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Original Research Article

Sustainable Pollutant Removal through Integrated Biological, Physical, Electrochemical Treatment: Resource Recovery and LCA Study

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Abstract

Vinasse from bioethanol distillation contains high levels of organic matter, suspended solids, color, sulfides, and acidity, requiring integrated treatment beyond biological methods. This study tested a sequential system comprising anaerobic digestion, aerobic oxidation, sedimentation, and electrochemical oxidation using a Ti/RuO_2 anode and stainless-steel cathode at different NaCl concentrations. The system reduced pollutants in 10% diluted vinasse, lowering COD, BOD, and TSS by 97.9 %, 99%, and 93.6%, respectively, eliminating sulfide, and increasing pH to 8.2. The electrochemical step polished water by generating hydroxyl radicals and reactive chlorine species. Six grams per liter of NaCl provided optimal water quality, with high color removal, turbidity reduction, sulfide removal, and pH stabilization. The GWP of the four resource-recovery techniques was assessed in a life cycle study. Sludge and biogas recovery produced the least climatic impact, according to Monte Carlo statistical analysis, which revealed GWP emissions of 0.842–1.125 kg CO_2 eq/kg treated water across four suggested scenarios with a ≤3% coefficient of variation and a tiny standard error of the mean. Overall, this system combines pollutant removal, water recovery, sludge valorization, and environmental impact assessment to provide an efficient circular method for vinasse treatment.

Keywords: Aerobic oxidation; anaerobic digestion; electrochemical oxidation; life cycle assessment; resource recovery; vinasse wastewater

1. Introduction

Vinasse is a high-strength wastewater produced during ethanol and alcohol distillation, characterized by a high organic load, acidity, dark brown color, suspended solids, and sulfur compounds. Large amounts of vinasse waste, usually 10–15 L/L of ethanol, are produced worldwide during bioethanol production (Devi et al., 2023; Silva et al., 2023). Recent research has reported that vinasse typically has COD levels ranging from 10^4–10^5 mg/L, along with high BOD, melanoidin pigments, phenolics, sulfides, and dissolved salts that can seriously harm aquatic ecosystems if exposed to the environment (do Vale Borges et al., 2025; Eng et al., 2022; Farfán et al., 2024; Otieno & Apollo, 2021). Anaerobic ponds, aerobic lagoons, coagulation-flocculation, and activated sludge systems are examples of traditional treatment techniques that frequently fall short of eliminating refractory organic molecules and color-causing components (Kamel et al., 2026; Zhang et al., 2026). Furthermore, poor treatment stability, sludge accumulation, odor issues, and secondary pollution are frequently caused by excessive pollutant loads and the limited biodegradability of certain organic fractions.

Integrated biological and electrochemical systems are becoming increasingly popular among the sophisticated treatment solutions available today because of their capacity to oxidize persistent pollutants and simultaneously break down biodegradable organics at the same time. Anaerobic digestion effectively reduces biodegradable organic matter and produces methane-rich biogas via microbial pathways, while aerobic oxidation provides an efficient polishing stage to oxidize residual dissolved organics (Manju and Manu, 2026). However, melanoidins, sulfides, and other resistant substances in vinasse effluent are frequently not completely eliminated by biological processes alone (Comparato et al., 2024; Sreekutty and Chellapandi, 2024). The electrochemical oxidation process using mixed metal oxide (MMO) electrodes, especially Ti/RuO_2 anodes, has become a promising advanced oxidation method owing to its high resistance to corrosion, catalytic activity, and ability to produce reactive oxidants such as hydroxyl radicals (•OH) and reactive chlorine species from NaCl electrolytes. (Dória et al., 2023). These oxidants can non-selectively break down sulfides, phenolics, dissolved organics, and color-causing chemicals into simpler and less dangerous byproducts. Combining sedimentation with electrochemical oxidation further reduces the suspended particles and sludge-bound pollutants created during biological treatment. For genuine vinasse wastewater, a few studies still combine anaerobic digestion, aerobic oxidation, sedimentation, and electrochemical polishing, particularly for sulfide removal and effluent optimization under different electrolyte strengths (Kumar Biswas et al., 2022; Qiang et al., 2025).

An integrated vinasse treatment system including anaerobic digestion, aerobic oxidation, sedimentation, and electrochemical oxidation using a Ti/RuO2 anode, a stainless-steel cathode, and varying concentrations of NaCl electrolyte is featured in this study. This system is intended to improve effluent quality and pollutant removal while methodically assessing the effect of electrolyte strength on oxidation performance. The main novelty of this study is the integration of a multistage biological–physical–electrochemical treatment system with life cycle assessment (LCA) to evaluate both the treatment performance and environmental implications of sludge and biogas resource recovery. To position the present study within the existing literature, Table 1 summarizes representative studies selected according to three criteria: (i) treatment of real or synthetic vinasse wastewater, (ii) application of one or more biological, physical, or electrochemical treatment processes, and (iii) evaluation of treatment performance and/or environmental sustainability. This comparison highlights the current research gap regarding the integration of resource recovery with life cycle assessment in vinasse treatment.

Table 1. Comparative matrix of vinasse treatment approaches

Study	Anaerobic	Aerobic	Sedimentation	Electrochemical	LCA
Bayu et al., (2022)	√	x	x	x	x
Prazeres et al., (2019)	x	x	√	x	x
Saavedra et al., (2024)	x	x	√	√	x
Kim & Criddle, (2023)	√	x	x	x	√
Mazaheri et al., (2024b)	√	√	√	x	x
Avendaño et al., (2026)	x	x	x	√	√
Vilar et al., (2018)	√	√	√	√	x
This Study	√	√	√	√	√

2. Methods

2.1. Vinasse Sampling

The raw material was obtained from Polokarto and Mojolaban, Central Java, Indonesia (traditional bioethanol plant). It was transported in a sealed vessel under ambient conditions to the laboratory and processed upon arrival. The other supporting materials, that is, distilled water, activated sludge as microbial inoculum in the anaerobic system and biodegradation under oxy-rich conditions, sodium chloride (NaCl, Sigma-Aldrich) was used as the electrolyte, Ti/RuO_2 from Insolube Anode Technology was used as the mixed metal oxide (MMO) anode, and stainless steel was used as the cathode in the electrochemical experiment.

