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Suitability of Characteristic Wastewater Treatment Technologies: An Approach to Water Environment Protection in Major River Basins in the Former Binh Thuan Province, Vietnam

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ABSTRACT

In 2025, Binh Thuan Province was merged into Lam Dong Province as part of a broader restructuring initiative by the Vietnamese government. In the former Binh Thuan Province, Vietnam, increasing pollution pressure in river basins (where wastewater is received) requires identifying and applying wastewater treatment technologies suitable to the actual situation of the wastewater sources. This study conducted a multi-criteria analysis (MCA) combined with the weighted sum method and visualized through radar charts to assess the suitability of treatment technologies, identify operational incidents, evaluate impact levels and prioritize rehabilitation of wastewater treatment systems (WWTSs) currently applied to five typical wastewater types: domestic, industrial, seafood processing, livestock and hospital wastewater. A set of criteria comprising 22 sub-criteria in four groups (technical, environmental, economic, social) is applied and the criteria are quantified based on field surveys and expert consultations. Results showed that domestic WWTS achieved the highest score (75/100) reflecting stable performance and a high level of suitability, while seafood processing WWTS scored lowest (50.625/100) due to high costs and unstable efficiency. Industrial WWTS (68.125/100), livestock WWTS (64.375/100) and hospital WWTS (68.75/100) systems performed moderately, with good technical outcomes but constraints in cost, energy use and emissions. Recurrent incidents such as aeration failures, sludge flotation and odor generation were common, though generally remediable. Seafood processing and industrial WWTS were prioritized for urgent rehabilitation. This study provides essential data and a practical MCA-based decision-support framework to improve existing WWTSs under local environmental and operational conditions, thereby supporting water resource protection in Vietnam's river basins.

HIGHLIGHTS

- First MCA framework applied to wastewater treatment technologies in Binh Thuan Province.
- Novel set of 22 sub-criteria integrating four sustainability dimensions.
- Five typical wastewater types were evaluated for current treatment technology suitability.
- Proposed technical fixes prioritized high-risk but feasible interventions.

1. INTRODUCTION

The former Binh Thuan Province (now part of Lam Dong Province) is located in the southern part of the South-Central Coast of Vietnam. It consists of 88 river basins, seven of which are classified as major basins: the Long Song, Luy, Cai Phan Thiet, Ca Ty, Phan, Dinh and La Nga rivers. These rivers collectively drain a basin area of more than 5,000 km² and flow through industrial and residential areas of the province (Huynh et al., 2024; Binh Thuan Statistics

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Office, 2024). They are also the places that receive the wastewater stream generated across the region. The results of the load-carrying capacity calculations of major river basins in the former Binh Thuan Province during the 2022-2023 period indicate that surface water has been primarily polluted by organic matter (COD, BOD_5) and nutrients (NH_4^+, NO_3^-, PO_4^{3-}). Most river basins have exceeded their carrying capacity for the analyzed parameters (Huynh et al., 2023; Huynh et al., 2025).

A distinctive characteristic of the former Binh Thuan Province is that a large number of wastewater sources discharge less than 10 m³/day and are widely distributed. They primarily consist of five types of sources: domestic, centralized industrial zones, livestock, seafood processing and hospital wastewater. Many studies indicate that these wastewater sources are typically characterized by high loads of organic matter, nutrients and pathogens, with BOD, COD, TSS, and TN levels often exceeding standards (Burton and Turner, 2003; Verlicchi et al., 2010; Muthukumaran and Baskaran, 2013; Tchobanoglous et al., 2014). If untreated or inadequately treated, such wastewater contributes to ecological degradation, oxygen depletion, odor generation and the spread of pathogens, thereby posing serious environmental and public health risks (Ortigara and Connor, 2017; Jordan and Eaton, 2024).

Although investment in wastewater treatment has increased in the former Binh Thuan Province, field investigations reveal that many treatment facilities still do not comply with national standards, highlighting the need to reassess the suitability of existing treatment technologies. Environmental researchers argue that a technology aligned with the principles of sustainable development should be characterized by the lowest possible costs (both capital and operational), technical and legal feasibility, proven effectiveness in pollution control and acceptance by the local community (Ferguson et al., 2003). Thus, an appropriate technology does not necessarily have to be the most advanced or expensive option, it should be capable of reaching discharge standards while being well-adapted to the local natural, economic and social conditions. In practice, such multidimensional factors are often insufficiently considered in Vietnam, resulting in suboptimal technology selection and inefficient resource use. Meanwhile, many studies have shown that sustainable development is built on four essential aspects: technical, economic, environmental and social (Omran et al., 2021).

