
DESIGN OPTIMISATION AND IMPACT ASSESSMENT OF A BIOGAS-INTEGRATED ANAEROBIC BAFFLED REACTOR WASTEWATER TREATMENT SYSTEM AT NIGERIAN CORRECTIONAL CENTRE

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ABSTRACT

This paper presents the design optimisation and field-based impact assessment of a biogas-integrated anaerobic baffled reactor (ABR) at Ikoyi Correctional Centre, Lagos. Empirical monitoring was undertaken for 30 consecutive days at three matched wastewater sampling points: ABR influent (SP-01), ABR effluent (SP-02) and final effluent after polishing (SP-03). The campaign comprised 90 point-specific wastewater samples, daily biogas-quality records and kitchen-energy logs, separated into pre-optimisation (10 days), transition (5 days) and optimised operation (15 days). The installed system consists of two parallel six-chamber ABR trains. Engineering reconciliation gave 337.34 m³ active volume; restoration from a 286.74 m³ pre-optimisation effective condition yielded calculated HRT values of 33.60 and 39.53 h at the monitored mean flow of 204.82 m³/day. During optimised operation, mean final-effluent COD, BOD₅ and TSS were 90.6, 37.47 and 30.53 mg/L, while overall removals reached 89.99%, 91.90% and 91.27%, respectively. Mean biogas production was 57.03 m³/day compared with 42.99 m³/day pre-optimisation; methane fraction was 63.39% compared with 57.15%, and hydrogen sulphide was 266.9 ppm compared with 510.1 ppm. Mean LPG, diesel and firewood displacement reached 51.82%, 50.10% and 53.83%. The repair-first configuration retained the installed shell and prioritised active-volume recovery, flow balancing, polishing, gas conditioning, storage-demand matching and preventive maintenance. These operating-phase differences are associations from a sequential field intervention rather than proof of single-variable causality. Physical fuel savings were quantified; monetary valuation was outside scope.

Keywords: anaerobic baffled reactor; biogas; correctional wastewater; design optimisation; resource recovery

1. INTRODUCTION

Wastewater treatment in a correctional facility is simultaneously an environmental-engineering, public-health, institutional-management and human-dignity requirement. Large populations live within restricted compounds, water and sanitation fixtures are used continuously, kitchens operate at institutional scale, and land for conventional treatment may be limited. Failure of containment or treatment can expose detainees, correctional personnel, maintenance workers and surrounding communities to sewage overflow, odour, vectors and contamination of surface water or groundwater. The World Health Organization (WHO, 2018) therefore frames sanitation as an entire service chain from containment and conveyance to treatment, disposal or safe reuse, while its sanitation-safety-planning approach requires risk identification and operational control across that chain (WHO, 2022). In places of detention, the same systems must remain robust under crowding, restricted movement, security procedures and constrained maintenance access (International Committee of the Red Cross [ICRC], 2012).

Anaerobic baffled reactors are attractive for such settings because they divide the flow path into successive compartments, promoting contact between wastewater and retained anaerobic biomass without continuous mechanical mixing or aeration. Their comparatively simple civil works, low sludge yield, resilience to organic shocks and potential for methane recovery make them relevant to

decentralised sanitation in warm climates. Yet ABR performance is not automatic. Hydraulic short-circuiting, unequal flow between parallel trains, excessive sludge accumulation, high upflow velocity, intermittent loading and inadequate downstream polishing can reduce effective volume or produce an effluent that remains unsuitable for discharge. Full-scale studies have repeatedly shown that operation and maintenance, rather than the presence of an ABR shell alone, determine long-term performance (Yulistyorini et al., 2019; Yenji et al., 2021; Saif et al., 2021).

Biogas generation is continuous, whereas cooking demand occurs in peaks; daily production can therefore coexist with short-period shortages, pressure instability or unused gas. Prison biogas programmes identify ownership, sizing, operator competence, safety and recurrent maintenance as decisive sustainability conditions (Gauthier et al., 2012). The Ikoyi intervention integrated wastewater collection, two ABR trains, polishing and kitchen-gas delivery for a design population of 3,000. The current count of 2,541 is 84.7% of that basis. The empirical campaign measured actual wastewater flow, treatment performance, biogas production and composition, gas-holder pressure, burner operating hours and conventional-fuel use, allowing the technical and energy impacts to be quantified rather than inferred from population alone.

The purpose of this paper is to present a title-aligned design optimisation and impact assessment based on field and empirical evidence. Specifically, the paper (a) characterises wastewater at three matched sampling points; (b) reconciles the physical ABR geometry with the active-volume calculation; (c) formulates hydraulic, treatment, gas-utilisation and hydrostatic constraints; (d) compares pre-optimisation and optimised operating phases; (e) quantifies wastewater-removal, biogas-quality and fuel-displacement outcomes; and (f) assesses technical, environmental, social, economic and institutional implications. The contribution is a repair-first optimisation strategy that restores and verifies the installed asset before considering additional chambers or a larger reactor shell.

2. TECHNICAL BACKGROUND AND RESEARCH CONTEXT

2.1 ABR performance and operating controls

The ABR behaves as a staged anaerobic system. Wastewater is directed down and upward through a series of compartments; solids settle and biomass is retained, while the baffled pathway improves contact between substrate and microorganisms. Foundational design and decentralised-sanitation literature identifies hydraulic retention time (HRT), organic loading rate (OLR), compartment geometry, upflow velocity, temperature, influent biodegradability and sludge distribution as major controls (Barber & Stuckey, 1999; Sasse, 1998; Gutterer et al., 2009; Tilley et al., 2014). Long retention times can improve hydrolysis and stabilisation, but nominal HRT is meaningful only when active volume is not lost to sludge, gas pockets, blocked openings or dead zones. Similarly, a satisfactory total volume can conceal overloading if flow is not divided evenly between parallel trains.

Field evidence supports cautious optimisation. Dynamic loading changed full-scale ABR behaviour (Yenji et al., 2021), while loading-shock experiments also demonstrated the sensitivity of staged anaerobic treatment to abrupt organic and hydraulic changes (Jin et al., 2024). A four-chamber ABR still required tertiary treatment before reuse or discharge (Saif et al., 2021). In a nine-month ABR-biofilter study, the ABR removed about 57% total COD while the integrated train achieved 92% COD and 98% TSS removal, demonstrating that polishing is part of system performance (Echeverría et al., 2022). Sponge media achieved 60–77% organic and 74–81% TSS removal across 18–6 h HRTs (Ullah et al., 2024), with a later real-wastewater study reporting 79% COD and 96% TSS removal at 8 h (Ullah et al., 2026). These controlled results cannot be transferred directly to Ikoyi. Modelled recirculation also produced limited or adverse effects under some conditions (Ullah et al., 2025).

Post-treatment is particularly important for nutrients, pathogens and residual suspended matter. Field ABRs often remove organic carbon and settleable solids more effectively than nitrogen, phosphorus and faecal indicators. Satyendra and Vijay (2024) demonstrated an ABR followed by an upflow constructed wetland for municipal wastewater, while Munavalli et al. (2022) evaluated an ABR-hybrid-wetland system under dynamic loading. Raja et al. (2025) similarly coupled an ABR with a plant biofilter for decentralised sewage treatment and energy recovery. The literature therefore supports a treatment-train perspective: the ABR provides anaerobic primary or secondary treatment,

and the downstream unit is selected according to discharge route, land, operator capacity and required effluent quality.

