

Effluent Quality Trends of a Vocational School WWTP (2021–2024) and Performance of a Mini Water Hyacinth Wetland as a Polishing Unit

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ARTICLE INFO

Keywords: Quality Trend, Performance of a Mini Water Hyacinth Wetland

Received : 27, December

Revised : 29, January

Accepted: 28, February

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ABSTRACT

This study evaluates whether effluent compliance also implies ecological safety in a vocational-school WWTP in Padang, Indonesia. We analyzed semester effluent data (2021–2024) and an influent–effluent snapshot (October 2025), then tested a mini water hyacinth wetland as a polishing unit (*Eichhornia crassipes*; 13 L; ~8-day HRT). Variables included pH, BOD, COD, NH₃-N, and selected metals. COD and BOD consistently met the national effluent standard, whereas pH showed episodic extremes. Snapshot removal was high for organics (BOD 98.9%; COD 90.4) but moderate for NH₃-N (47.1%) under acidic influent. The wetland raised pH and improved Fe/Cu removal yet increased COD and NH₃-N, indicating a need for better pH control, nitrification, and polishing design

INTRODUCTION

Wastewater management remains a core sustainability challenge because population growth and intensified activities increase pollutant loads while safe treatment coverage is still limited in many regions (Matesun & al., 2024; UNESCO, 2022; World Health Organization, 2023,2024). In the context of education facilities, improving wastewater management also supports SDG 6 and interacts with SDG 3, SDG 4, and SDG 12 through public health protection, safer learning environments, and responsible resource use (Ibrahim & Bayangkara, 2025; Nations, 2024; Wati & Jin, 2024).

Vocational chemical schools are a distinctive niche because laboratory wastewater is often low in volume but can be high in pollutant concentrations, including heavy metals, ammonia, solvents, and dissolved organics (Hicks & al., 2021; Novita et al., 2022). Such variability can trigger episodic pH shocks and metal spikes that challenge small-scale WWTP stability and may reduce biological process performance if neutralization and segregation are inadequate (Ahmad, 2016).

Natural solutions, such artificial wetlands, are widely investigated as low-cost and adaptable polishing units to complement conventional WWTPs, particularly for residual nutrients and metals (Domínguez-Solís et al., 2025; Kurniadie, 2018; Rahman & al., 2022). There have been reports of water hyacinth (*Eichhornia crassipes*) to support phytoremediation via plant uptake, adsorption, and rhizosphere-mediated transformations (Aqdas & Hashmi, 2023); Monroy-Licht et al., 2024 ; (Vymazal & Brezinova, 2018;Vymazal, 2010). However, evidence from school-scale systems that combines multi-year effluent trends with a mini wetland polishing test remains limited, especially for laboratory wastewater settings.

This paper contributes a practical, school-scale evaluation that links operational monitoring to a testable polishing intervention. Using semester-based effluent data (2021–2024) and a mini wetland experiment, we provide evidence on which parameters are stable, which are most vulnerable (e.g., pH shocks), and how a simple wetland configuration may improve—or inadvertently worsen—specific pollutants.

Accordingly, this study addresses two questions: how do the WWTP effluent quality trends during 2021–2024 compare with Indonesia’s effluent standard (Minister of Environment and Forestry Regulation No. 5 of 2014; Republic of Indonesia Ministry of Environment, 2014), and which parameters show the greatest instability; and to what extent can a mini water hyacinth wetland act as a polishing unit by stabilizing pH and improving the removal of selected pollutants in WWTP effluent ?.

THEORETICAL REVIEW

WWTP performance and compliance as an operational reliability framework

WWTP performance is commonly evaluated through effluent quality indicators (e.g., BOD, COD, pH, nutrients, and metals) and their consistency relative to regulatory limits. For biological treatment, stable pH is critical because rapid pH shifts can inhibit microbial activity and reduce nitrification performance (Kokina et al., 2022; Kemmou & Amanatidou., 2023). Acidic

conditions are particularly challenging for nitrifiers, contributing to lower ammonia removal efficiency Y. Li et al., 2018). From an asset-management perspective, monitoring multi-year trends helps identify reliability issues and operational weak points even when average compliance appears acceptable (Silva & Jo., 2022).