2.2. Experimental Design

An integrated vinasse treatment system was developed that incorporated biological, sedimentation, and electrochemical processes. The treatment sequence included four stages: anaerobic, aerobic, sedimentation, and electrochemical oxidation (Figure 1). In this process, the vinasse influent enters the anaerobic reactor, then undergoes aerobic treatment and sedimentation, and finally undergoes electrochemical treatment before being discharged as treated effluent.

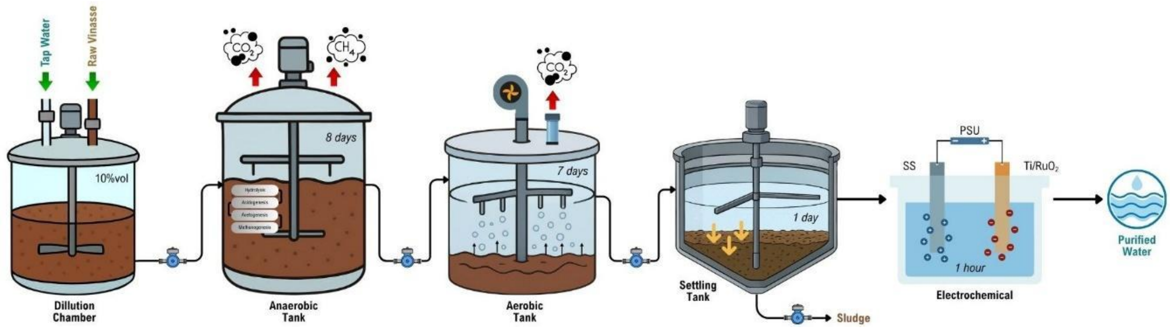

Figure 1. Integrated vinasse treatment flow diagram.

2.2.1. Anaerobic and Aerobic Treatment

A total of 24 L of 10% vinasse was treated anaerobically in a 160 L reactor containing 136 L of activated sludge, and the mixture was continuously mixed for 8 days to promote hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Pinheiro et al., 2026; Sahil and Nanda, 2025). The remaining organic compounds were then oxidized to CO2 and H2O for 7 days by transferring 24 L of anaerobic effluent into an aerobic reactor containing 60 L of activated sludge (Mastropetros et al., 2022). Samples were collected before and after treatment to observe stage performance.

2.2.2. Sedimentation treatment

The effluent from the aerobic reactor was then transferred to a settling tank for gravity-based sedimentation. The procedure traps biological flocs and suspended particles from the treated wastewater over the course of a day. Water quality changes following solid-liquid separation were assessed by analyzing the influent and effluent samples from the sedimentation unit.

2.2.3. Electrochemical treatment

The sedimented effluent was further polished through electrochemical oxidation using a Ti/RuO_2 anode (28.3–35.4 mA/cm^2) and a stainless-steel cathode (11.3–14.1 mA/cm^2). NaCl electrolyte at 4, 6, and 8 g/L was applied to 2 L of wastewater per run for 60 minutes at 8 V, and it was operated at an applied current of 8–10 A with an electrode spacing of 1.5 cm. According to Equations (1)–(4), the oxidation process occurred through direct anodic oxidation and indirect oxidation by reactive species such as hydroxyl radicals (•OH), chlorine (Cl_2), hypochlorous acid (HClO), and hypochlorite ions (ClO^-). These oxidants promoted the degradation and mineralization of organic pollutants in vinasse wastewater (Santacruz et al., 2022).

$$MOx + H_2O \rightarrow MOx(\bullet OH) + H^+ + e^- \quad (1)$$

$$2Cl^- \rightarrow Cl_2 + 2e^- \quad (2)$$

$$Cl_2 + H_2O \rightarrow HClO + Cl^- + H^+ \quad (3)$$

$$HClO \leftrightarrow ClO^- + H+ \tag{4}$$

The energy performance of the electrochemical process was evaluated using specific energy consumption (SEC) and electrical energy per order (EE/O) according to Equations (5) and (6), where Ecell is voltage (V), I is current (A), t is time (h), V is wastewater volume, ΔCOD is COD reduction, and Co and Ct are the initial and final pollutant concentrations. SEC represents the energy required to remove COD, and EE/O represents the energy required to reduce the pollutant concentration by one order of magnitude.

$$SEC = \frac{E_{Cell} \times I \times t}{\Delta COD \times V} \tag{5}$$

$$EE/O = \frac{E_{Cell} \times I \times t}{V \times log_{10}\left(\frac{C_o}{C_t}\right)} \tag{6}$$

2.3. Analytic Methods

Wastewater quality was analyzed at each treatment stage using Indonesian National Standard (SNI) methods, including pH, total suspended solids (TSS), chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), and sulfide. The data obtained from the electrochemical process (2 replications) were analyzed using two-way ANOVA (α=0.05) using OriginPro. The pH was measured following SNI 6989.11:2019 using a pH meter (HACH HQ11D, USA), while the TSS was determined according to SNI 6989.3:2019 using an oven (Binder ED53, Germany) and an analytical balance (Mettler Toledo AB204-S, Switzerland). COD was analyzed following SNI 6989.2:2019 using a thermo-reactor and UV–Vis spectrophotometer (HACH DR2800, USA), whereas BOD_5 and sulfide were measured according to SNI 6989.72:2009 and SNI 6989.70:2009, respectively, using a digital burette (Vitlab Continuous RS, Germany) and a magnetic stirrer (HI300N-1, USA). Additionally, color testing was performed using the Pt–cobalt (Pt-Co) method with a UV–Vis spectrophotometer (HACH DR2800, USA), and turbidity was measured with a turbidimeter (HACH 2100Q, USA).