Multi-Criteria Analysis (MCA), also referred to as Multi-Criteria Decision Analysis (MCDA) is a systematic methodology that combines the hierarchical structures of a problem with priorities for alternatives in many fields (Akdogan and Guven, 2023). In the environmental field, the integration of these criteria through MCDA methods has become a widely adopted tool in wastewater management and the selection of appropriate treatment options (Plakas et al., 2016; Lizot et al., 2021; Ko et al., 2024). In recent studies, notably in China, Multi-Dimensional Comprehensive Assessment (MDCA) represents a specific extension of MCDA that explicitly integrates environmental, economic, social and technical dimensions for sustainability-oriented evaluations. To guide the selection of wastewater treatment technologies in a scientific and rational manner, it is necessary to apply technology assessment methods based on MCDA approaches, including the MDCA framework. Establishing an MDCA framework with a sustainability-based approach is essential to identify potential technologies, as it begins with defining and scoring indicators, assigning weights, selecting appropriate evaluation models, conducting uncertainty analysis and ultimately determining preferred alternatives (Li et al., 2023).

In view of the above situation, this study conducted a multi-criteria analysis (MCA) to evaluate the suitability of existing wastewater treatment technologies for typical wastewater types in the former Binh Thuan Province. In Vietnam, a case study applying MCA methods has also been conducted, in which life cycle assessment (LCA) was integrated to select sustainable wastewater treatment scenarios for Toan Thang Town in Vietnam (Pham et al., 2010). However, that study was limited to the proposal of hypothetical scenarios. In fact, MCA-based studies in Vietnam remain very limited, with only a few applications and a lack of validation using real treatment systems. The present study focuses on real wastewater treatment systems in the former Binh Thuan Province, aiming to identify optimal solutions adapted to wastewater characteristics and local conditions. The goal was to improve existing treatment facilities, enhance effluent quality, minimize secondary pollution risks to receiving waters and support sustainable water resource management in this area.

2. METHODOLOGY

2.1 Study area

The study was conducted across seven major river basins stretching from the north to the south of the former Binh Thuan Province (Figure 1), covering a total catchment area of about 6,890 km², which represents nearly the entire provincial territory.

The former Binh Thuan Province, located in the south-central coastal region of Vietnam, covers a total area of 7,943.93 km², with geographical coordinates from 10°33'42" to 11°33'18" N latitude and from 107°23'41" to 108°52'42" E longitude (Binh Thuan Statistics Office, 2024). The study area has a tropical monsoon climate with two distinct seasons: a rainy season from May to November and a dry season from December to April. Annual rainfall varies considerably, ranging from 2,000-2,564 mm in the northwest and 1,400-1,600 mm in the south to only 730-1,110 mm in the northeastern and central regions (Binh Thuan DoNRE, 2020).

Figure 1. Study area location

2.2 Survey and data collection methods

2.2.1 Characterization survey of typical wastewater types

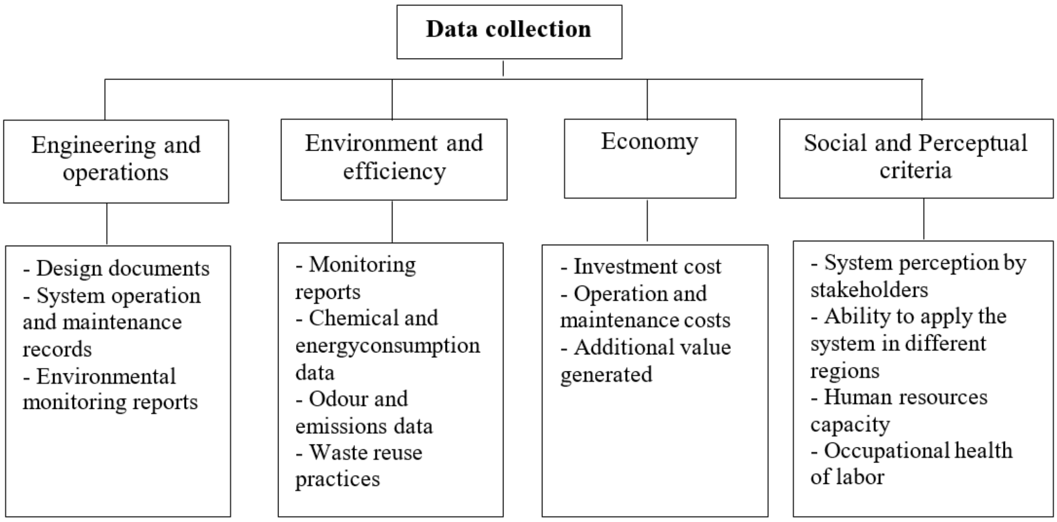
The wastewater sources were surveyed by river basin at the former Binh Thuan Province for the first time, including information on generation sources, the number of wastewater-generating facilities, discharge locations, total discharge volume and wastewater composition characteristics. The data were collected and classified into five major types of wastewater: domestic, centralized industrial zone, seafood processing, livestock and hospital wastewater.

2.2.2 Survey of wastewater treatment processes

The survey was conducted at wastewater-generating facilities in the former Binh Thuan Province. The study focused on assessing treatment technologies and system performance in removing typical pollution parameters (pH, Temperature, TSS, Turbidity, Color, BOD_5, COD, NH_4-N, Total N, Total P, PO_4-P, Oil and grease compounds, Total surfactants, Residual chlorine, Coliforms) in accordance with MoNRE (2008), MoNRE (2010), MoNRE (2011), MoNRE (2015), and MoNRE (2016) as well as evaluating operating conditions, treatment status and environmental monitoring practices.