H1: The WWTP effluent quality during 2021–2024 complies with the national effluent standard (Minister of Environment and Forestry Regulation No. 5 of 2014; Republic of Indonesia Ministry of Environment, 2014) for major indicators, but shows episodic instability in pH and/or specific pollutants.

Constructed wetlands and phytoremediation as polishing units

Constructed wetlands integrate physical settling/filtration, adsorption, microbial degradation, and plant uptake. Water hyacinth can support metal removal and pH buffering through rhizosphere processes and biomass accumulation (Aqdas & Hashmi, 2023; Vymazal & Brezinova., 2018; Verma et al., 2017). Nevertheless, wetlands may also increase COD or ammonia if plant exudates and biomass decay contribute additional organic matter and nitrogen, especially under low dissolved oxygen conditions (Pelissari et al., 2018); Sedlacek et al., 2019; (Zhuang Lin-Lan a, 2019). Consequently, it is anticipated that a small wetland's efficacy as a polishing unit will depend on both design and parameter.

H2: A mini water hyacinth wetland installed as a polishing unit improves WWTP effluent quality by increasing pH toward neutrality and enhancing removal of selected metals and nutrients compared with WWTP effluent alone.

In accordance with the theoretical description and a number of previous research results, we created a conceptual framework that will be guided in this research as can be seen in Figure 1 below:

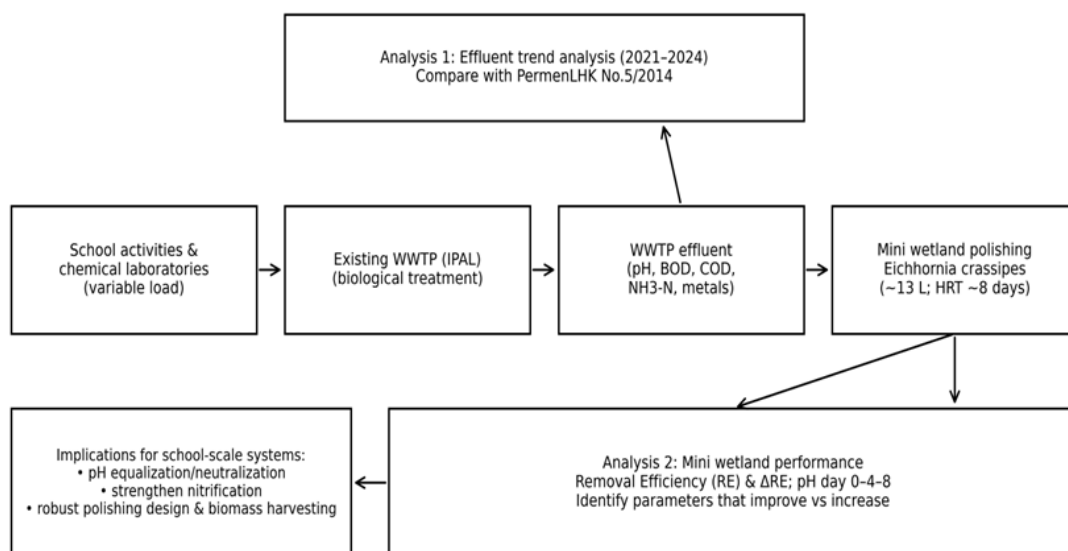


Figure 1. Conceptual Framework

METHODOLOGY

This study applied a quantitative descriptive–evaluative design. The population was the existing WWTP (IPAL) serving a vocational chemical school in Padang, Indonesia. Two datasets were used: (1) semester-based effluent monitoring records from 2021–2024 (secondary data from routine laboratory tests), and (2) primary measurements collected during the mini wetland experiment (inlet to WWTP, WWTP outlet, and wetland outlet).