2.4. Life Cycle Assessment

A cradle-to-grave LCA was conducted to evaluate the environmental impacts of the integrated vinasse treatment system using mass allocation and heat balance data from the system under development. The assessment followed the ISO 14040 and ISO 14044 standards, including (1) goal and scope definition, (2) life cycle inventory (LCI), (3) life cycle impact assessment (LCIA), and (4) interpretation stages. The functional unit was defined as the treatment of 1 L of treated water (1 kgTW). The inventory was developed based on pilot-scale experimental data; consequently, the results may not fully represent the environmental performance of a full-scale industrial system. The biogas was obtained from a previous Indonesian vinasse anaerobic treatment, consisting of 51.58% CH_4, 10.7% CO_2, and 1% CO, at a rate of 0.53 m^3 CH_4/kg COD·d (Harihastuti et al., 2021). Several assumptions were also applied, particularly for direct gas emissions, while all COD and BOD removed were transformed to CO_2 and H_2O (Appx A.1-A.2), in the worst scenario when Cl_2 was fully released into the environment (Appendix A.3), and biogas combustion was predicted through stoichiometric calculation (Appendix A.4). While sludge-to-fertilizer recovery was estimated from the chemical analysis results for solid organic fertilizer based on mass recovery (Table S1), its nutrient quality, agronomic effectiveness, heavy metal content, pathogen safety, and potential to substitute for commercial fertilizer have not yet been fully evaluated (Table S2). As shown in Figure 2, this study assessed four treatment scenarios under an operational system boundary, excluding the construction stage owing to limited pilot-scale construction inventory data and its expected minor contribution over the system lifetime. The sludge generated during the sedimentation stage was used to make the fertilizer. This study used Monte Carlo data simulation (10,000 iterations) for uncertainty analysis, and data quality was assessed using Ecoinvent to determine the standard deviation (Table S3) (Purba et al., 2026). The environmental impact category focused on global warming potential

(GWP), using the IPCC 2021 and ReCiPe midpoint (H) 2016 methods, and was assessed using SimaPro 9.6.

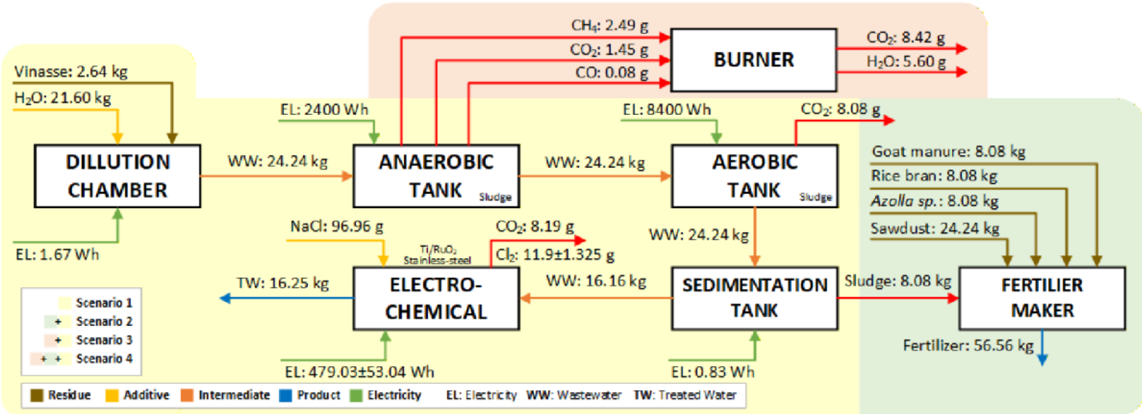

Figure 2. Study boundary for LCA analysis.

3. Result and Discussion

3.1. Characterization of Raw Vinasse Wastewater

Table 2 shows the exceptionally high pollution levels in raw vinasse, particularly in terms of organic load and suspended solids. As is characteristic of effluents from bioethanol distilleries, the wastewater was initially acidic (pH 4) and contained extremely high amounts of COD, BOD, TSS, and sulfide. The exceptionally high organic, suspended particle, and sulfur pollutant loads in raw vinasse and the requirement for rigorous treatment were confirmed by COD, BOD, TSS, and sulfide levels that exceeded the discharge limit.

Table 2. Physicochemical properties of raw vinasse wastewater

No	Parameter	Value		Standard*	Unit
		Mean	±(SD)		
1	TSS	30,075.50	24.50	100.0	mg/L
2	pH	4.00	0.00	6.0-9.0	-
3	COD	217,132.00	49,471.00	300.0	mg/L
4	BOD_5	51,699.00	7,281	100.0	mg/L
5	Sulfide	696.80	10.40	0.5	mg/L

*)based on Regulation of the Minister of Environment Number 5 of 2014 concerning Wastewater Quality Standards (KLH, 2014).

3.2. Evaluation of Integrated Treatment Performance

The integrated treatment system demonstrated a progressive and cooperative elimination pattern across the anaerobic, aerobic, sedimentation, and electrochemical phases (Figure 3). Biological treatment mainly eliminates biodegradable organic matter, sedimentation eliminates suspended and particle impurities, and electrochemical oxidation refines the effluent by utilizing hydroxyl radicals and reactive chlorine species to break down sulfur species and refractory organics. Overall, the combined techniques reduced COD, BOD, TSS, and sulfide by 97.9%, 99.0%, 93.6%, and 100%, respectively, while changing the pH from acidic to stable neutral–alkaline.

