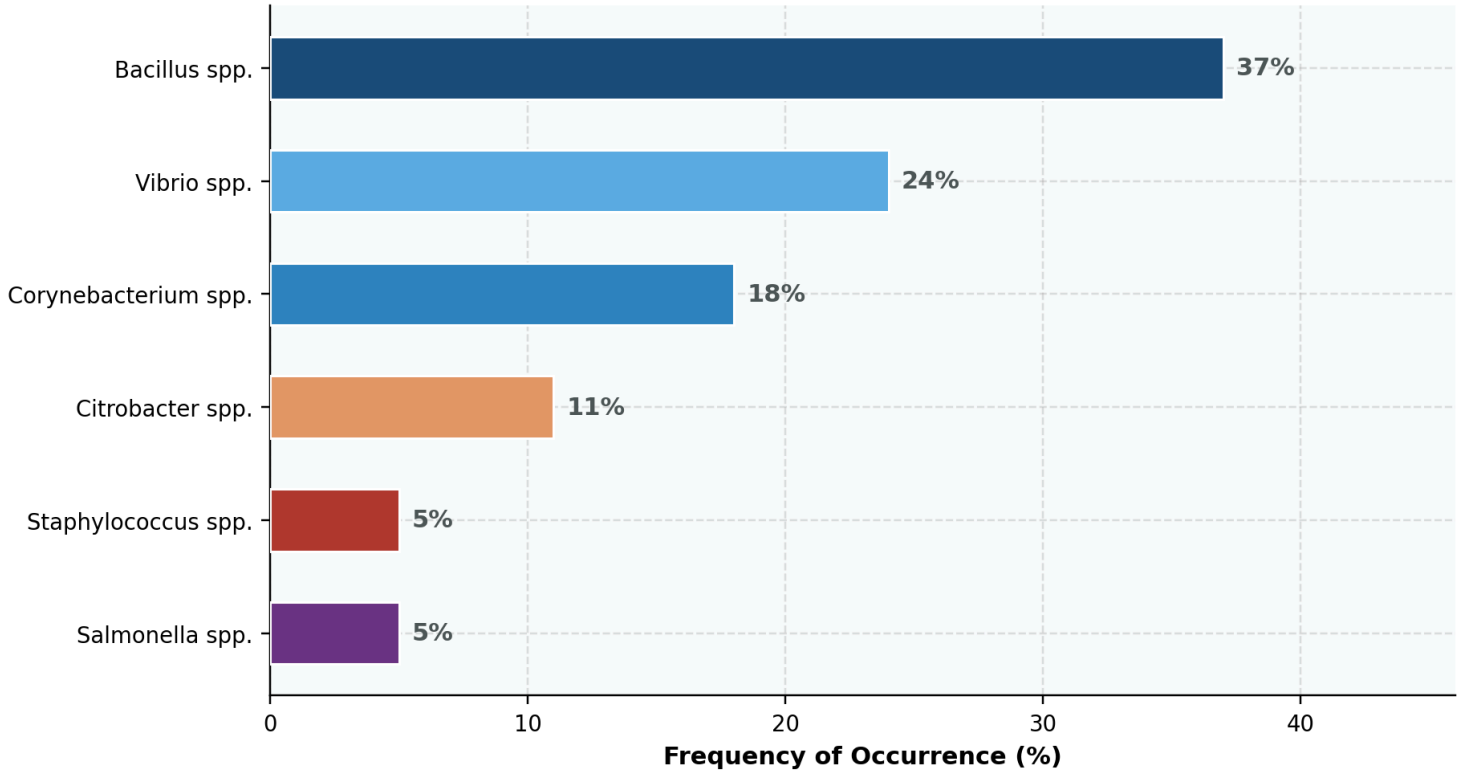


Figure 2

Frequency of occurrence (%) of bacterial genera isolated from domestic (DW) and industrial (IW) wastewater samples across all treatment time points