Parameters included pH, BOD, COD, ammonia (NH₃-N), and heavy metals (Pb, Cd, Cr, Mn, Zn, Fe, Cu). The mini wetland was built in a ~13 L container (~37 × 15 × 28 cm) filled with 10 water hyacinth clumps (~160 g per clump). The system was worked with an approximate HRT, or hydraulic retention time of 8 days, following Verma et al. (2017). pH was measured at day 0, day 4, and day 8, while COD, BOD, NH₃-N, and metals were analyzed before and after treatment.

Removal Efficiency (RE) was calculated as: $RE (\%) = (C_{in} - C_{out}) / C_{in} \times 100\%$

For the 2021–2024 trend analysis, effluent concentrations were summarized and plotted across semesters and compared against the national effluent standard (Minister of Environment and Forestry Regulation No. 5 of 2014; Republic of Indonesia Ministry of Environment, 2014). For the assessment of wetlands, RE was computed for the WWTP alone, the wetland unit, and the combined system, and the incremental contribution of the wetland was expressed as ΔRE.

RESEARCH RESULTS

Effluent quality trends (2021–2024)

Table 1 summarizes semester-based effluent quality from 2021–2024 and compares it to Minister of Environment and Forestry Regulation No. 5 of 2014; Republic of Indonesia Ministry of Environment, 2014. Overall, organic indicators (COD and BOD) remained well below the effluent limits across the monitoring periods, indicating stable organic-load control. In contrast, pH exhibited an extreme acidic event (pH 4.15 in 2023.1), highlighting vulnerability to laboratory discharges and the need for stronger pH equalization.

Table 1. Summary of WWTP effluent quality (2021–2024) compared with Minister of Environment and Forestry Regulation No. 5 of 2014; Republic of Indonesia Ministry of Environment, 2014.

N o	Parameter	Satuan	2021. 1	2021. 2	2022. 1	2022. 2	2023. 1	2023. 2	202 4 *	202 4.2	ST D
1	COD	Mg/ L	38.40	21.60	19.50	9.74	46.40	19.10	19. 46	12.9 0	10 0
2	BOD	Mg/ L	13.40	13.10	8.73	3.33	20.10	10.70	7.8 8	6.80	50
3	pH		9.23	8.82	7.31	7.58	4.15	6.05	8	6.89	6-9
4	Amoni ak	Mg/ L	-	-	-	0.410 0	0.330 0	0.042 0	0	5.7	5

5	TSS	Mg/L	-	-	-	1.02	10.4	1.44	0	2.46	100
6	Fe	Mg/L	0.951	1.470	0.078	0.106	1.210	0.277	-	-	5
7	Pb	Mg/L	<0.1	<0.1	<0.1	<0.1	0.178	<0.1	-	-	0.1
8	Mn	Mg/L	0.061	0.020	<0.0	0.108	0.277	0.394	-	-	2
9	Cd	Mg/L	<0.0	<0.0	<0.0	<0.0	<0.0	<0.0	-	-	0.0
10	Cr	Mg/L	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	-	-	0.5
11	Zn	mg/L	0.099	0.098	<0.0	0.247	0.593	0.314	-	-	5