2.2 Biogas recovery and institutional impact

Anaerobic treatment can convert part of the removed organic load into methane-rich gas, thereby reducing the net energy burden of sanitation. UNEP (2023) identifies wastewater as a resource for water, energy and nutrient recovery rather than only a waste stream. For institutions with large kitchens, direct thermal use can avoid the conversion losses and operating complexity associated with small-scale electricity generation. The relevant performance measure is not daily biogas production alone, but the fraction safely captured, conditioned, stored and delivered at useful pressure when cooking is required.

Correctional settings make this integration unusually valuable. Gauthier et al. (2012) assessed 13 prison biogas systems and reported production of 26–62 L/person/day, with higher values where kitchen waste supplemented excreta. The systems were generally perceived positively because of cleaner cooking and improved hygiene, but the study warned that responsibilities, finance, user acceptance and maintenance must be designed with the technology. At Ikoyi, daily kitchen logs and conventional-fuel records were used to quantify operating-hour and fuel-displacement effects, while health outcomes and indoor-air quality remain outside the present measurement scope.

Nigeria's National Environmental (Sanitation and Wastes Control) Regulations provide the legal framework for sustainable sanitation and waste management, while the Surface and Groundwater Quality Control Regulations address protection of water bodies (National Environmental Standards and Regulations Enforcement Agency [NESREA], 2009, 2011). WHO guidance supplies a risk-management framework but does not replace the applicable Nigerian permit or discharge conditions. For international context only, the United States secondary-treatment regulation uses 30-day and 7-day averages rather than a single grab sample (Electronic Code of Federal Regulations, n.d.). This reinforces the need to separate screening targets from a formal compliance determination.

3. MATERIALS AND METHODS

3.1 Study design and evidence classification

The study was structured as a practice-based engineering case study with a field before-transition-after monitoring design. Data were collected over 30 consecutive operating days from 1 to 30 April 2024. Days 1–10 represented pre-optimisation operation, Days 11–15 the transition and stabilisation period, and Days 16–30 optimised operation. The evidence base comprised matched wastewater samples, measured flow and temperature, daily biogas flow and composition, gas-quality and pressure records, kitchen burner-hours and conventional-fuel logs, together with project drawings, as-built dimensions and engineering calculations (Ikoyi ABR Design and Field Records, 2019–2024). No individual detainee data were used. Security-sensitive coordinates and internal layouts were excluded, and the treatment arrangement is presented only at process level.

Three evidence classes were maintained. Class F comprised direct field and laboratory measurements. Class C comprised quantities calculated from field measurements, including removal efficiencies, mass loads, methane energy and fuel displacement. Class D comprised design-audit and optimisation calculations, including active volume, HRT, OLR, upflow velocity and hydrostatic screening. This classification preserves the empirical status of the underlying monitoring data while preventing calculated design quantities from being misrepresented as instrument readings.

The monitoring dataset is treated throughout this paper as primary field and empirical evidence. The wastewater, biogas and energy-use observations are reported by operating phase and by measurement point. Arithmetic means and sample standard deviations describe within-phase variability; removal efficiencies are paired-day calculations based on matched influent and outlet concentrations. The study evaluates operating-phase differences descriptively because the sequential observations arose from a full-scale facility intervention rather than random assignment. No causal effect is attributed to a single optimisation action, and the terms pre-optimisation and optimised operation identify field phases rather than randomised treatment groups.

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Table 1: Field, calculated and design evidence used in the study

Evidence item	Value or scope	Class	Permissible interpretation
Wastewater monitoring	30 matched days at SP-01, SP-02 and SP-03; 90 point-specific samples	F	Direct field and laboratory measurements
Operating conditions	Flow, temperature and pH recorded daily	F	Hydraulic and process context
Treatment performance	COD, BOD ₅ , TSS, NH ₃ -N and PO ₄ -P by point and phase	F/C	Measured concentrations; paired removal calculations
ABR geometry	Two trains; one settler and six chambers per train	F/D	As-built and design audit
Active volume and loading	286.74 to 337.34 m ³ ; HRT, OLR and upflow calculations	D	Before-and-after optimisation basis
Biogas monitoring	30 daily records of flow, CH ₄ , CO ₂ , H ₂ S, moisture, pressure and use	F/C	Measured gas performance and derived energy
Kitchen energy	30 daily burner and LPG, diesel and firewood records	F/C	Measured use and calculated fuel displacement
Operational impact	Sanitation, odour, O&M and kitchen-use observations	F	Field operational assessment

Note. F = field or laboratory measurement; C = calculation from measured data; D = design or optimisation calculation.

3.2 System configuration and study boundaries

The treatment plant consists of two parallel ABR trains serving separate sewer catchments. Each train contains an inlet settler followed by six baffled chambers. Gas generated within the anaerobic system is collected, conditioned, conveyed to a nominal 45 m³ gas holder documented in the project records and delivered to the institutional kitchen. Treated liquid is conveyed toward final disposal or polishing. The optimisation boundary begins at the combined wastewater inflow and ends at final effluent management and useful kitchen-gas delivery. External sewer rehabilitation, individual toilet fixtures and unrelated facility energy loads are outside the numerical optimisation, although they influence institutional outcomes.

The design population of 3,000 comprised detainees and personnel included in the original hydraulic basis. The current population value of 2,541 represents 84.7% of design capacity. The historical design flow of 154.45 m³/day was retained for design reconciliation, while the empirical campaign measured a mean operating flow of 204.82 ± 7.93 m³/day. This distinction allows the installed geometry to be checked against its original basis and against current field loading. Train-specific metering remains necessary because aggregate flow cannot reveal unequal distribution between parallel reactors.

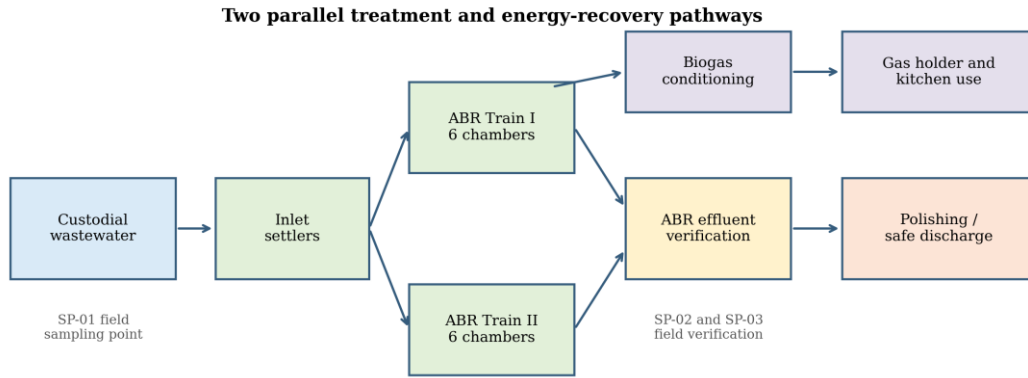


Figure 1: Process-level configuration and optimisation boundary of the biogas-integrated ABR system.

3.3 Wastewater characterisation and compliance screening

Wastewater samples were collected daily at the ABR inlet chamber (SP-01), ABR outlet chamber (SP-02) and polishing-unit outlet (SP-03). The resulting 30 matched events produced 90 point-specific samples. Flow and wastewater temperature were recorded concurrently. Samples were analysed for pH, COD, BOD₅, TSS, ammonia-nitrogen (NH₃-N) and orthophosphate-phosphorus (PO₄-P) using APHA procedures and the study laboratory protocol (American Public Health Association, American Water Works Association, & Water Environment Federation, 2023). Matched-point sampling allowed both ABR-stage removal and overall system removal to be calculated for each day.