3.2.1. pH Level in Each Process Step

The integrated treatment system altered the acidity of the vinasse effluent through a sequence of anaerobic, aerobic, sedimentation, and electrochemical processes. Raw vinasse had a pH of 4.0, indicating considerable acidity, whereas diluted vinasse (10%vol) had a pH of 4.2. The presence of phenolic compounds and fatty acids generated during fermentation is what causes this characteristic acidity (Hosseini et al., 2025). pH rose to 7.2 during anaerobic treatment, indicating that acids were converted to CH_4 and CO_2, creating a natural buffer (de Oliveira et al., 2026). Similar studies indicate that pH increased from 3.5–5.0 to near-neutral due to methanogenesis and sulfate reduction (Mazaheri et al., 2024b, 2024a; Rogeri et al., 2024). The aerobic phase also increased pH to 8.2 via oxygenation, CO_2 stripping, and microbial activity (Jurczyk et al., 2020; Nie et al., 2023). The water remained within the neutral range, even though sedimentation lowered the pH to 7.7, likely because of biomass settling. The pH increased to 8.2 after electrochemical treatment owing to cathodic processes that produced hydroxyl ions. This creates more stable circumstances that are favorable for the elimination of pollutants. Similar trends observed in contemporary electrochemical systems have successfully balanced acidity and maintained wastewater at pH 7–8, reducing toxicity and corrosiveness (Alizadeh et al., 2023; Saavedra et al., 2024). The combined treatment lowered pollutants and improved wastewater stability and environmental safety.

3.2.2. COD Removal Performance

As shown in Figure 3a, the integrated treatment process achieved a 97.9% removal rate by reducing the COD from 14,534 mg/L in diluted vinasse to 307 mg/L after electrochemical polishing. By converting biodegradable organic matter into CH_4 and CO_2 through hydrolysis, acidogenesis, acetogenesis, and methanogenesis, the anaerobic stage facilitated the primary reduction, lowering COD to 5,574 mg/L (61.6% reduction) (de Oliveira et al., 2026). This removal was lower than the result reported for UASB treatment of synthetic vinasse at 80.4–88.4% (Mazaheri et al., 2024b, 2024a), likely due to the higher recalcitrant organic and sulfur content of real vinasse. The aerobic stage further decreased the COD to 1,147 mg/L, while sedimentation reduced it to 676 mg/L by removing the sludge-bound particulate organic matter. Finally, electrochemical oxidation reduced the effluent to 307 mg/L via hydroxyl radicals and reactive chlorine species generated by NaCl oxidation, thereby degrading melanoidins, phenolics, and persistent dissolved organics (CHEMetrics, 2022). The overall COD removal was comparable to recent electro-oxidation and multi-anaerobic vinasse systems, which reported 97.7% and 99.6% removal, respectively (Alizadeh et al., 2023; Mazaheri and Doosti, 2023), and higher than the 66% reported for a biological–electrochemical process (Vilar et al., 2018).

3.2.3. BOD Removal Performance

The BOD concentration decreased significantly during the treatment, from 4,126 mg/L in diluted vinasse to 43 mg/L after electrochemical treatment, indicating a 99.0% removal efficiency (Figure 3b). The anaerobic process reduced the BOD to 994 mg/L (75.9%), indicating effective microbial metabolism of biodegradable compounds. During anaerobic digestion, bacteria break down complex organic matter into volatile fatty acids, which methanogens then use to produce methane (Alipoursarbani et al., 2026). This reduction was brought about by the microbial breakdown of fermentation products, volatile fatty acids, and soluble carbohydrates (Chen et al., 2023). Identical anaerobic vinasse treatments removed 68–75% of BOD (Otieno and Apollo, 2021; Utami et al., 2016). This considerable decrease suggests that vinasse has a high biodegradable organic content, which qualifies it for microbial conversion and bioenergy production. By quickly oxidizing any remaining soluble organic matter, the aerobic step significantly decreased the BOD, removing 97.5% of it. By settling particle debris, sedimentation subsequently lowered the BOD to 94 mg/L. The final electrochemical step lowered the BOD to 43 mg/L, with a 99.0% overall removal, likely mineralizing the remaining organics into CO_2 and water via hydroxyl radicals and active chlorine. Previous studies reported 85% removal with electro-oxidation (Rajeswari et al., 2016), and the current system outperformed ozonation-assisted electrocoagulation by about 4% (Das et al., 2021), demonstrating the synergistic effect of biological, physical, and electrochemical treatments in eliminating the high-strength organics in vinasse wastewater.

3.2.4. TSS Removal Performance

The integrated treatment system reduced the TSS, with an overall removal efficiency of 93.6% (Figure 3c). During anaerobic treatment, TSS decreased to 570 mg/L due to biodegradation and partial settling of particles. Conversely, the aerobic stage increased TSS to 1,400 mg/L, attributed to intensive microbial proliferation, activated sludge formation, and the production of extracellular polymeric substances under elevated organic loads (Li et al., 2022). The same outcome was also reported in another study on textile wastewater (Lin et al., 2024). The sedimentation process then significantly reduced TSS to 150 mg/L through gravitational settling of flocs, reaching an 89.1% reduction. Moreover, the electrochemical treatment further reduced the load to 88 mg/L through electrocoagulation and particle destabilization induced by the electric field and reactive oxidizing species (ROS).

3.2.5. Sulfide Removal Performance

The dynamic behavior of sulfide removal throughout the treatment process is shown in Figure 3d, with variations resulting from complex sulfur transformations under integrated process conditions. At the outset, the sulfide concentrations increased by approximately 11% during anaerobic treatment. It primarily because sulfate-reducing bacteria converted sulfate and organic sulfur compounds into sulfide in oxygen-limited environments (Qiang et al., 2025; Viotti et al., 2024). Sulfide concentrations marginally decreased to 520 mg/L during the aerobic stage, suggesting minimal oxidation. This might be caused by sulfur emitted by decomposing biomass or by microzones inside thick flocs, where sulfate reduction continued. During sedimentation, a significant decrease was observed, with sulfide decreasing by 61.3%. Adsorption onto settling biomass is likely the cause of this decrease. The most efficient elimination method was electrochemical oxidation, which completely eliminated sulfide and rendered it undetectable. Sulfide was oxidized in this process by reactive chlorine species such as Cl_2, HOCl, and ClO^- and by direct anodic oxidation. Sulfide was transformed into elemental sulfur, thiosulfate, sulfite, or sulfate depending on the local environment (Figure 4) (Shao et al., 2022).