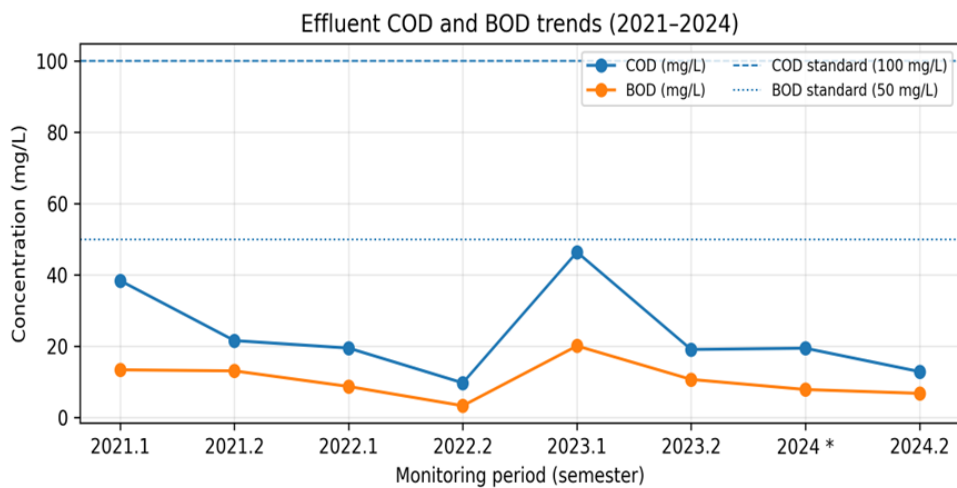


Figure 2. COD and BOD effluent trends (2021–2024) compared with national effluent standards.

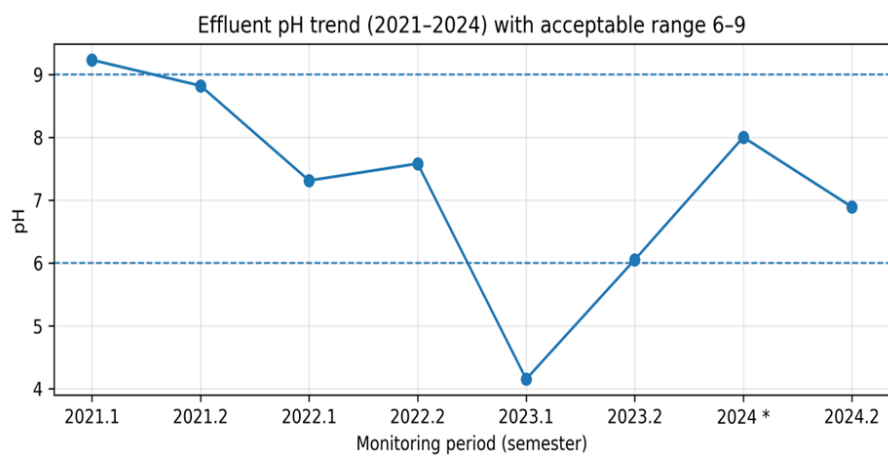


Figure 3. Effluent pH trends (2021–2024) compared with the acceptable range (6–9).

Mini Water Hyacinth Wetland Polishing Performance

Table 2 presents the comparison between the WWTP inlet, WWTP outlet, and the mini wetland outlet, including removal efficiencies (RE) and Δ RE. At the tested scale, the wetland increased pH from 5.4 to 6.5 (day 4) and 6.7 (day 8), approaching neutrality. The wetland improved the overall removal of Fe and Cu (Δ RE +15% and +16%, respectively). However, COD, NH₃-N, Mn, and Zn increased after the wetland, indicating that the polishing unit was not yet stable for organic matter and nitrogen under the applied configuration.

Table 2. Comparison of WWTP Outlet vs Mini Wetland Outlet And Performance Changes (Δ RE)

Parameter	Inlet IPAL (mg/L)	Outlet IPAL (mg/L)	Outlet Wetland (mg/L)	RE IPAL (%)	RE Wetland Only (%)	RE Total (%)	Δ RE (%)
Cd	0.0474	0.0088	< 0.0070	81	20	85	+4
Fe	14.14	2.7356	0.6525	80	76	95	+15
Mn	0.4540	0.2537	1.1705	44	Negatif	Negatif	Negatif
Cu	1.6484	0.3916	0.1326	76	66	92	+16
Zn	0.3633	0.1125	0.6831	69	Negatif	Negatif	Negatif
Pb	0.1300	< 0.1	< 0.1	23	0	23	0
Cr	0.0964	<0.0600	<0.0600	37	0	38	+1
BOD	92.7	1.00	1.85	98.92	-85	98	-1
COD	206.53	19.91	55.51	90.36	-179	73	-17
Amonia	7.01	3.71	11.27	47	Negatif	Negatif	Negatif
pH	5.4	5.4	6.5 (hari-4); 6.7 (hari-8)	Meningkat	Terpenuhi		