Concentration screening used the study targets of 200 mg/L COD, 50 mg/L BOD₅ and 100 mg/L TSS. Results are reported as field performance against the accepted study basis; formal statutory compliance remains dependent on the facility's discharge route, permit conditions and required regulatory sampling frequency. A positive concentration gap indicates that further treatment or operational adjustment is needed. Phase summaries are expressed as mean $\pm$ sample standard deviation.

$$E_r = C_{in} / C_t \quad (1)$$

E_r is the influent exceedance ratio; C_{in} is the measured influent concentration and C_t is the applicable study screening target, in matching concentration units.

$$G = \max(C_{out} - C_t, 0) \quad (2)$$

G is the positive concentration gap; C_{out} is the measured outlet concentration and C_t is the study target. $G = 0$ indicates no positive gap against the screening target. Removal efficiency and mass load were calculated as follows.

$$\eta = [(C_{in} - C_{out}) / C_{in}] \times 100 \quad (3)$$

η is paired-day removal efficiency (%), calculated from the matched inlet concentration C_{in} and outlet concentration C_{out} .

$$L = Q C / 1,000 \quad (4)$$

L is pollutant mass load (kg/day), Q is wastewater flow (m³/day), C is concentration (mg/L), and 1,000 is the unit-conversion factor.

3.4 Hydraulic and organic-loading audit

The physical audit separated gross internal envelope from effective hydraulic volume. Per train, the settler measures 2.50 $\times$ 8.20 $\times$ 2.50 m and each of six chambers measures 1.20 $\times$ 8.20 $\times$ 2.40 m. Gross volume therefore includes the full box dimensions before deductions for baffle walls, downflow shafts, freeboard, sludge and dead zones. Effective active volume was independently reconciled from project flow and HRT. This step corrected the earlier dimensional confusion in which 154.45 m³/day could be mistaken for reactor volume.

The pre-optimisation hydraulic audit used an effective active volume of 286.74 m³, equivalent to 85% of the 337.34 m³ design-implied active volume. The post-optimisation condition restored the full effective volume through desludging, clearing baffle openings, correcting dead zones and balancing the two trains. The volume figures are engineering audit calculations supported by field operating observations; they are not direct laboratory measurements. No additional chamber or larger ABR shell was required.

$$V_g = 2[(2.50 \times 8.20 \times 2.50) + 6(1.20 \times 8.20 \times 2.40)] \quad (5)$$

V_g is gross internal envelope volume (m³). The factor 2 represents the two parallel trains; each train comprises one inlet settler and six chamber boxes.

$$V_a = Q \theta / 24 \quad (6)$$

V_a is hydraulically active volume (m³), Q is daily flow (m³/day), θ is HRT (h), and 24 converts days to hours.

$$\theta = 24 V_a / Q \quad (7)$$

θ is calculated hydraulic retention time (h) at active volume V_a and daily flow Q .

$$OLR = Q(COD_{in} / 1,000) / V_a \quad (8)$$

OLR is volumetric organic loading (kg COD m⁻³ d⁻¹); COD_{in} is measured influent COD (mg/L), Q is flow and V_a is active volume.

$$v_u = [PF \times Q / (2 \times 24)] / A_c \quad (9)$$

v_u is direct chamber upflow velocity (m/h), PF is the peak factor, the divisor 2 represents equal flow to two trains, and $A_c = 1.20 \times 8.20 = 9.84$ m² is the chamber plan area. Peak factors of 1.50 before balancing and 1.05 after effective equalisation were applied only as transparent design scenarios.

3.5 Optimisation formulation and selection criteria

The optimisation used a constrained, repair-first screening procedure. Candidate interventions were evaluated in the following order: verify the installed geometry and flow boundary; restore active volume; balance the two trains; test hydraulic and organic-loading constraints; calculate effluent gaps; identify the need for polishing; test gas-conditioning and storage-demand requirements; and screen hydrostatic stability. The installed two-train, six-chamber configuration was the reference. Alternatives that required structural enlargement were considered only if restoration and operational control could not meet the hydraulic constraints.

A multi-criteria penalty function maintained an auditable link between water quality, energy recovery, cost, footprint and robustness. The field wastewater, gas and kitchen datasets supplied the performance terms; project dimensions and design calculations supplied the hydraulic and footprint terms. Each penalty was normalised from zero (best) to one (worst), and any alternative violating a hard constraint was rejected regardless of its weighted score. The weights were specified a priori as transparent engineering decision priorities rather than statistically calibrated coefficients: water quality received the highest weight because sanitation protection and effluent control are mandatory; energy utilisation reflected the biogas objective; cost represented institutional affordability; robustness protected operational reliability; and footprint received the lowest weight because the installed shell was retained.

$$\min J(x) = 0.35P_q + 0.22P_e + 0.18P_c + 0.10P_f + 0.15P_r \quad (10)$$

$J(x)$ is the aggregate penalty for candidate x ; P_q , P_e , P_c , P_f and P_r are the normalised water-quality, gas-utilisation, life-cycle-cost, footprint and robustness penalties. The weights sum to one. They reflect the stated engineering priorities and were not derived through formal stakeholder elicitation.

$$P_q = \sum \max[(C_{j,out} - C_{j,target}) / C_{j,target}, 0] \quad (11)$$

P_q sums positive normalised effluent gaps across parameter j ; $C_{j,out}$ is the predicted or observed outlet value and $C_{j,target}$ is the corresponding screening target.

$$R = N_{feasible} / N_{total} \quad (12)$$

R is robustness; Nfeasible is the number of monitoring days meeting the combined final-effluent COD, BOD₅ and TSS targets and Ntotal is the number of days evaluated. The acceptance gate was $R \geq 0.90$. All 15 optimised-operation days met the three targets simultaneously, giving $R = 1.00$ for that phase, compared with 0.00 during the 10-day pre-optimisation phase.

Because hard constraints were applied before the weighted comparison, a favourable aggregate score could not compensate for a non-compliant candidate. A formal multi-weight sensitivity analysis was not undertaken; the reported weights should therefore be interpreted as a transparent screening preference set rather than proof of a unique global optimum. Future work should vary the weights and test whether feasible candidate rankings remain stable.

Table 2: Hard constraints and decision rules used in optimisation

Criterion	Screening condition	Engineering purpose	Evidence status
COD	≤ 200 mg/L; robust design goal 160 mg/L	Control residual organic load and retain margin	Permit confirmation required
BOD ₅	≤ 50 mg/L; robust design goal 40 mg/L	Control biodegradable residual	Permit confirmation required
TSS	≤ 100 mg/L; robust design goal 50 mg/L	Limit solids carryover	Measured at SP-03
HRT	≥ 36 h planning gate	Protect anaerobic contact time	Design-derived
OLR	≤ 3.0 kg COD m ⁻³ d ⁻¹	Avoid volumetric overloading	Project design screen
Peak upflow	Prefer ≤ 0.60 m/h	Reduce washout and hydraulic shock	Design screen; verify diurnal flow
Flotation safety	FS ≥ 1.20 , empty-tank case	Control groundwater uplift	Structural verification required
Robustness	$\geq 90\%$ compliant monitoring days	Reject fragile optima	$R = 1.00$ during optimised phase
Gas storage	Daily available gas $\geq$ kitchen use; unused gas minimised	Match production to cooking demand	Evaluated from daily field logs

Note. The concentration values are study screening targets. They are not presented as a substitute for a current, route-specific Nigerian discharge permit.