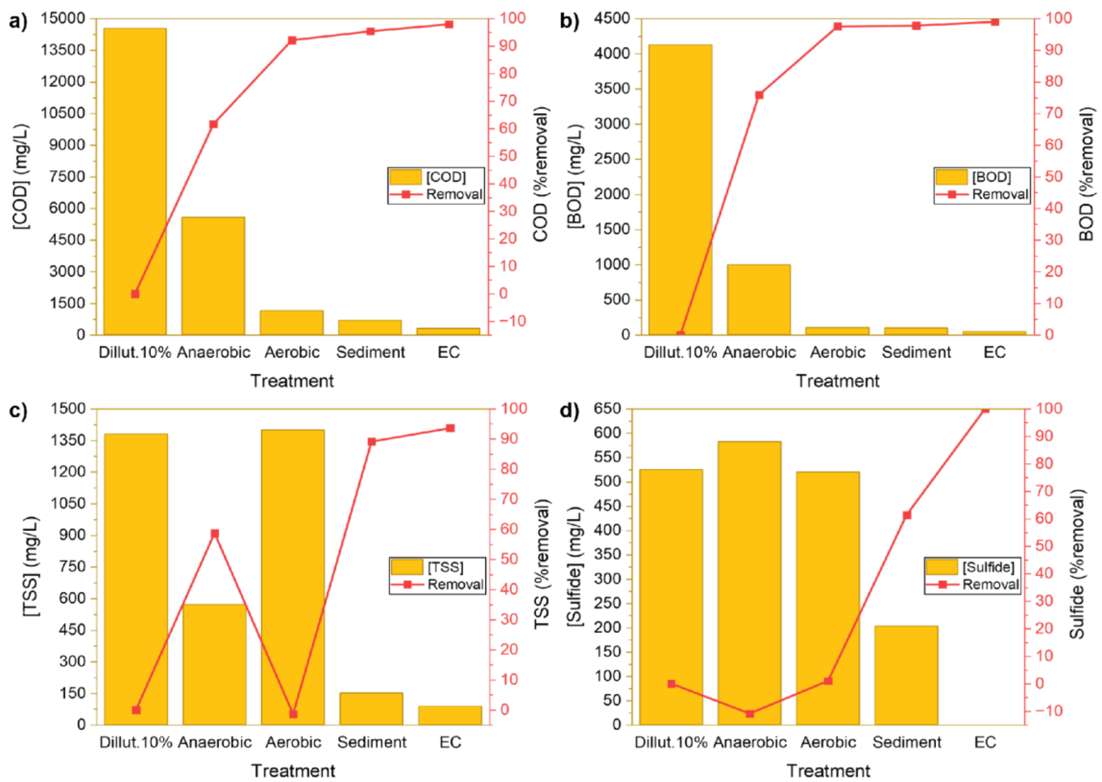

Figure 3. Physicochemical properties removal performance via the integrated process: a) COD, b) BOD, c) TSS, and d) sulfide

3.3. Effect of Electrolyte Strength on the Quality of Treated Water

The NaCl added as an electrolyte had a noticeable impact on the final treated water quality. As the NaCl concentration increased, the conductivity of the solution improved, supporting the generation of stronger oxidizing agents, including active chlorine species (Cl_2, HOCl, and ClO^-), which play an important role in the indirect oxidation of organics, as shown in Figure 4.

Among the tested conditions, 6 g/L NaCl offered the most favorable results. At this dosage, COD and BOD were reduced by 54.56% and 54.58%, respectively (Figure 5a–b). It also achieved the highest TSS removal (Figure 5c), significant color removal of 99.1% (Figure 5e), a 90.2% decrease in turbidity (Figure 5f), complete sulfide removal (Figure 5d), and a stable final pH of 8.24. In Table S4, the two-way ANOVA further confirmed that the electrochemical treatment response was significantly affected by the measured water-quality parameter and NaCl concentration with significant effects for parameter type ($F = 11{,}512.61$; $p < 0.0001$), NaCl concentration ($F = 45.99$; $p = 0.00023$), and their interaction ($F = 1{,}242.98$; $p < 0.0001$). COD, BOD, TSS, color, turbidity, sulfide, and pH reacted differently to variations in electrolyte strength, indicating that the effect of NaCl content was not consistent across all parameters. These results show that 6 g/L NaCl is effective in oxidizing organics and has an appropriate ionic strength for optimal oxidant production. Additionally, it has sufficient oxidant availability and conductivity without producing excessive side reactions or particle disturbance, resulting in the best-balanced treated water quality of all the evaluated circumstances. This condition reduced the treatment effectiveness and increased the effluent residuals and color. The procedure did not improve when the dose was increased to 8 g/L. Rather, it increased turbidity, TSS, BOD, and residual color while lowering the quality of the treated water. This decrease might be attributed to increased gas emissions, instability of the produced flocs, or undesired chloride-driven side reactions. Overall, the results show that an intermediate NaCl concentration offered the best balance between oxidation efficiency and final effluent quality (Alizadeh et al., 2023; Phan et al., 2023).

The SEC of the electrochemical process was estimated to be 332.72 ± 52.28 kWh/kg COD removed. The EE/O of the electrochemical oxidation process was estimated to be 35.74 ± 5.61 kWh/m^3 per order, with values ranging from 31.77 to 39.71 kWh/m^3 per order. This result indicates that approximately 35.74 kWh of electrical energy is required to achieve a one-order-of-magnitude reduction in the pollutant concentration per cubic meter of treated vinasse wastewater.