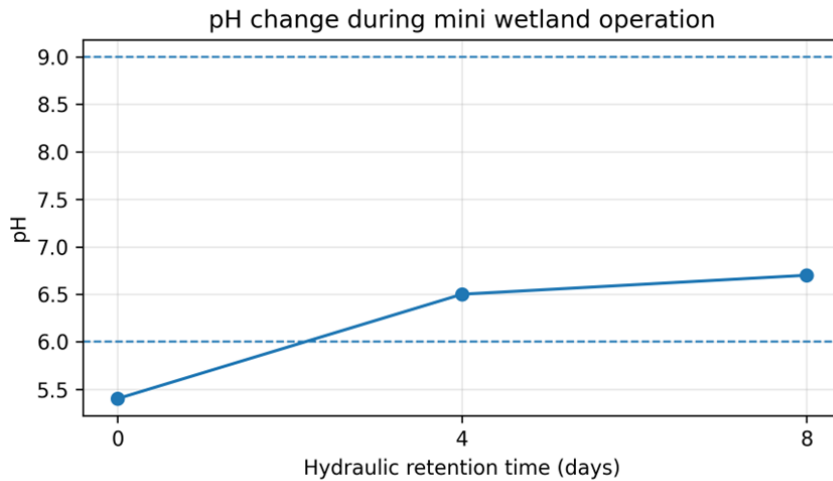


Figure 4. pH change during mini wetland operation (day 0–4–8).

DISCUSSION

The multi-year monitoring indicates that the school WWTP was effective in controlling organic pollution, as shown by consistently low COD and BOD levels. Such performance is consistent with properly operated biological treatment where oxygen supply and process stability support organic degradation (American Public Health Association, 2017; Metcalf & Eddy, 2014). Nonetheless, the observed pH shock demonstrates a critical operational risk for school-based systems that receive laboratory wastewater. Rapid pH changes can destabilize activated sludge communities and suppress nitrification, which explains why ammonia control is often more sensitive than BOD/COD removal in variable influent conditions (Kokina et al., 2022; Y. Li et al., 2018).

The mini water hyacinth wetland showed clear potential as a polishing step for pH stabilization and for removing certain metals, particularly Fe and Cu. These improvements can be linked to adsorption and precipitation on surfaces, absorption of plants, and rhizosphere-mediated transformations (Aqdas & Hashmi., 2023; Vymazal & Brezinova, 2018; Verma et al., 2017; Vymazal., 2010). However, increases in COD and NH₃-N suggest that plant biomass and root exudates may add organic matter, while nitrogen mineralization and limited nitrification (due to low dissolved oxygen) can elevate ammonia (Pelissari et al., 2018); Sedlacek et al., 2019; Zhuang Lin-Lan a., 2019). Therefore, the design of the wetland (media, aeration, HRT, and biomass harvesting) must be optimized to achieve stable polishing performance rather than relying on plants alone.

CONCLUSIONS AND RECOMMENDATIONS

The 2021–2024 effluent trend analysis shows that COD and BOD consistently met the national effluent standard, indicating reliable organic-load treatment, while pH exhibited episodic extremes that represent a key weakness of the system. The mini water hyacinth wetland improved pH toward neutrality and enhanced overall removal of Fe and Cu, but increased COD and NH₃-N at the tested scale, meaning that polishing performance was parameter-specific and not yet stable. For school-scale applications, the WWTP should prioritize pH equalization/neutralization upstream of biological units, strengthen nitrification (e.g., aeration and operational control), and redesign the wetland with appropriate media and planned biomass harvesting to prevent pollutant release.

This study relied on routine semester monitoring and a single wetland trial; therefore, results may not capture all seasonal and operational variability. Future work should include repeated wetland runs, longer monitoring horizons, dissolved oxygen profiling, and alternative wetland configurations (e.g., hybrid systems with media and staged aerobic–anoxic zones) to stabilize COD and nitrogen removal and to quantify performance uncertainty.

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