3.6 Effluent polishing, gas-energy and hydrostatic calculations

The polishing-stage removal was calculated from each matched SP-02 and SP-03 observation. This avoids the misleading practice of quoting overall removal while ignoring the contribution of downstream treatment. The field data were also screened against the final-effluent targets so the optimisation could distinguish ABR performance from whole-system performance.

Biogas assessment used 30 daily field records of total flow, methane, carbon dioxide, hydrogen sulphide, moisture, gas-holder pressure, kitchen use, unused gas and burner hours. Gross methane energy was calculated from measured gas use and methane fraction. Daily kitchen logs provided conventional-fuel baselines and quantities used while biogas was available, from which LPG, diesel and firewood displacement were calculated.

$$\eta_{\text{polish,req}} = [(C_{\text{ABR}} - C_{\text{target}}) / C_{\text{ABR}}] \times 100 \quad (13)$$

$\eta_{\text{polish,req}}$ is the minimum polishing removal required (%); C_{ABR} is ABR effluent concentration and C_{target} is the final-effluent screening target.

$$E_{\text{gas}} = V_{\text{gas}} \times y_{\text{CH}_4} \times \text{LHV}_{\text{CH}_4} \quad (14)$$

E_{gas} is gross methane energy, V_{gas} is measured useful biogas volume, y_{CH_4} is measured methane fraction and LHV_{CH_4} is methane lower heating value.

$$S_t = S_{t-1} + G_t - U_t - F_t \quad (15)$$

S_t and S_{t-1} are gas inventory at the end of the current and preceding time steps; G_t is generation, U_t is useful demand and F_t is controlled loss or flaring.

$$D_f = [(F_{\text{baseline}} - F_{\text{biogas}}) / F_{\text{baseline}}] \times 100 \quad (16)$$

D_f is conventional-fuel displacement (%), F_{baseline} is the comparable conventional-fuel baseline and F_{biogas} is the quantity used while biogas was available.

Because Ikoyi is in a coastal groundwater environment, empty-tank uplift was screened. The combined base plan was derived explicitly as $A_b = 2 \times 8.20 \times 9.70 = 159.08 \text{ m}^2$ for the two trains. Groundwater heads between 0.5 and 2.0 m above the base were examined. The calculation is a screening check and does not replace structural design, verified concrete dead load, cover depth, anchorage or drainage assessment.

$$F_u = \gamma_w h_w A_b \quad (17)$$

F_u is groundwater uplift force, γ_w is the unit weight of water (9.81 kN/m³), h_w is groundwater head above the base and A_b is combined base area (159.08 m²).

$$FS = R_{\text{stabilising}} / F_u \geq 1.20 \quad (18)$$

FS is flotation factor of safety and $R_{\text{stabilising}}$ is verified stabilising resistance from structural dead load, cover, anchorage and other applicable permanent actions.

4. RESULTS

4.1 Empirical wastewater characteristics at the three sampling points

The 30-day campaign produced 90 matched point-specific wastewater observations. Mean monitored flow was $204.82 \pm 7.93 \text{ m}^3/\text{day}$ and mean wastewater temperature was $29.93 \pm 0.73 \text{ }^\circ\text{C}$. Across all days, mean SP-01 influent concentrations were 907.67 mg/L COD, 467.13 mg/L BOD₅, 349.27 mg/L TSS, 55.05 mg/L NH₃-N and 10.27 mg/L PO₄-P. Corresponding mean SP-02 concentrations were 229.47, 110.47, 88.40, 42.64 and 8.59 mg/L; mean SP-03 concentrations were 117.77, 51.50, 41.83, 24.77 and 5.59 mg/L. The concentration sequence confirms progressive treatment through the ABR and polishing stage.

Influent strength was comparable between the pre-optimisation and optimised phases: COD averaged 903.9 and 903.4 mg/L, BOD₅ 464.2 and 461.33 mg/L, and TSS 347.6 and 350.0 mg/L, respectively. Mean flows were likewise close at 201.77 and 205.77 m³/day. This stability in incoming load supports descriptive comparison of treatment outcomes. Final-effluent concentrations during optimised operation were 90.6 mg/L COD, 37.47 mg/L BOD₅ and 30.53 mg/L TSS, compared with 160.1, 71.6 and 59.6 mg/L during pre-optimisation operation.

Table 3: Empirical wastewater concentrations before and after optimisation (mean $\pm$ SD)

Parameter	Pre SP-01	Pre SP-02	Pre SP-03	Optimised SP-01	Optimised SP-02	Optimised SP-03
pH	7.22 $\pm$ 0.11	7.22 $\pm$ 0.10	7.30 $\pm$ 0.05	7.18 $\pm$ 0.12	7.32 $\pm$ 0.10	7.25 $\pm$ 0.08
COD (mg/L)	903.9 $\pm$ 45.2	274.7 $\pm$ 10.9	160.1 $\pm$ 4.8	903.4 $\pm$ 48.8	197.6 $\pm$ 16.5	90.6 $\pm$ 9.6
BOD ₅ (mg/L)	464.2 $\pm$ 26.9	133.8 $\pm$ 4.4	71.6 $\pm$ 3.5	461.3 $\pm$ 27.7	94.4 $\pm$ 8.7	37.5 $\pm$ 4.8
TSS (mg/L)	347.6 $\pm$ 24.2	105.9 $\pm$ 9.5	59.6 $\pm$ 1.7	350.0 $\pm$ 25.9	75.0 $\pm$ 5.5	30.5 $\pm$ 3.6
NH ₃ -N (mg/L)	55.76 $\pm$ 3.45	45.92 $\pm$ 2.79	29.48 $\pm$ 1.17	55.17 $\pm$ 3.37	41.13 $\pm$ 2.93	22.02 $\pm$ 1.65
PO ₄ -P (mg/L)	10.40 $\pm$ 0.84	9.02 $\pm$ 0.66	6.38 $\pm$ 0.48	10.32 $\pm$ 0.81	8.41 $\pm$ 0.59	5.17 $\pm$ 0.49

Note. Pre-optimisation n = 10 days; optimised operation n = 15 days. SP-01 = ABR influent; SP-02 = ABR effluent; SP-03 = final effluent after polishing.

4.2 Corrected reactor sizing and hydraulic state

The gross internal envelope was derived step by step. Each settler volume was $2.50 \times 8.20 \times 2.50 = 51.25 \text{ m}^3$; for two trains this gave 102.50 m^3 . Each chamber box was $1.20 \times 8.20 \times 2.40 = 23.616 \text{ m}^3$; for six chambers in each of two trains this gave $23.616 \times 6 \times 2 = 283.392 \text{ m}^3$. The combined gross internal envelope was therefore $102.50 + 283.392 = 385.892 \text{ m}^3$. Gross volume is not equivalent to working volume because structural and hydraulic exclusions must be deducted. The independent flow-HRT relationship gave a design-implied active volume of 337.34 m^3 , consistent with the project design flow of $154.45 \text{ m}^3/\text{day}$ and reported HRT of 52.42 h.