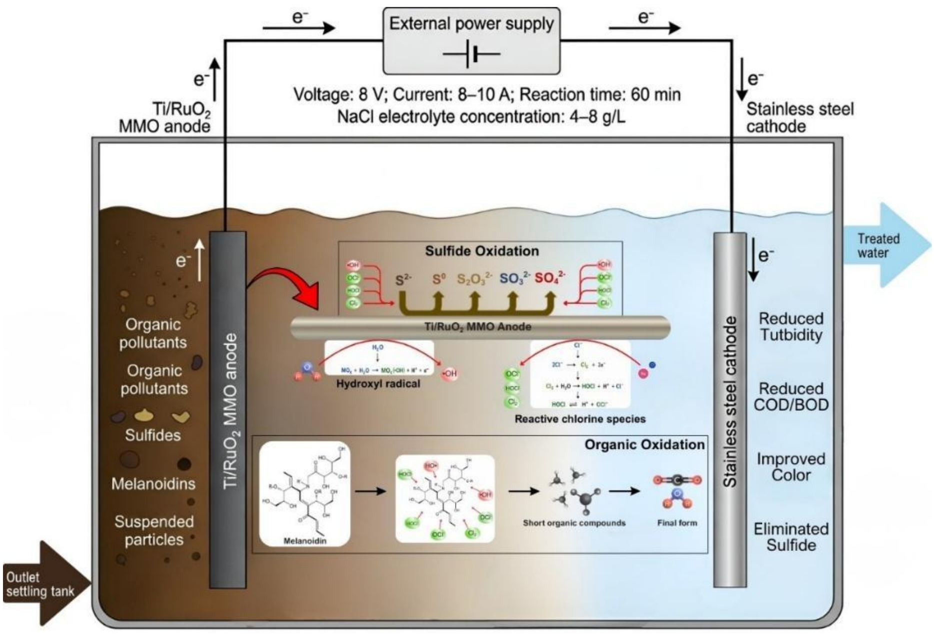

Figure 4. Sulfide and organic oxidation mechanisms in vinasse wastewater using Ti/RuO_2 anode and stainless-steel cathode.

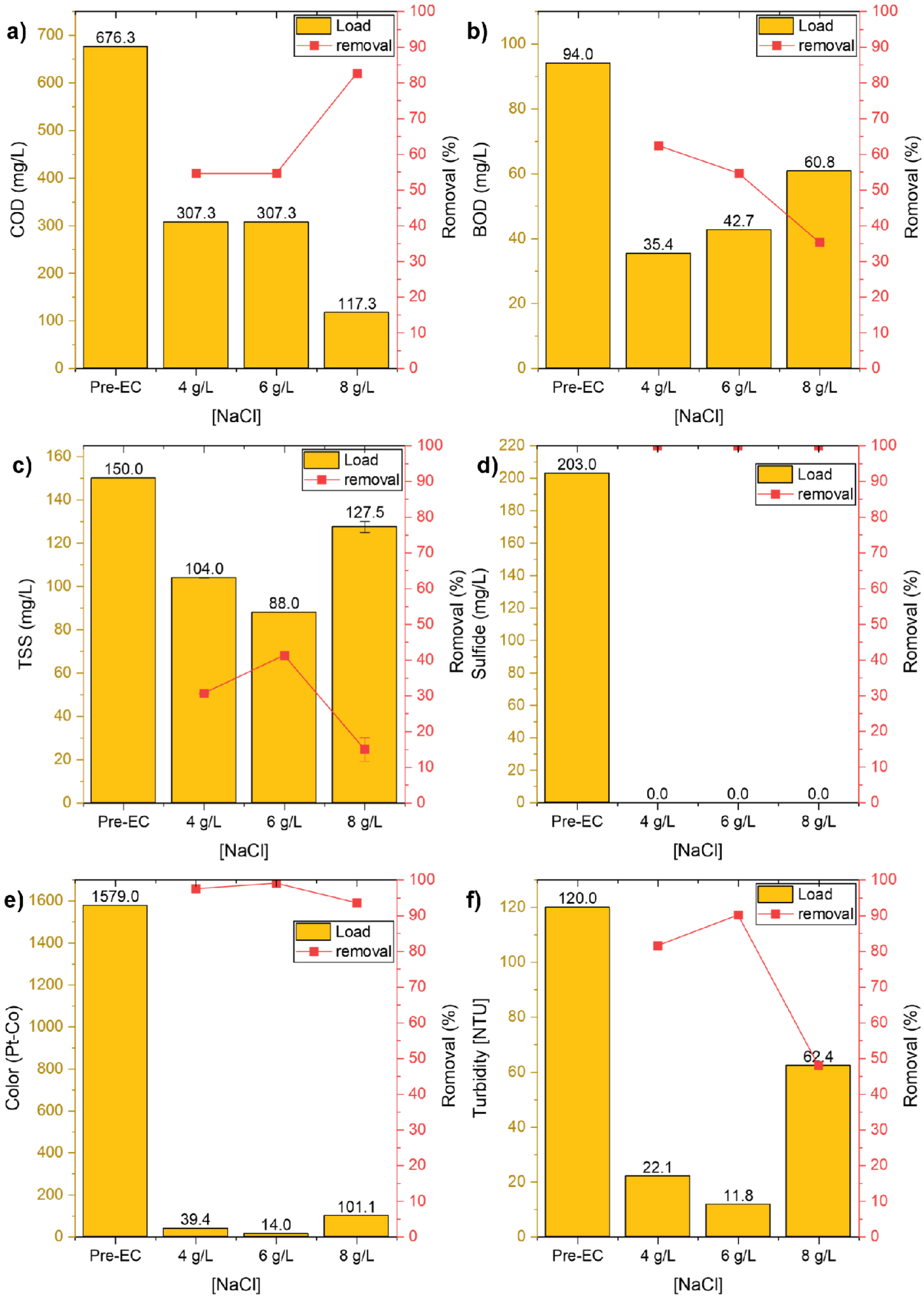

Figure 5. Effect of NaCl concentration on electrochemical treatment: a) COD, b) BOD, c) TSS, d) sulfide, e) color, and f) turbidity

3.4. Life cycle assessment

3.4.1. Life Cycle Inventory

The LCI of the integrated vinasse treatment system was developed by determining the material inputs, energy use, intermediate flows, direct emissions, and recovered products for each unit process within the defined boundary (Table S5). The inventory was carried out in batch mode to treat 2.64 kg of raw vinasse diluted with 21.60 kg of water, yielding 24.24 kg of diluted vinasse wastewater. The system boundary included the dilution chamber, anaerobic tank, burner, aerobic tank, settling tank, electrochemical reactor, and fertilizer production units. This allowed for the evaluation of the GWP contributions of electricity, biological emissions, chemical inputs, sludge management, and product recovery.