2.2.3 Investigation and data collection of WWTSs

In order to establish a basis for developing a set of criteria for assessing technology suitability, the study combined multiple data sources derived from the results of actual investigations and surveys. The collected data includes:



2.3 MCA method for assessing the suitability of wastewater treatment technologies

2.3.1 Structured interviewing method

The interviewees included environmental experts. The sample size was calculated for expert interviews will be calculated using the following formula (Yamane, 1967):

$$n = \frac{N}{1+N(e)^2} \qquad (1)$$

Where; n is the sample size, N is the population size, and e is allowance for inaccuracy (5%).

2.3.2 Identification and quantification method for criteria groups

The assessment of the suitability of wastewater treatment technologies was carried out using an MCA framework, including four main criteria groups: technical (A), environmental (B), economic (C) and social (D) with a total of 22 sub-criteria (Table 1) as suggested by VEA (2011) and Li et al. (2023) (except for cost-related sub-criteria, which were determined based on actual costs at the time of the study).

2.3.2.1 Assign weights to criteria groups

The weights of the criteria groups were determined based on expert opinions combined with actual conditions at wastewater treatment plants. The technical and environmental criteria groups were considered the most important, with each assigned a weight of 0.3. The economic and social criteria groups were assessed as having a lower level of importance, with each assigned a weight of 0.2. The total weight of the four criteria groups equals 1.

2.3.2.2 Scoring method

The overall evaluation score was normalized to a 100-point scale, in which the score for each main criteria group (A, B, C, D) was calculated as the sum of the scores of its corresponding sub-criteria (formula 2) (VEA, 2011).

$$A = \sum_{i=1}^{n} A_i \quad B = \sum_{j=1}^{n} B_j \quad C = \sum_{p=1}^{n} C_p \quad D = \sum_{q=1}^{n} D_q \qquad (2)$$

When; A + B + C + D =100

Where; A_i, B_j, C_p, and D_q are the scores of the sub-criteria within each corresponding criteria group, and n is the number of sub-criteria belonging to each criteria group. Each sub-criterion score was calculated using Formula 3.

$$B_j = c_j \times w_j \qquad (3)$$

Where; c_j is the score of the sub-sub-criterion within the j-th sub-criterion, and w_j is the weight of the main criterion group containing the sub-criterion.

The scoring of a sub-sub-criterion (c_j) depends on the ranking of its relative importance. Within the same sub-criterion, if all sub-sub-criteria are of equal importance, the evaluation score assigned to each is identical and equal to $\overline{X}$ (the average score of the sub-subcriteria). Conversely, if the sub-sub-criteria are ranked, the scores are assigned in descending order of importance, as follows:

$$c_j = (m - r) \times \overline{X} \qquad (4)$$

Where; m is the total number of sub-sub criteria, r is rank of the sub-sub-criterion (r=1 indicates the highest importance) and $\overline{X}$ is the average score of the sub-sub-criteria.

Table 1. Set of construction criteria to assess the suitability of wastewater treatment technology

Group	Code	Criteria	Sub-Criteria
Technical	TC1	Treatment efficiency of the technology	pH, BOD, COD, TSS, Coliform
	TC2	Treatment efficiency of the technology under abnormal operating conditions	Pump failure, oxygen deficiency, valve misoperation, nutrient/microbial imbalance Note: The impact of various incidents on the treatment efficiency of the technology is regarded as equivalent.
	TC3	Frequency of system maintenance and servicing	2 times/month, 1 time/month, 1 time/2 months, 1 time/3 months
	TC4	Service life and structural/equipment durability	Repairs: >5 years, >3 years, >1 year
	TC5	Availability and ease of replacement for spare parts and equipment	Equipment and components available locally; Equipment and components not available locally (but available in Vietnam); Equipment and components must be imported.
	TC6	Compatibility of wastewater treatment technology with workers' technical proficiency	Highly suitable, Suitable, Not suitable
	TC7	Impact of system incidents or malfunctions on treatment performance	Uncontrolled exceedance to No impact
Environmental	TC8	Potential for the reuse of secondary outputs (e.g., biogas, organic sludge)	None, Partial, Full
	TC9	Chemical consumption in wastewater treatment (kg/m³/day)	From <0.3 to >0.5 m³/day
	TC10	Energy consumption (kWh/m³ of wastewater)	From <0.5 to >1.5 KWh/m³
	TC11	Noise impact on system operators and surrounding communities	Significant without control to no impact
	TC12	Probability of environmental incidents (e.g., chemical spills, wastewater or sludge discharge into the environment)	From >4 times/year to no cases/year
	TC13	Pollutant emissions into soil, water and air	No pollutant emissions, Gases, Secondary emissions
Economic	TC14	Capital cost for construction and equipment installation (VND/m³ of wastewater)	From <10 million to >15 million VND/m³
	TC15	Operating cost of the system (VND/m³ of wastewater)	From <2,000 to >8,000 VND/m³
	TC16	Treatment cost of wastewater (VND/m³)	From <4,000 to >15,000 VND/m³
	TC17	System maintenance cost (including microbiological, equipment, electrical and aeration components)	From <8 million to >15 million VND/year
	TC18	Revenue potential from secondary outputs of the wastewater treatment system	Yes, No
Social	TC19	Aesthetic and visual aspects of the system	From not suitable to very suitable
	TC20	Adaptability to regional conditions (e.g., climate, weather)	From site-specific to universal
	TC21	Primary sources of human resources for system management and operation	Experienced workers, engineers and environmental engineers
	TC22	Health impacts on system operators	From significant to none