The pre-optimisation effective condition contained 286.74 m^3 , representing 85% of the design-implied active volume. Restoration increased usable volume by 50.60 m^3 or 17.65%. At the monitored mean flow of $204.82 \text{ m}^3/\text{day}$, calculated HRT increased from 33.60 to 39.53 h. Using the measured 30-day mean influent COD of 907.67 mg/L , calculated OLR declined from 0.648 to $0.551 \text{ kg COD m}^{-3} \text{ d}^{-1}$. Both values were below the $3.0 \text{ kg COD m}^{-3} \text{ d}^{-1}$ screen, while the restored condition achieved the 36-h HRT planning gate.

At the same monitored mean flow, the equal-split chamber upflow velocity was 0.434 m/h . Applying the pre-optimisation peak factor of 1.50 gave 0.650 m/h ; the equalised 1.05 peak factor gave 0.455 m/h after optimisation. The improvement depends on field flow balancing together with clear baffle openings and cannot be achieved by volume recovery alone. At the historical design flow of $154.45 \text{ m}^3/\text{day}$, the corresponding HRT values remain 44.56 and 52.42 h.

Table 4: ABR configuration before and after the corrected optimisation

Parameter	Reduced-usable-volume scenario	Restored/optimised scenario	Change
Arrangement	2 parallel trains	2 parallel trains	No shell change
Chambers	6 per train; 12 total	6 per train; 12 total	No chamber added
Gross internal envelope	385.892 m ³	385.892 m ³	0 m ³
Hydraulically active volume	286.74 m ³	337.34 m ³	+50.60 m ³ ; +17.65%
HRT at field mean flow	33.60 h	39.53 h	+5.93 h
Mean COD load	185.90 kg/day	185.90 kg/day	Same 30-day loading basis
OLR at field mean	0.648 kg COD m ⁻³ d ⁻¹	0.551 kg COD m ⁻³ d ⁻¹	-15.0%
Peak upflow	0.650 m/h at PF 1.50	0.455 m/h at PF 1.05	-30.0%
Required action	Sludge/dead-zone and flow imbalance	Desludge, clear baffles, balance and meter trains	Operational restoration

Note. Hydraulic parameters are calculated from field flow and wastewater data together with the audited reactor geometry. Physical shell and chamber dimensions remain unchanged.

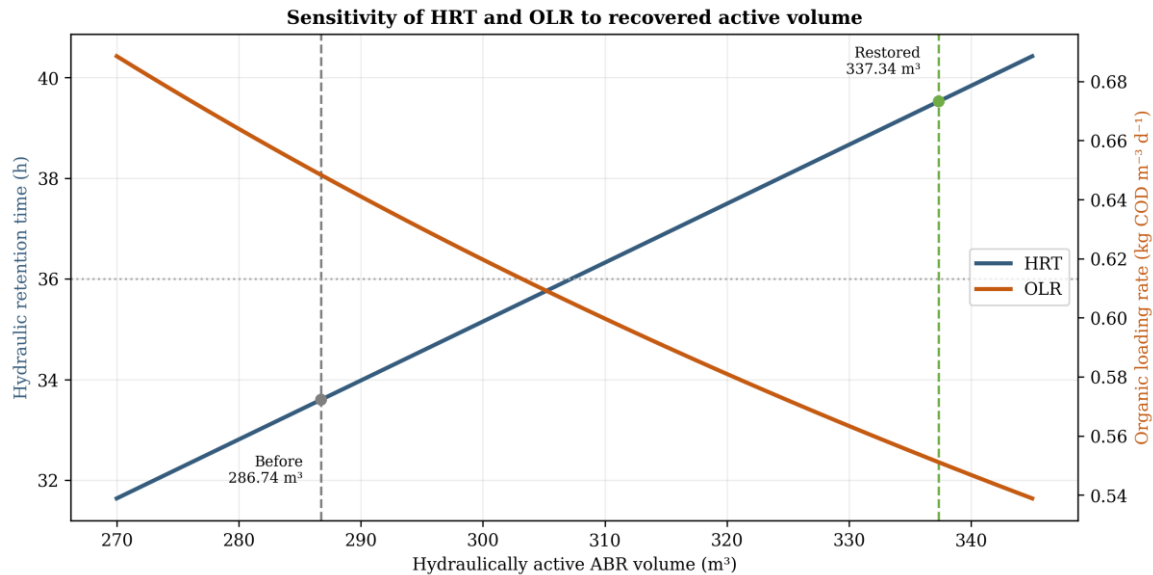


Figure 2: Sensitivity of hydraulic retention time and organic loading rate to active-volume recovery.

4.3 Empirical treatment performance before and after optimisation

ABR-stage removal was higher during optimised operation. Mean COD, BOD₅ and TSS removals were 78.15%, 79.56% and 78.55%, compared with 69.58%, 71.14% and 69.57% during pre-optimisation operation. The downstream polishing stage further reduced residual concentrations, producing mean overall removals of 89.99% COD, 91.90% BOD₅ and 91.27% TSS during the optimised phase, compared with 82.26%, 84.55% and 82.80% in the pre-optimisation phase.

Nutrient removal remained lower than carbon and solids removal but was also higher during optimised operation. Mean ABR-stage $\text{NH}_3\text{-N}$ removal was 25.49%, compared with 17.64% pre-optimisation, while overall removal was 60.11%, compared with 47.06%. $\text{PO}_4\text{-P}$ removal was 18.49% across the ABR and 49.93% across the complete system during optimised operation, compared with 13.22% and 38.62%. These operating-phase differences support continued use of polishing while showing that nutrient management remains a separate design consideration.

All 15 optimised-operation final-effluent observations met the combined study targets of $\text{COD} \leq 200 \text{ mg/L}$, $\text{BOD}_5 \leq 50 \text{ mg/L}$ and $\text{TSS} \leq 100 \text{ mg/L}$. During pre-optimisation operation, COD and TSS met their concentration targets, but none of the ten BOD_5 observations met 50 mg/L; only two of five transition observations met all three targets. Combined performance reliability was therefore $R = 1.00$ during optimised operation, compared with $R = 0.00$ during pre-optimisation operation.

Table 5: Empirical wastewater-removal performance before and after optimisation

Parameter	Pre ABR removal	Optimised ABR removal	Pre overall removal	Optimised overall removal	Optimised final effluent
COD	$69.58 \pm 0.95\%$	$78.15 \pm 0.88\%$	$82.26 \pm 0.65\%$	$89.99 \pm 0.69\%$	$90.6 \pm 9.6 \text{ mg/L}$
BOD_5	$71.14 \pm 0.85\%$	$79.56 \pm 0.95\%$	$84.55 \pm 0.79\%$	$91.90 \pm 0.69\%$	$37.47 \pm 4.76 \text{ mg/L}$
TSS	$69.57 \pm 0.82\%$	$78.55 \pm 1.01\%$	$82.80 \pm 0.86\%$	$91.27 \pm 0.88\%$	$30.53 \pm 3.56 \text{ mg/L}$
$\text{NH}_3\text{-N}$	$17.64 \pm 0.99\%$	$25.49 \pm 1.05\%$	$47.06 \pm 1.46\%$	$60.11 \pm 1.23\%$	$22.02 \pm 1.65 \text{ mg/L}$
$\text{PO}_4\text{-P}$	$13.22 \pm 0.88\%$	$18.49 \pm 0.82\%$	$38.62 \pm 0.99\%$	$49.93 \pm 1.08\%$	$5.17 \pm 0.49 \text{ mg/L}$

Note. Values are means $\pm$ sample SD calculated from matched field measurements; pre-optimisation $n = 10$ and optimised operation $n = 15$.