The anaerobic unit generated 2.49 g CH_4, 1.45 g CO_2, and 0.08 g CO gas emissions, which were combusted in the burner (efficiency = 45%) to produce 8.42 g CO_2 and 5.60 g H_2O, and consumed 2,400 Wh of electricity. The aerobic tank was the greatest energy consumer, consuming 8,400 Wh for aeration and emitting 8.08 g CO_2. The sedimentation process consumed only 0.83 Wh to separate 16.16 kg of wastewater for electrochemical polishing and 8.08 kg of sludge for the production of fertilizer. The electrochemical reactor consumed 479.03 ± 53.04 Wh to treat 16.25 kg of water and produced 8.19 g of CO_2 and 11.91 ± 3.25 g of Cl_2 using 96.96 g of NaCl. The recovered sludge was processed to produce 56.56 kg of organic fertilizer by mixing vinasse sludge, cattle manure, rice bran, *Azolla microphylla*, and sawdust in the ratio of 1:1:1:1:3. Because the fertilizer was mixed manually, no additional electricity was allocated to this step. Treated water and fertilizer were recorded as products, whereas substitution credits were applicable only under the avoided-burden or system-expansion approach.

3.4.2. Life Cycle Impact Assessment

The LCA results indicated that the four vinasse wastewater treatment scenarios had different environmental performances: S1 treated vinasse without biogas use or sludge recovery; S2 included sludge recovery for fertilizer production; S3 included biogas recovery; and S4 included both biogas and sludge recovery. S4 has the best environmental performance with the lowest overall climate change impact, followed by S2. Figure 6 illustrates the LCIA comparison according to the IPCC method, Table S6 summarizes the results according to the ReCiPe midpoint (H) method, and Table S7 tabulates the cumulative energy demand in this study. In contrast, the contribution of GWP was much higher for S1 and S3, showing that the lack of valorization of sludge and the additional operational requirements of biogas management in S3 limited the environmental benefits. The lower impact in S2 means that, according to the current inventory, the environmental benefit of converting sedimented vinasse sludge into organic fertilizer is higher than that of biogas recovery alone. This is largely because fertilizer production shifts the burden of waste disposal and encourages the circularity of resources without increasing electricity use compared to hand mixing. This trend is consistent with recent wastewater LCAs, in which resource recovery (e.g., valorization of sludge and energy substitution) can reduce environmental impacts. The coefficient of variation and standard error of the mean were relatively low, indicating low data dispersion and high measurement consistency (Table S8).

The LCA profile indicates that the environmental burden of the vinasse treatment system was primarily driven by the use of operational electricity. Figure 6 shows that the contribution of GWP was dominated by fossil-based carbon, with biogenic carbon being minor, which was associated with the high energy requirements for mixing, aeration, and electrochemical oxidant production such as •OH, Cl_2, HClO, and ClO^-. Hence, even if the system is very efficient at removing pollutants, its climate benefit strongly depends on the electricity source. This is in line with recent LCA studies of wastewaters that demonstrate that GWP is highly sensitive to energy demand, particularly for aerobic or activated sludge-based processes. Paulu et al. observed that coupling process modelling with LCA allows to identify unit-process hotspots, and found that the activated sludge process is a significant contributor to GWP due to electricity consumption and N_2O emissions (Paulu et al., 2021). Similarly, Viotti et al. emphasized that energy consumption is a critical hotspot in wastewater treatment LCA, particularly when biological emissions show limited variation across treatment scenarios (Viotti et al., 2024).