Note: "TC"- sub-criteria, "VND"- Vietnamese Dong (currency of Vietnam) (IPCC, 2006; MoNRE, 2008; MoNRE, 2010; MoNRE, 2011; VEA, 2011; GoV, 2014; MoNRE, 2015; MoNRE, 2016; GoV, 2020)

2.3.3 Weighted sum method combined with radar chart

The simple additive weighting method (SAW) is one of the most popular multi-criteria decision-making techniques due to its simplicity and efficiency in processing quantitative data (Ayyıldız and Özçelik, 2018). In this study, the SAW method was applied to evaluate and determine the level of impact of technical incidents in wastewater treatment systems. The method is based on the principle of weighted aggregation of independent criteria and allows the quantification of the severity of each incident.

Survey data were collected for five types of wastewater in the former Binh Thuan Province. Assessments were standardized in quantitative form through five level (1-5) or three level (1-3) rating scales depending on the specific criterion, including the level of impact of the incident (5=very severe to 1=very minor), the priority of improvement (5=unnecessary to 1=mandatory rehabilitation) and consensus regarding the solution (3=disagree to

1=agree). The average score at each rating level was calculated according to Formula 5. The final results were visually presented using a spider diagram to clarify the level of impact and priority of improvement of incidents.

$$A = \frac{\sum a_i}{N} \quad (5)$$

Where; A is the average score of each factor, a_i is rating score ($a_i = i \times n$), i is rating value of level i (ranging from 1 to 5 or 1 to 3), n is the rating frequency for each level, and N is total number of evaluation responses.

3. RESULTS AND DISCUSSION

3.1 Characteristics of typical wastewater types

3.1.1 Characteristic composition of wastewater sources

The ranges of wastewater quality parameters recorded during the study period are presented in Table 2, where considerable variability is observed across different wastewater sources.

Table 2 presents the characteristic composition of five typical wastewater types in the former Binh Thuan Province. Domestic wastewater generally matched reported ranges (Tchobanoglous et al., 2014), though with slightly lower NH_4-N concentrations. Industrial effluents exhibited very high organic loads (BOD_5 up to 1,156 mg/L; COD up to 3,200 mg/L) and contained oil, grease and surfactants, reflecting their complex composition (Lam et al., 2014). Seafood processing wastewater showed moderate pollution levels compared to previous studies (Muthukumaran and Baskaran, 2013; Vidya et al., 2020), but elevated residual chlorine concentrations (approximately 130 mg/L) posed risks of aquatic toxicity. Livestock wastewater contained extremely high organic concentrations (BOD_5 up to 8,900 mg/L; COD up to 12,000 mg/L), nearly twice the typical ranges reported elsewhere (Burton and Turner, 2003; Chastain and Vanotti, 2003). Hospital wastewater presented hazardous loads of organics, nutrients and pathogens, comparable to the findings of Verlicchi et al. (2010), with coliform counts up to 10^7 MPN/100 mL.

Overall, these findings highlight heterogeneous and often severe pollution levels, emphasizing the need for appropriate treatment technologies and management measures.

3.1.2 Characteristics of wastewater treatment systems

Each of the five representative wastewater types in the former Binh Thuan Province is subject to specific treatment processes, as shown in Figure 5. Although the processes differ in technology, they all employ a combined treatment approach consisting of mechanical, biological and physicochemical methods.

Table 2. Characteristics of wastewater types in the former Binh Thuan Province

No.	Parameter	Unit	Domestic wastewater	Industrial zone wastewater	Seafood processing wastewater	Livestock wastewater	Hospital wastewater
			Range				
1	pH	-	7.52-8.01	6.5-8.0	5.99-6.51	6.1-7.9	4-10
2	Temperature	(°C)	-	28.5-32.0	-	-	-
3	TSS	mg/L	156-205	484-512	440-490	680-1,200	75-250
4	Turbidity	NTU	-	-	-	420-550	-
5	Color	Pt-Co	-	-	-	350-870	-
6	BOD_5	mg/L	156-173	925-1,156	768-816	3,500-8,900	120-200
7	COD	mg/L	328-368	2,420-3,200	1,319-1,581	5,000-12,000	150-250
8	NH_4-N	mg/L	13.6-14.5	55.6-78.2	67.2	-	80-120
9	Total N	mg/L	-	168-172	105-151.9	220-460	50-90
10	Total P	mg/L	-	-	-	36-72	-
11	PO_4-P	mg/L	3.53-4.21	-	-	-	-
12	Oil and grease compounds	mg/L	6.45-8.36	-	123.1-143.8	-	-
13	Total surfactants	mg/L	3.57-4.69	-	-	5-58	-
14	Residual chlorine	mg/L	-	-	129.7-132.6	-	-
15	Coliforms	MPN/100 mL	$21\text{-}95\times10^5$	9×10^3	15×10^4 - 46×10^5	14×10^3	$10^5\text{-}10^7$