Empirical wastewater concentrations before, during and after optimisation

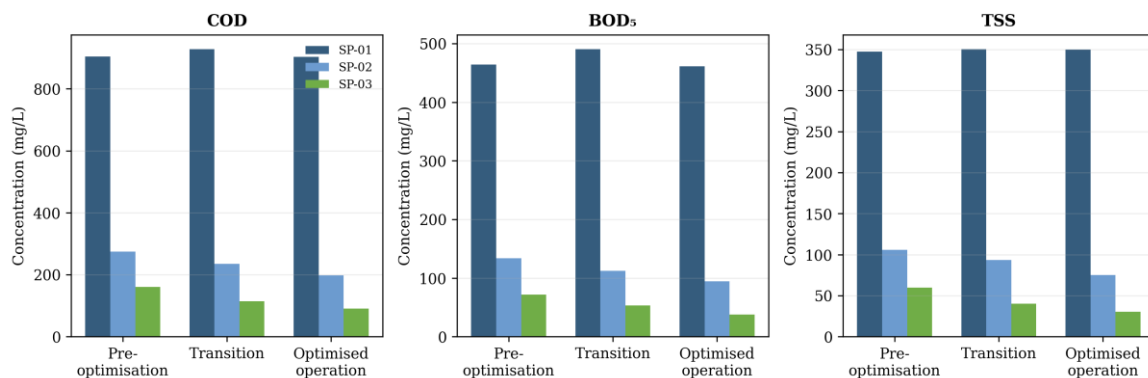


Figure 3: Empirical phase-mean wastewater concentrations at SP-01, SP-02 and SP-03.

4.4 Biogas production, storage and useful-energy implications

Daily field monitoring showed higher gas quantity and quality during optimised operation. Mean total biogas production was $57.03 \pm 2.15 \text{ m}^3/\text{day}$, compared with $42.99 \pm 2.34 \text{ m}^3/\text{day}$ pre-optimisation, a descriptive difference of 32.7%. Mean methane fraction was 63.39%, compared with 57.15%, while carbon dioxide was 35.30%, compared with 40.26%. Hydrogen sulphide was 266.9 ppm, compared with 510.1 ppm, and moisture was 22.64 g/m^3 , compared with 32.53 g/m^3 . These

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differences coincided with the observed optimised-operation gas-quality profile and conditioning controls.

The nominal installed gas-holder capacity was 45 m³. Mean useful kitchen delivery during optimised operation was 49.32 m³/day with 7.83 burner h/day, compared with 29.78 m³/day and 4.99 h/day pre-optimisation. Unused or flared gas was 6.00 m³/day, compared with 11.92 m³/day. Mean holder pressure was 1.667 kPa, compared with 1.343 kPa. Across all 30 days, 1,551.8 m³ of biogas was produced, 1,256.5 m³ was used in the kitchen and calculated gross methane energy used was 7,706.0 kWh.

The kitchen-energy logs documented displacement of conventional fuels. Mean LPG, diesel and firewood displacement during optimised operation was 51.82%, 50.10% and 53.83%, compared with 23.09%, 18.79% and 20.61% during pre-optimisation operation. Over the 30-day campaign, the recorded physical savings were 412.3 kg LPG, 61.0 L diesel and 927.0 kg firewood. The association between operating phase and performance therefore extended beyond gas production to useful energy delivery; monetary valuation was not undertaken.

Table 6: Empirical biogas and kitchen-energy performance before and after optimisation

Indicator	Pre-optimisation	Optimised operation	Change	Interpretation
Nominal gas-holder capacity	45 m ³	45 m ³	No change	Installed design capacity
Biogas flow	42.99 ± 2.34 m ³ /day	57.03 ± 2.15 m ³ /day	+32.7%	Higher stable production
Methane fraction	57.15 ± 0.68%	63.39 ± 0.69%	+6.24 pp	Higher methane fraction
H ₂ S	510.1 ± 29.8 ppm	266.9 ± 28.0 ppm	−47.7%	Lower corrosive/toxic impurity
Moisture	32.53 ± 1.65 g/m ³	22.64 ± 1.84 g/m ³	−30.4%	Lower moisture content
Gas used	29.78 ± 2.08 m ³ /day	49.32 ± 2.75 m ³ /day	+65.6%	Greater useful utilisation
Burner hours	4.99 ± 0.34 h/day	7.83 ± 0.32 h/day	+56.9%	Longer cooking support
LPG displacement	23.09 ± 1.06%	51.82 ± 1.41%	+28.73 pp	Reduced LPG dependence
Diesel displacement	18.79 ± 1.62%	50.10 ± 1.90%	+31.31 pp	Reduced diesel dependence
Firewood displacement	20.61 ± 1.52%	53.83 ± 1.51%	+33.22 pp	Reduced firewood dependence

Note. Gas-holder capacity is from the project design record; other values are field means ± sample SD. pp = percentage points. Pre-optimisation n = 10; optimised operation n = 15.

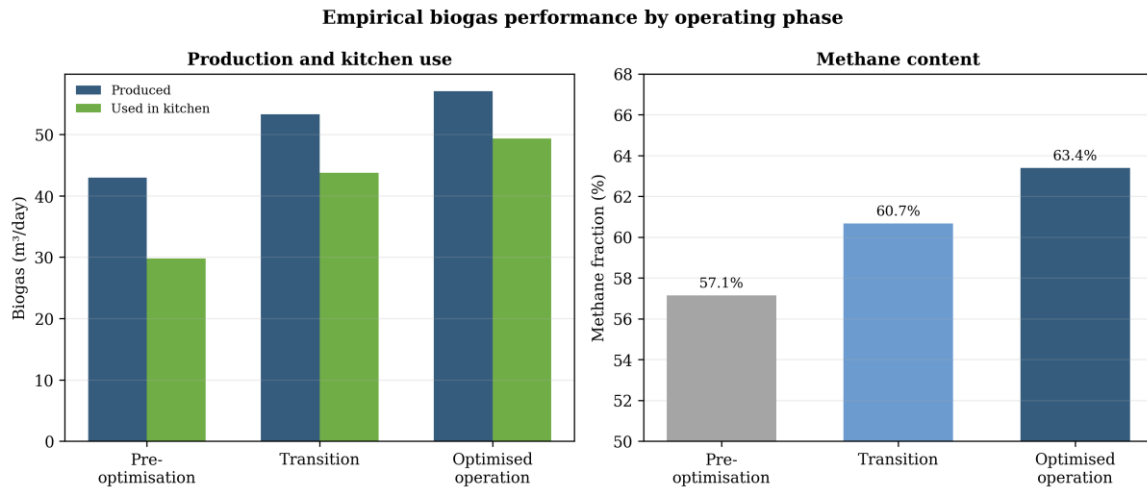


Figure 4: Empirical biogas production, kitchen use and methane fraction by operating phase.