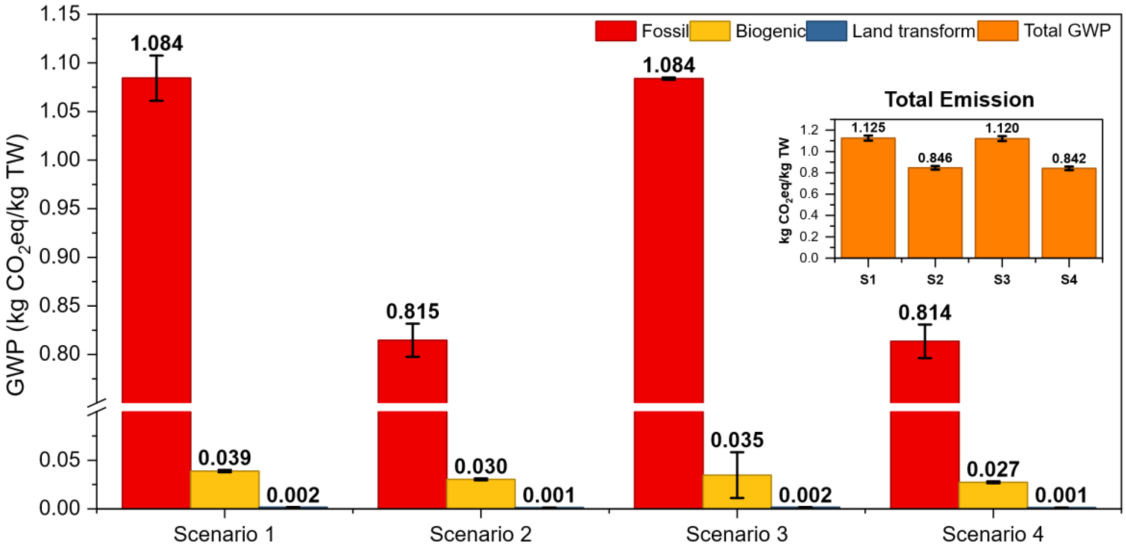

Figure 6. Global warming potential impact assessment of the system

The low contribution of residual materials indicates that sludge valorization and resource recovery can improve environmental impact but cannot fully compensate for high electricity use without renewable energy or biogas recovery. Anaerobic treatment generates biogas for combustion, and the sludge is converted into organic fertilizer by manually mixing cattle manure, rice bran, *A. microphylla*, and sawdust. These methods shift from waste treatment to resource creation processes. Recent studies have confirmed these findings. Kim and Criddle noted that anaerobic wastewater treatment reduces energy demand but requires post-treatment to recover methane and eliminate sulfide (Kim and Criddle, 2023). Karolinczak et al. found that anaerobic digestion and biogas recovery significantly cut the carbon footprint of wastewater treatment (Karolinczak et al., 2024). Vassalle et al. highlighted that bioenergy recovery improves global warming performance when it offsets external energy use (Vassalle et al., 2023).

Sensitivity analysis was chosen for electricity consumption as the main operational input in the LCI. According to Figure 7, the variation in electricity use by ±20% resulted in a change in the total GWP of approximately 15%, suggesting that the climate impact of the system is highly sensitive to the demand for energy and should be optimized by improving the tool's efficiency or using low-carbon electricity sources.

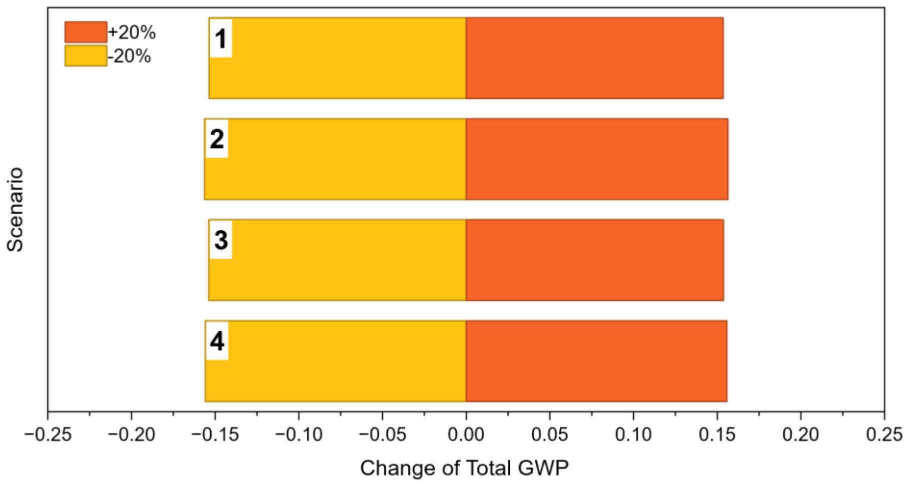

Figure 7. Sensitivity analysis of electricity consumption to GWP emission

3.4.3. Recommendations

Future system development should be oriented towards larger-scale sludge recovery and biogas efficiency to make S4 the most sustainable option. Nutrient analysis, safety, and performance should reinforce the fertilizer pathway, guaranteeing sludge valorization as a safe alternative to traditional fertilizers. The valorization of sludge for the recovery of carbon and nutrients is increasingly recognized, but careful assessment of product safety remains important. Methane losses undermine climate benefits, and future studies should address methane yield, burner efficiency, fuel savings, and leak detection. Aerobic and electrochemical units can be optimized by reducing aeration, improving oxygen transfer, adjusting the current and electrolytes, and using green electricity. Earlier, LCA also indicated that biomass use influences the ranking of recovery methods, highlighting the importance of scenario-specific analyses. In general, the integrated process reduces vinasse pollutants and promotes circular recovery. To ensure long-term sustainability, fossil-based electricity consumption must be minimized, fertilizer quality assessment must be developed (until the elementary stream source), and biogas efficiency must be improved.

4. Conclusions

The integrated vinasse wastewater treatment system by anaerobic digestion, aerobic oxidation, sedimentation, and electrochemical oxidation could efficiently decrease the main pollutant load in 10% diluted vinasse: COD from 14,534 to 307 mg/L (97.9% removal), BOD from 4,126 to 43 mg/L (99.0% removal), TSS from 1,380 to 88 mg/L (93.6% removal), sulfide from 525.2 mg/L to non-detectable level (100% removal), and improve the pH from 4.2 to 8.2, as demonstrated in this study. These findings suggest that combining biological, physical, and electrochemical treatments offers a highly effective approach for treating high-strength vinasse wastewater, which is characterized by high organic loading, suspended solids, and sulfur compounds. Based on the proposed LCI scenarios evaluated by Monte Carlo simulation (10,000 iterations), the median GWP results indicated that incorporating both sludge and biogas recovery reduced GWP emissions by approximately 25%, whereas biogas recovery alone reduced the GWP by only 0.44%. This suggests that sludge recovery has a greater potential to reduce the impacts of global warming. However, the environmental benefit of biogas recovery was limited by the relatively low methane yield assumed in the inventory, which reduced its capacity to substitute fossil-based energy. Future LCA work should therefore use full-scale operational data, expand the impact categories beyond GWP, conduct sensitivity analyses on the electricity mix and recovery efficiency, and verify the environmental credits from fertilizer and biogas utilization. In summary, this study shows that integrated treatment can overcome the limitations of single-stage treatments, and resource recovery is an essential strategy for improving the environmental performance of decentralized vinasse wastewater management.

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Ethics Statement

This study did not involve human participants, animals, or sensitive data; therefore, no ethical approval was required.

CRediT Author Statement

Agus Suprapto: Idea Development, Investigation, Software, Writing–original draft; **Prabang Setyono:** Formal Analysis, Supervision, Manuscript Review and Revision; **Jatmiko Wahyudi:** Result Verification, Formal Analysis; **Sajidan Sajidan:** Result Verification, Supervision, Manuscript Review and Revision.

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