Note: "-" Undetermined

The survey revealed that wastewaters is conveyed to a receiving sump or equalization tank to stabilize flow and quality prior to subsequent treatment in the preliminary stage. Biological processes, including aerobic (aerotank), anoxic and anaerobic (UASB-Upflow Anaerobic Sludge Blanket, biogas) systems, are strategically integrated to facilitate the removal of organic matter and nutrients (N, P). For high-strength wastewater streams, such as those from livestock operations and seafood processing, coagulation-flocculation, flotation and physicochemical sedimentation are incorporated. In addition, the treatment processes include disinfection and sludge management.

The quality of treated effluent in all treatment systems is required to comply with the permissible limits specified in the relevant national technical regulations, including QCVN 14:2008/BTNMT (domestic wastewater), QCVN 40:2011/BTNMT (industrial wastewater), QCVN 11-MT:2015/BTNMT (seafood processing wastewater), QCVN 62:2016/ BTNMT (livestock wastewater) and QCVN 28:2010/ BTNMT (hospital wastewater).

3.2 Determination of the maximum score for the set of technology suitability assessment criteria

The study quantified the maximum scores of the four main criteria groups (Figure 2), the sub-criteria and sub-sub criteria. TC1 (Treatment efficiency of the technology) and TC2 (Treatment efficiency of the technology under abnormal conditions) have equivalent sub-subcriteria. Therefore, the score for each sub-subcriteria is equal and corresponds to $\bar{X}$ as described in section 2.3.2.2. The remaining criteria, which include ranking levels, were assigned scores according to their respective ranking levels. The results of the maximum scores of the sub-criteria are presented in Table 3.

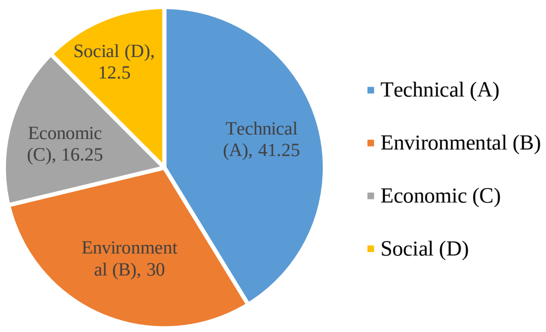


Figure 2. Maximum scores for the main criteria groups

The score distribution is designed to identify key determinants in evaluating the suitability of wastewater treatment technologies.

In this study, the maximum scores of the 22 sub-criteria (Table 3) indicate that treatment efficiency (TC1, TC2) was given the highest weights, reflecting its primary importance in technology selection. Criteria related to operation and environmental safety (TC3-TC13) were assigned medium scores, highlighting their supportive role in overall performance. In contrast, cost-related aspects (TC14-TC17) received relatively lower weights, suggesting that while economic considerations are relevant, they are not prioritized over technical effectiveness. Overall, the scoring distribution emphasizes treatment performance and environmental protection as the key determinants in evaluating the suitability of wastewater treatment technologies.

While the present study employed a distinct multi-criteria analysis (MCA) framework compared with previous works, the outcomes are consistent with earlier studies (Srivastava and Singh, 2022; Eseoglu et al., 2022; Selerio, 2024), confirming that treatment performance and environmental protection outweigh cost and operational factors in the selection of wastewater treatment technologies.

Table 3. Maximum scores of the sub-criteria

Criteria groups							
Technical		Environmental		Economic		Social	
Code	Maximum Score	Code	Maximum Score	Code	Maximum Score	Code	Maximum Score
TC1	9.375	TC8	3.75	TC14	3.75	TC19	3.75
TC2	7.50	TC9	5.625	TC15	3.75	TC20	2.50
TC3	5.625	TC10	5.625	TC16	3.75	TC21	3.75
TC4	3.75	TC11	5.625	TC17	3.75	TC22	2.50
TC5	3.75	TC12	5.625	TC18	1.25		
TC6	5.625	TC13	3.75				
TC7	5.625						

3.3 Assessment of the suitability of wastewater treatment technologies

Figure 3 indicates significant differences in the suitability levels of wastewater treatment technologies. Among the five systems surveyed, the domestic wastewater treatment system (WWTS) achieved the highest overall score (75/100), performing particularly well in the technical (33.75/41.25) and economic (15/16.25) criteria groups. This performance may be attributed to its technical stability and reasonable operating costs, which are factors directly related to the relatively stable and controllable pollution characteristics of domestic wastewater type. However, limitations in by-product utilization and secondary emission control indicate that the system's environmental recovery potential and long-term sustainability remain constrained.