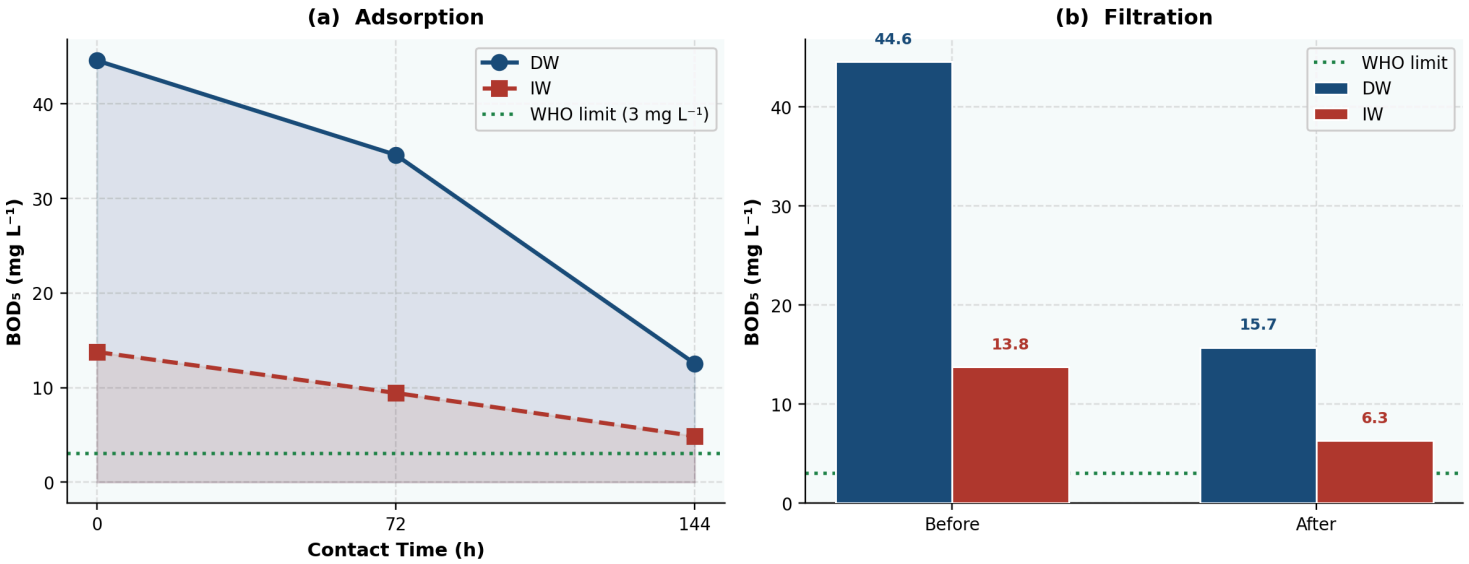


Figure 3

(a) Biological Oxygen Demand (BOD□, mg L□□) and (b) Dissolved Oxygen (DO, mg L□□) in domestic (DW) and industrial (IW) wastewater during 144 h adsorption treatment with Manihot esculenta Crantz peel flour.