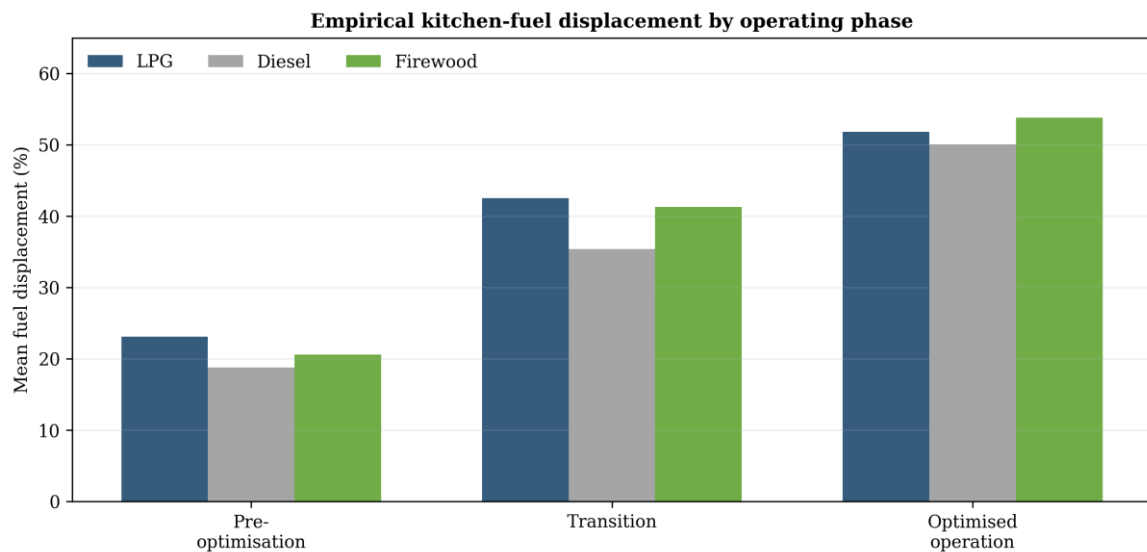


Figure 5: Empirical LPG, diesel and firewood displacement by operating phase.

4.5 Hydrostatic stability screening

The two-train base plan was derived as $2 \times 8.20 \times 9.70 = 159.08 \text{ m}^2$. At groundwater heads of 0.5, 1.0, 1.5 and 2.0 m above the base, calculated uplift was approximately 0.78, 1.56, 2.34 and 3.12 MN. At a minimum factor of safety of 1.20, required stabilising resistance was 0.94–3.75 MN. The range confirms that groundwater is not merely a geotechnical description; it is a structural design action that can control the empty-tank condition.

The screening result does not establish adequacy because verified concrete dimensions, self-weight, soil cover, internal water level, drainage, anchorage and load combinations were not available. The optimisation therefore includes an explicit hold point: do not empty, modify or construct adjoining units until the critical groundwater level and structural resistance are confirmed.

Table 7: Groundwater-uplift sensitivity for the combined ABR footprint

Groundwater head above base	Calculated uplift	Resistance required at FS = 1.20	Design implication
0.5 m	0.78 MN	0.94 MN	Verify empty-tank dead load
1.0 m	1.56 MN	1.87 MN	Check cover, drainage and construction stage
1.5 m	2.34 MN	2.81 MN	Ballast or anchorage may govern
2.0 m	3.12 MN	3.75 MN	Critical coastal-groundwater scenario

Note. Screening uses $\gamma_w = 9.81 \text{ kN/m}^3$ and an approximate combined base area of 159.08 m^2 . Detailed structural verification is required.

4.6 Impact assessment

The intervention replaced an unsafe sewage-management condition with contained treatment and eliminated routine manual faecal evacuation. This represents a direct change in the sanitation service chain: wastewater is conveyed to engineered treatment rather than repeatedly removed through hazardous manual intervention. Field observations also recorded reduced odour nuisance, improved cleanliness around the centre and more reliable access to renewable cooking gas. These outcomes align with WHO's emphasis on exposure control and with prison-biogas experience in other countries (WHO, 2022; Gauthier et al., 2012).

The monitored mass balance showed higher pollutant removal during optimised operation. Mean COD removal was 167.25 kg/day , compared with 150.08 kg/day pre-optimisation, a difference of $+17.18 \text{ kg/day}$. Mean BOD_5 removal was 87.22 kg/day , compared with 79.21 kg/day ($+8.01 \text{ kg/day}$), while TSS removal was 65.74 kg/day , compared with 58.11 kg/day ($+7.63 \text{ kg/day}$). These differences are summarised together in Table 8. Final-effluent COD, BOD_5 and TSS met the combined study targets on all 15 optimised-operation days.

Energy logs showed higher useful delivery during optimised operation. Mean kitchen gas use was 65.6% higher than the pre-optimisation phase, burner support was 56.9% higher, and gross methane energy used was 311.70 kWh/day , compared with 169.79 kWh/day . The 30-day records showed aggregate physical savings of 412.3 kg LPG , 61.0 L diesel and $927.0 \text{ kg firewood}$. Monetary savings should be computed separately with contemporaneous invoice or issue prices to avoid distortion from fuel-price changes.

The social and institutional effects include reduced exposure to raw sewage, improved sanitation dignity, less dependence on smoky solid fuel and a cleaner kitchen environment. Sustainability depends on assigned O&M authority, recurrent financing, trained operators, spare parts, desludging schedules, gas-safety procedures and continued monitoring. Infrastructure transfer without these controls would reproduce the weakness observed in many decentralised ABR programmes (Yulistyorini et al., 2019).

Table 8: Field-based impact assessment of the integrated system

Impact domain	Indicator or finding	Evidence strength	Defensible conclusion
Technical	337.34 m ³ active volume; HRT 33.60 to 39.53 h	Field/design calculation	Installed shell supports repair-first optimisation
Sanitation/public health	Manual evacuation eliminated; sewage containment and odour improved	Field operational record	Exposure pathway materially reduced
Environmental	+17.18 kg/day COD, +8.01 kg/day BOD ₅ and +7.63 kg/day TSS removed	Field mass balance	Higher removal during optimised operation
Energy	57.03 m ³ /day gas; 49.32 m ³ /day used; 7.83 burner h/day	Field monitoring	Higher delivery during optimised operation
Fuel economy	412.3 kg LPG, 61.0 L diesel and 927.0 kg firewood saved in 30 days	Field kitchen logs	Reduced conventional-fuel requirement
Social	Cleaner sanitation and reduced smoky-fuel dependence	Field observation	Improved dignity and kitchen working conditions
Institutional	O&M, safety, logs, finance and spare parts required	Engineering assessment	Governance remains part of the optimised design

Note. Quantitative indicators are derived from field wastewater, biogas and kitchen-energy records. Monetary valuation is excluded because contemporaneous price documentation was outside this analysis.

5. DISCUSSION

5.1 Why the corrected sizing changes the optimisation

The most consequential correction is dimensional. The value 154.45 is the design flow in m³/day, not the installed active volume in m³. Combining it with the reported 52.42-h HRT produces 337.34 m³. Any optimisation search that restricts reactor volume to values near 154 m³ cannot represent the installed system and may falsely recommend extra chambers or a smaller optimum. The corrected basis reverses that logic: the system already contains a large active volume relative to design flow, so the first question is whether that volume is hydraulically available and evenly used.

The repair-first result is engineeringly and institutionally attractive. Recovering 50.60 m³ of inactive capacity yields a 17.65% gain in active volume without additional land or a new reactor shell. At the monitored mean flow, the restored-volume calculation yields 5.93 h additional HRT and 15% lower OLR; the balanced-flow scenario yields 30% lower peak upflow. Wastewater removal was also higher during the optimised phase despite no engineeringly significant change in influent COD, BOD₅ or TSS. This pattern is consistent with, but does not prove, a causal relationship between restored hydraulic function and treatment performance.