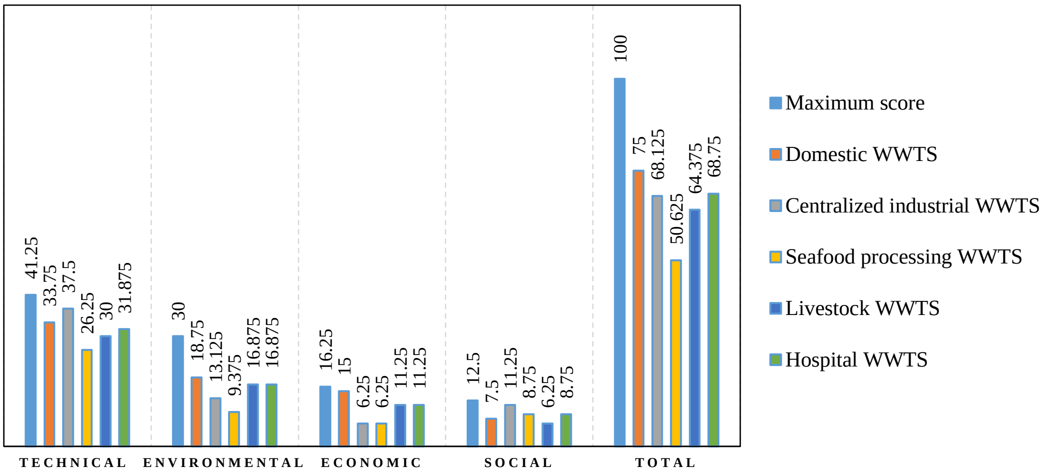


Figure 3. Quantified scores for the suitability assessment of WWTSs

Among the five wastewater types surveyed, the centralized industrial WWTS achieved a high score in the technical criteria group (37.5/41.25), indicating stable operation, ease of maintenance and compatibility with the skill level of the workforce. However, the environmental (13.125/30) and economic (6.25/16.25) criteria revealed existing issues related to high energy consumption, harmful gas emissions and limited potential for by-product recovery. Meanwhile, this system achieved the highest score in the social criteria group (11.25/12.5), reflecting its high adaptability to regional conditions and minimal impact on the community.

The seafood processing WWTS obtained the lowest overall score (50.625/100), with environmental and economic criteria at very low levels, 9.375/30 and 6.25/16.25, respectively. These results highlight the limitations of the currently applied technology in ensuring pollution control and cost efficiency. Although the social criteria reached an average level (8.75/12.5), low environmental and economic performance limits the overall sustainability of the system. This indicates the need for comprehensive technical and managerial interventions.

For the livestock and hospital WWTS, the total scores were 64.375 and 68.75, respectively. Both systems achieved relatively high technical scores (above 30/41.25) and reached the standards for effluent treatment efficiency. However, their economic performance was constrained by high capital, while environmental criteria were not fully met because of significant emissions of harmful gases, which are recognized as major contributors to climate change (IPCC, 2006) as well as high energy consumption. In particular, although the livestock WWTS demonstrated potential for by-product reuse, its low score in the social criteria group (6.25/12.5) reflected limitations related to aesthetics and negative community impacts.

In general, technical criteria dominated the evaluation, reflecting strong technical performance of the systems, whereas the lower weighting of environmental and economic criteria indicates unresolved sustainability issues in wastewater treatment in the study area.

3.4 Impact levels and priority for remediation of incidents in WWTSs

Based on the actual operating conditions of WWTS for the five wastewater types in the former Binh

Thuan Province, several types of operational incidents were identified and their impact levels assessed as follows: most systems experienced technical failures at varying degrees, predominantly ranging from minor to moderate, as shown in Figure 4.

In the five WWTS types surveyed, operational incidents were generally of minor to moderate severity (2.3-3.8 points), although recurrent technical issues were observed (Figure 4(a-1)-(e-1)). Domestic and livestock systems mainly faced aeration failures, sludge return problems and low biomass (Figure 4(a-1)-(d-1)), while seafood processing and centralized industrial systems were particularly affected by odor generation and sludge flotation (Figure 4(b-1)-(c-1)). Hospital systems exhibited sludge washout and oxygen deficiency resulting from malfunctioning pumps (Figure 4(e-1)). In all cases, remedial measures were rated as highly feasible (1-2 points), with priority actions focusing on aeration repair, pump replacement, sludge management and odor control (Figure 4(a-2)-(e-2)). Additional improvement options, such as installing an anoxic tank (Figure 4(a-2)), were identified for improving nutrient removal (Le, 2007; Lam and Tran, 2015), though limited by space and cost. Overall, while the types and causes of incidents varied among systems, the findings consistently indicate that preventive maintenance and targeted technological upgrades are critical for sustaining treatment efficiency across WWTSs.

This is the first study to investigate operational incidents, assess their impact levels and propose priority rehabilitation measures for existing wastewater treatment systems in Binh Thuan area as well as in Vietnam. A review of operating wastewater treatment systems in the former Binh Thuan Province indicates that, although the issues are currently manageable, they pose potential risks to treatment efficiency if not addressed promptly. Among them, seafood processing and centralized industrial WWTS were identified as high-priority targets for rehabilitation due to their significant environmental impacts and effects on surrounding communities.