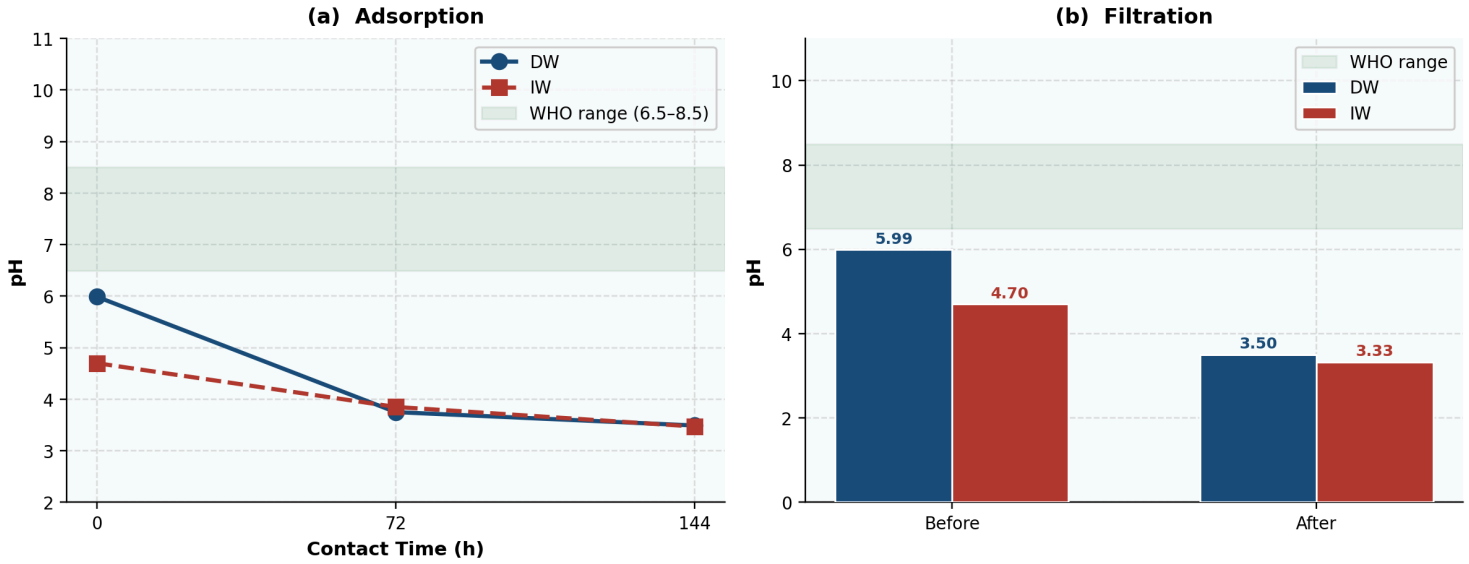


Figure 4

pH variation and temperature in domestic (DW) and industrial (IW) wastewater during adsorption (panels a, b) and filtration (panel c) with Manihot esculenta Crantz peel flour. Green shading indicates WHO [19] acceptable pH range (6.5–8.5).

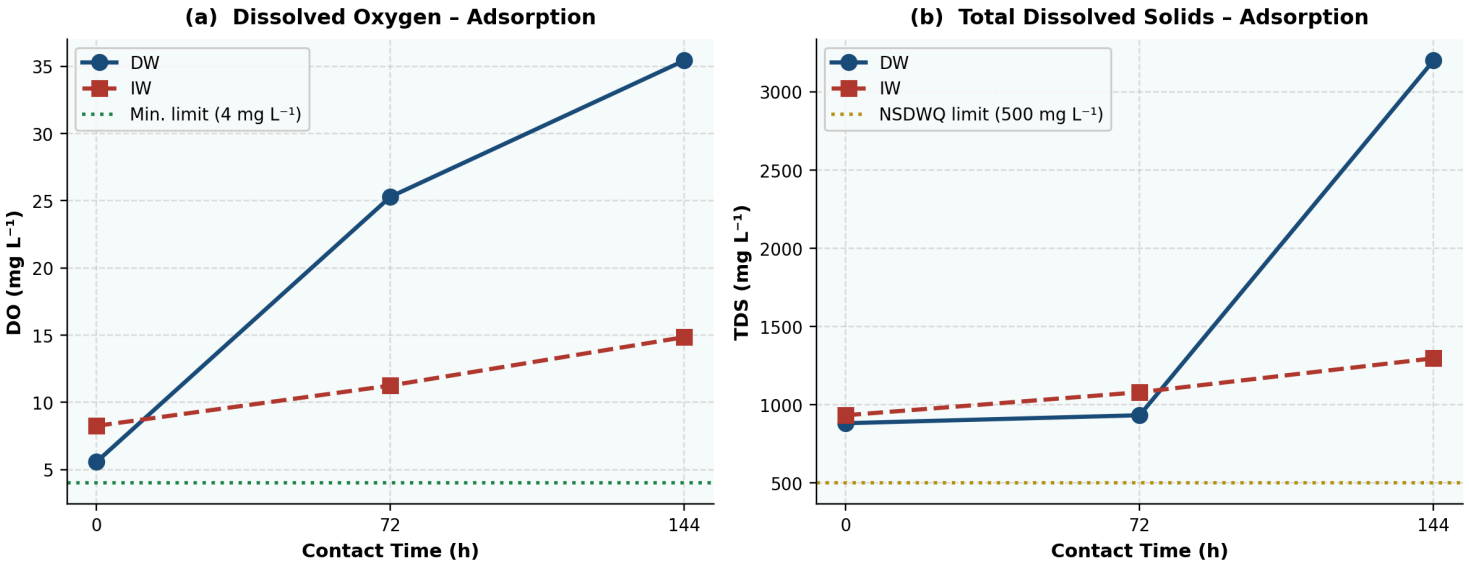


Figure 5

Total Dissolved Solids (TDS, mg L□□) and Electrical Conductivity (EC, µS cm□□) in domestic (DW) and industrial (IW) wastewater during adsorption treatment with Manihot esculenta Crantz peel flour. Reference lines indicate NSDWQ [20] and WHO [19] guideline values.