This conclusion aligns with field evidence showing that dynamic loading and O&M practices govern ABR performance. A nominal HRT calculated from drawings may differ materially from

residence time under intermittent flow, dead zones or unequal distribution. Echeverría et al. (2022) found that the monitored ABR performed below a design-model prediction and attributed the difference partly to temperature and intermittent flow. Yulistyorini et al. (2019) found that only a minority of surveyed decentralised ABRs achieved acceptable combined treatment and structural performance, largely because service delivery did not continue after construction. The Ikoyi optimisation therefore treats inspection, metering and maintenance as design components.

5.2 Treatment performance and the case for polishing

The empirical results demonstrate why both the ABR and downstream polishing unit must be evaluated. During optimised operation the ABR alone reduced COD to 197.6 mg/L, BOD₅ to 94.4 mg/L and TSS to 75.0 mg/L. Polishing then reduced these means to 90.6, 37.47 and 30.53 mg/L. The ABR met the COD and TSS screening targets on average but not the BOD₅ target; the complete treatment train achieved all three targets on every optimised-operation day.

The polishing stage was especially important for BOD₅ and nutrients. Constructed wetlands and biofilters have performed well after ABRs (Echeverría et al., 2022; Satyendra & Vijay, 2024), and high-strength decentralised systems can produce high-quality effluent when the complete train is properly designed and operated (Rahman et al., 2024). At Ikoyi, continued performance will depend on managing solids accumulation, groundwater, mosquito risk, media condition, hydraulic distribution, odour and access for maintenance.

The 30-day series is sufficient to demonstrate field-phase performance but not seasonal invariance. Continued matched monitoring at SP-01, SP-02 and SP-03 should retain COD, BOD₅, TSS, NH₃-N and PO₄-P and should add microbial indicators for public-health verification. The approach is consistent with Standard Methods and with the regulatory principle of using time-based averages rather than isolated samples (American Public Health Association et al., 2023; Electronic Code of Federal Regulations, n.d.).

5.3 Biogas optimisation: production is not utilisation

The empirical gas record answers both the production and utilisation questions. Optimised mean production of 57.03 m³/day was accompanied by 49.32 m³/day of kitchen use, 7.83 burner h/day and only 6.00 m³/day unused or flared. During that phase, methane content was higher and H₂S and moisture were lower than in the pre-optimisation phase, showing that useful energy assessment must consider gas quality and delivery as well as volume.

A robust gas system must reconcile production, kitchen use, storage change and controlled loss. During the optimised phase, higher production coincided with approximately half the pre-optimisation quantity of unused gas and greater useful consumption. The stated 45-m³ holder is below one day of optimised mean production, but its adequacy depends on the timing of generation and meal preparation. Pressure and burner-hour evidence supports current use, while an hourly inventory study would provide a stronger buffer-sizing check.

Condensate management, hydrogen-sulphide removal, leak testing, pressure monitoring, calibrated metering and burner scheduling remain essential. Gauthier et al. (2012) showed that operational responsibilities and maintenance influence whether prison biogas remains appropriate. The measured reduction in conventional-fuel use at Ikoyi strengthens the case for continued investment in these controls and for retaining a contingency cooking source for service continuity.

5.4 Contribution to sustainable development and engineering practice

The case connects sanitation, pollution control, renewable thermal energy and institutional resilience, consistent with resource-recovery and sanitation-safety principles (UNEP, 2023; WHO, 2022, 2026). Its quantified contribution is a transparent field decision basis: 337.34 m³ restored active volume; 5.93 h additional HRT at monitored mean flow; 15% lower OLR; 89.99%, 91.90% and 91.27% overall COD, BOD₅ and TSS removal; 57.03 m³/day biogas production during optimised operation; 63.39% methane; and conventional-fuel displacement above 50% for LPG, diesel and firewood. These values convert a general sustainability claim into measurable engineering outcomes.

6. LIMITATIONS AND VALIDATION REQUIREMENTS

The principal limitation is the 30-day, single-season monitoring window and the sequential rather than randomised intervention design. The results are empirical and field-based, but they should be interpreted as full-scale operating-phase evidence rather than proof that every observed change was caused by one isolated optimisation variable. Longer monitoring should test wet- and dry-season performance, sludge accumulation and resilience to unusual hydraulic or organic shocks.

The active-volume values are engineering calculations based on the audited geometry and operating condition; a detailed sludge-depth and residence-time survey would strengthen the hydraulic diagnosis. Aggregate flow does not resolve inequality between the two trains, and daily gas totals do not capture sub-daily storage peaks. The multi-criteria weights reflect transparent engineering priorities but were not established through formal stakeholder elicitation or tested through a complete multi-weight sensitivity analysis; future work should examine ranking stability across plausible weights. Microbial water-quality indicators, kitchen air-quality measurements, contemporaneous fuel prices and ethically collected stakeholder responses would extend the environmental, economic and social assessment beyond the present scope.

7. CONCLUSIONS AND RECOMMENDATIONS

The design audit confirms that the Ikoyi system comprises two parallel ABR trains with six chambers per train and a restored active volume of 337.34 m³. At the monitored mean flow of 204.82 m³/day, active-volume recovery increased calculated HRT from 33.60 to 39.53 h and reduced OLR from 0.648 to 0.551 kg COD m⁻³ d⁻¹. The optimised solution therefore retains the installed shell and chamber count and prioritises desludging, dead-zone recovery, clear baffle openings, equal flow division and metering.

The 30-day empirical campaign comprised 90 wastewater samples at SP-01, SP-02 and SP-03. During optimised operation, final-effluent COD, BOD₅ and TSS averaged 90.6, 37.47 and 30.53 mg/L, with overall removals of 89.99%, 91.90% and 91.27%. All 15 optimised-operation days met the combined study targets. Nutrient removal was higher during optimised operation but remained lower than carbon and solids removal, supporting continued attention to polishing and microbial-risk verification.

Mean biogas production during optimised operation was 57.03 m³/day, compared with 42.99 m³/day pre-optimisation; methane fraction was 63.39%, compared with 57.15%; and kitchen use was 49.32 m³/day, compared with 29.78 m³/day. LPG, diesel and firewood displacement reached 51.82%, 50.10% and 53.83% during optimised operation. The field records therefore show measurable sanitation, pollution-control and institutional-energy benefits, while the sequential design limits attribution to any single optimisation action.

For implementation, the authors recommend continued three-point wastewater monitoring; total and train-specific flow metering; scheduled sludge-depth surveys; maintenance of the polishing stage; gas-quality, pressure and kitchen-demand logging; an empty-tank hydrostatic check with FS ≥ 1.20 ; contemporaneous cost recording; and a funded O&M plan with named responsibilities, preventive schedules, safety procedures and spare parts. These measures will protect the gains demonstrated during the field campaign and allow seasonal verification.

DATA AVAILABILITY AND RESEARCH-INTEGRITY STATEMENT

The paper uses primary field and empirical monitoring records together with transparent engineering calculations. Security-sensitive layouts and individual-level custodial information are not disclosed. The wastewater, biogas and kitchen-energy datasets are held within the research project and are subject to institutional permissions; aggregated results are reported in this manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest in relation to the preparation of this manuscript.

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