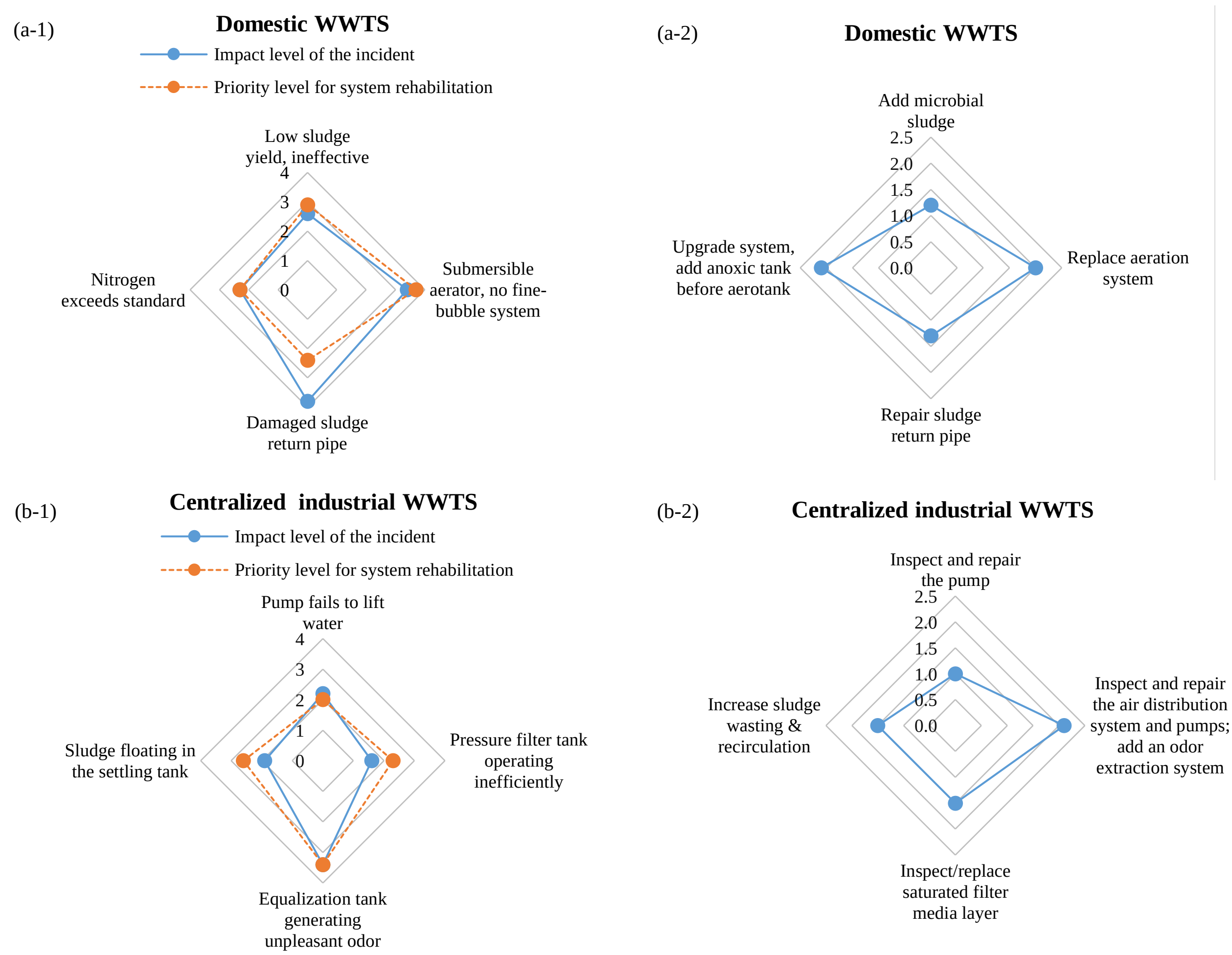


Figure 4. Impact level and renovation priority of incidents in wastewater treatment systems (a) Domestic wastewater, (b) Medical wastewater, (c) Livestock wastewater, (d) Seafood processing wastewater, (e) Centralized industrial wastewater (1) Incident impact level, (2) Renovation priority level