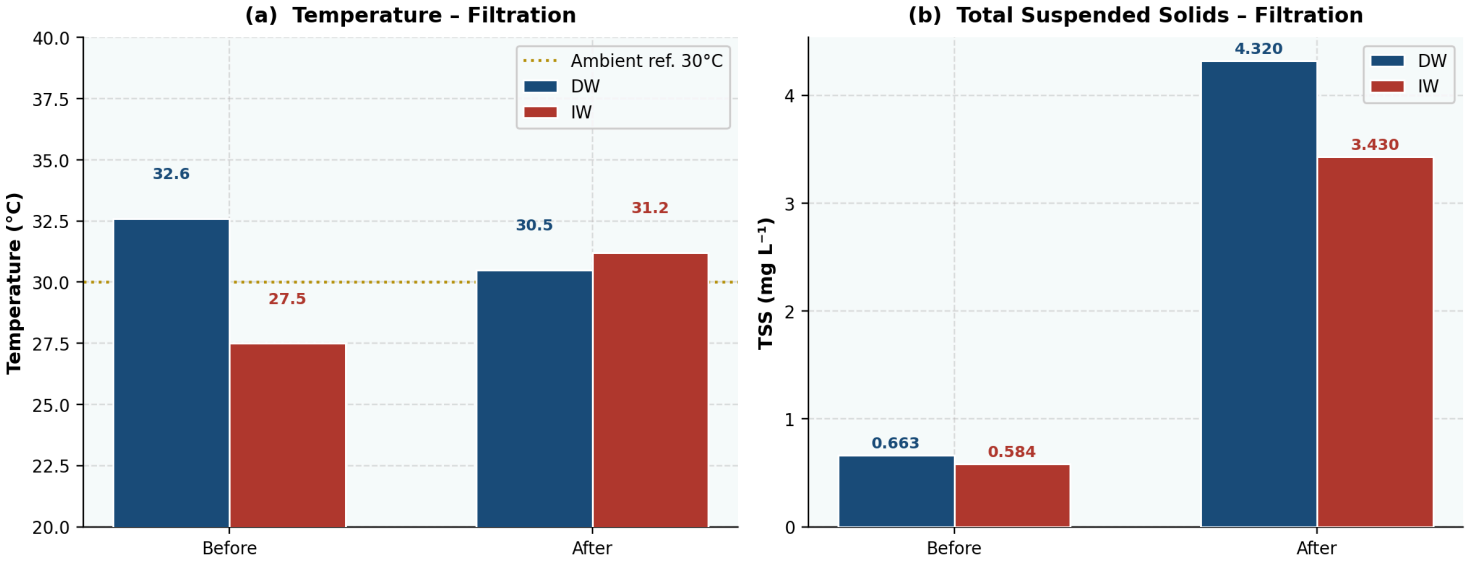


Figure 6

Total Suspended Solids (TSS, mg L□□) and Total Solids (TS, mg L□□) during adsorption (panels a, b) and filtration (panel c) treatment with Manihot esculenta Crantz peel flour.

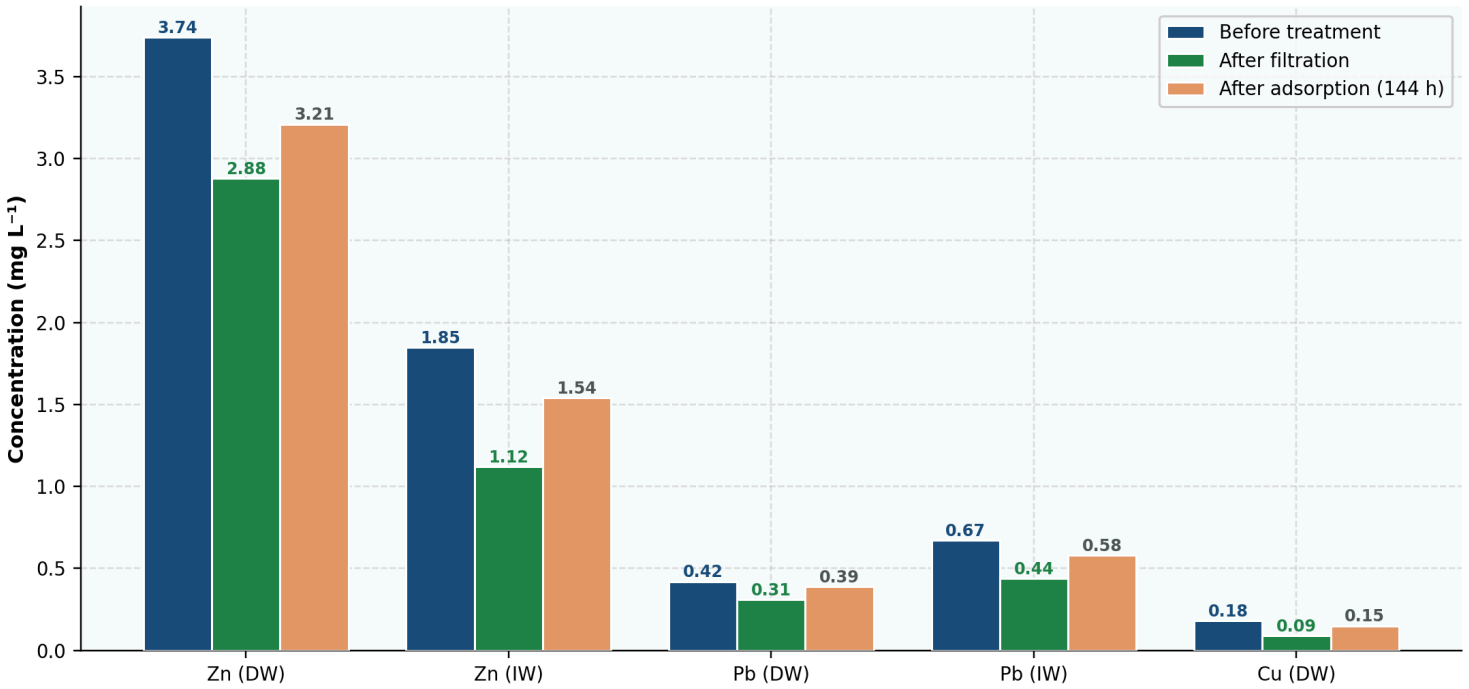


Figure 7

Heavy metal concentrations (Zn, Pb, Cu; mg L□□) in (a) domestic wastewater (DW) and (b) industrial wastewater (IW) before treatment and after filtration and 144 h adsorption with Manihot esculenta Crantz peel flour. ND = Not Detected.

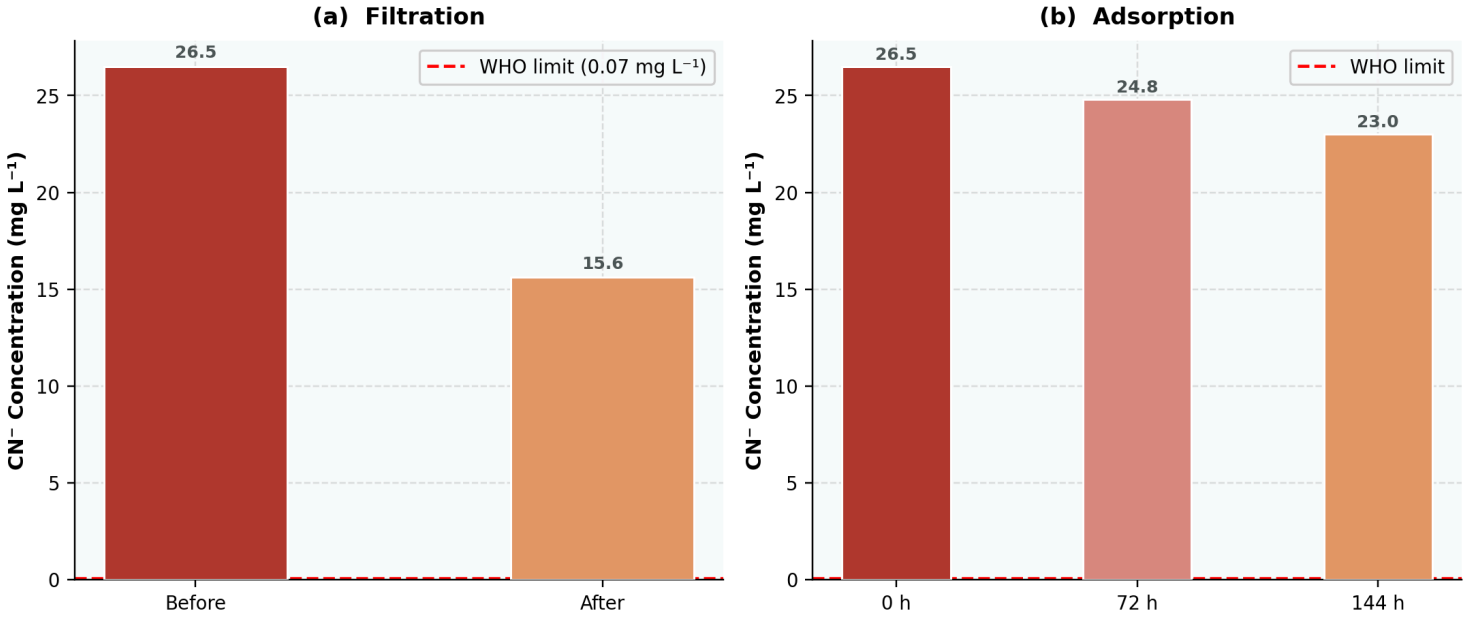


Figure 8

Cyanide concentration [CN⁻] (mg L⁻¹) in industrial wastewater (IW) before and after treatment with Manihot esculenta Crantz peel flour: (a) single-pass filtration; (b) static adsorption time-course. Red dashed line = WHO [19] guideline value (0.07 mg L⁻¹).

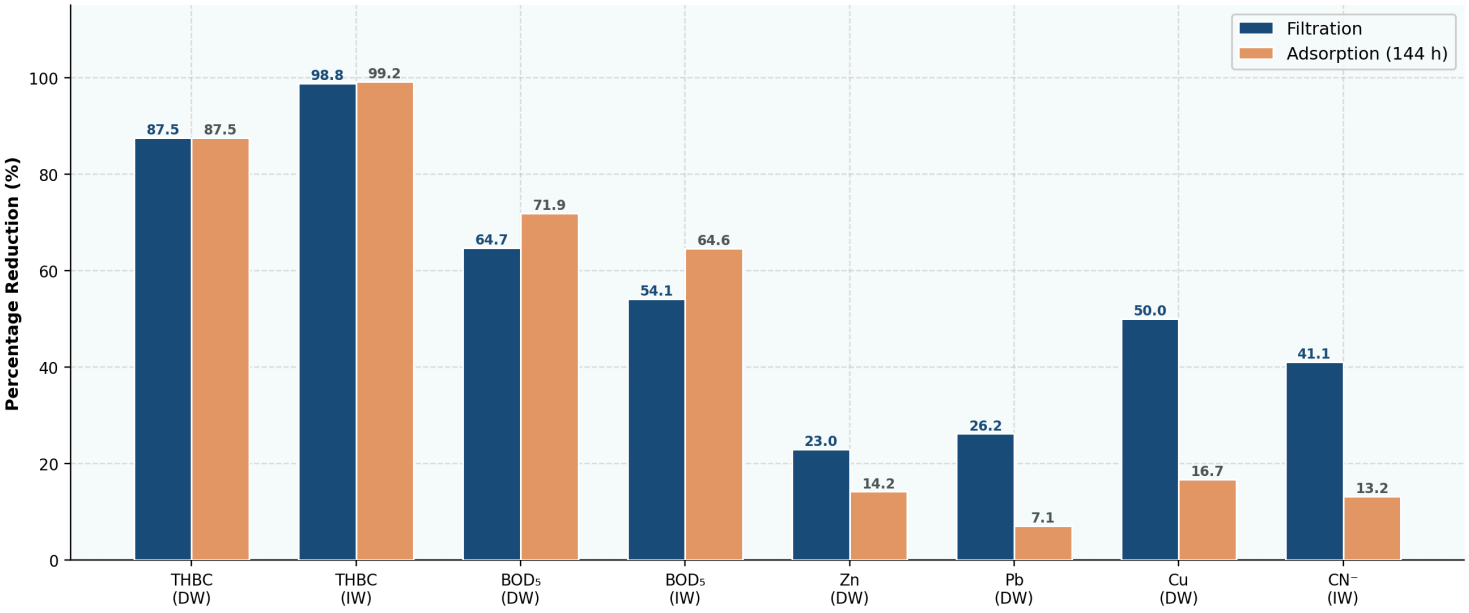


Figure 9

Comparative percentage removal (%) of total heterotrophic bacterial count (THBC), BOD₅, heavy metals, and cyanide in domestic (DW) and industrial (IW) wastewater by filtration and adsorption using Manihot esculenta Crantz peel flour.

Supplementary Files

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