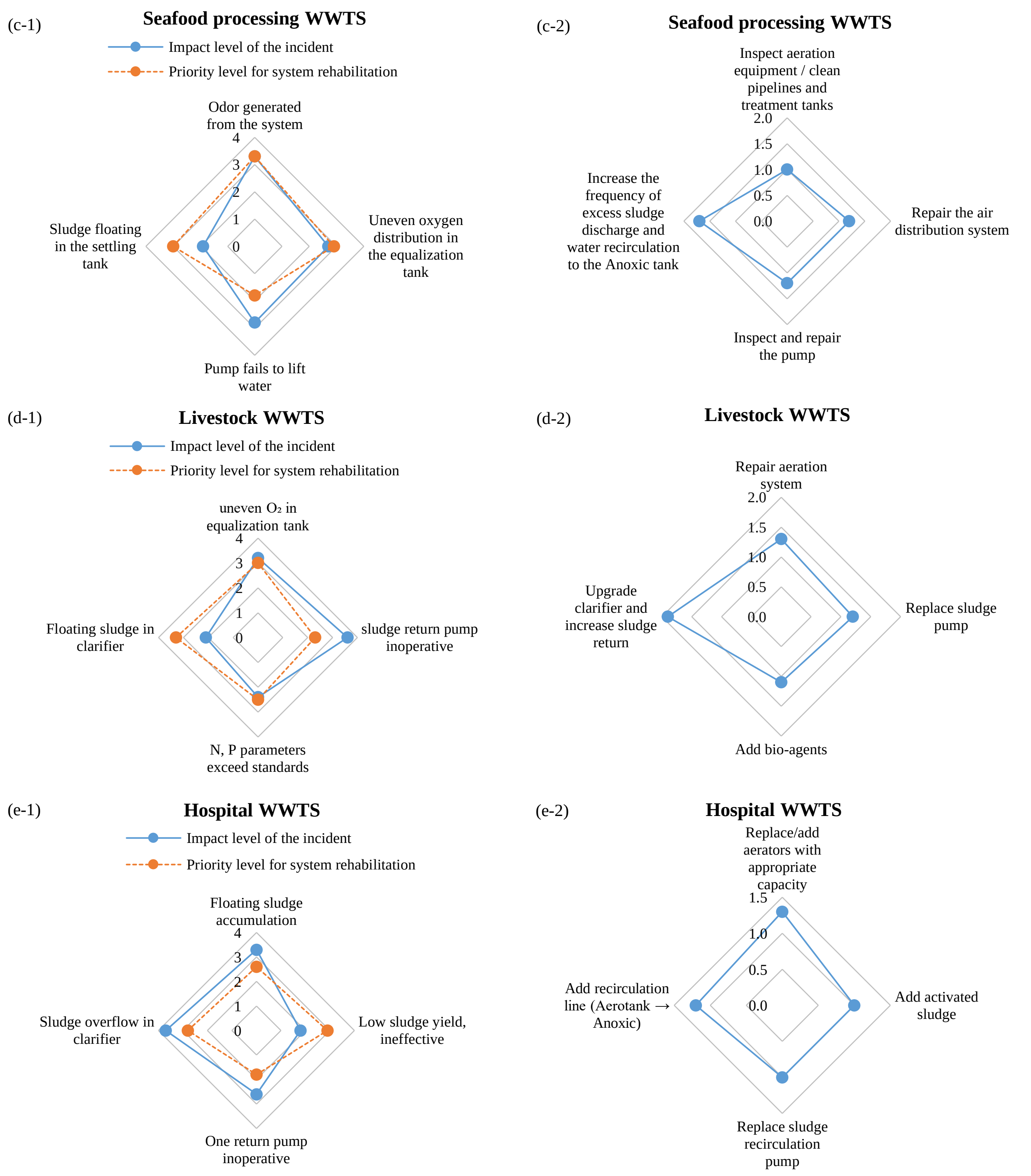


Figure 4. Impact level and renovation priority of incidents in wastewater treatment systems (a) domestic wastewater, (b) medical wastewater, (c) livestock wastewater, (d) seafood processing wastewater, (e) centralized industrial wastewater (1) incident impact level, (2) renovation priority level (cont.)

3.5 Incident localization and proposed technological improvements

Based on the survey and operational assessment of WWTSs, the study identified critical locations within the treatment processes that are prone to operational incidents and require priority improvement. Several key system components were therefore recommended for technological upgrading, with details summarized in Table 4 and Figure 5.

Table 4. Technical improvement solutions for the operation of WWTSs

WWTSs	Notation,Process location identified for remediation or improvement	Proposed solution
Domestic (Figure 5(a))	TK2	Replace the aeration distribution system to ensure uniform oxygen supply.
	▽	Add an anoxic tank upstream of the aerotank to enhance nitrogen and phosphorus removal efficiency.
	TK3	Supplement with activated sludge and repair/replace the return sludge system.
Centralized industrial (Figure 5(b))	TK2	Inspect and repair pumps and the aeration distribution system
	TK5	Increase both return sludge flow and excess sludge wasting frequency
	TK7	Replace the filter media
Seafood processing (Figure 5(c))	TK1	Conduct regular inspection and maintenance of pumps
	TK5	Inspect and improve the aeration system
	TK7	Increase the recirculation flow from the aerotank to the anoxic tank. Increase the frequency of excess sludge wasting
	TK8	Adjust sludge loading and add a sludge collection mechanism
Livestock (Figure 5(d))	TK3	Repair the aeration distribution system
	TK4	Add biological treatment agents
	TK6	Repair the sludge recirculation pump Increase the return sludge volume
Hospital (Figure 5(e))	▽	Add an additional water recirculation line.
	TK4	Add activated sludge Replace the air blower with one of appropriate capacity
	TK5	Replace the sludge recirculation pump

(a) Domestic WWTS

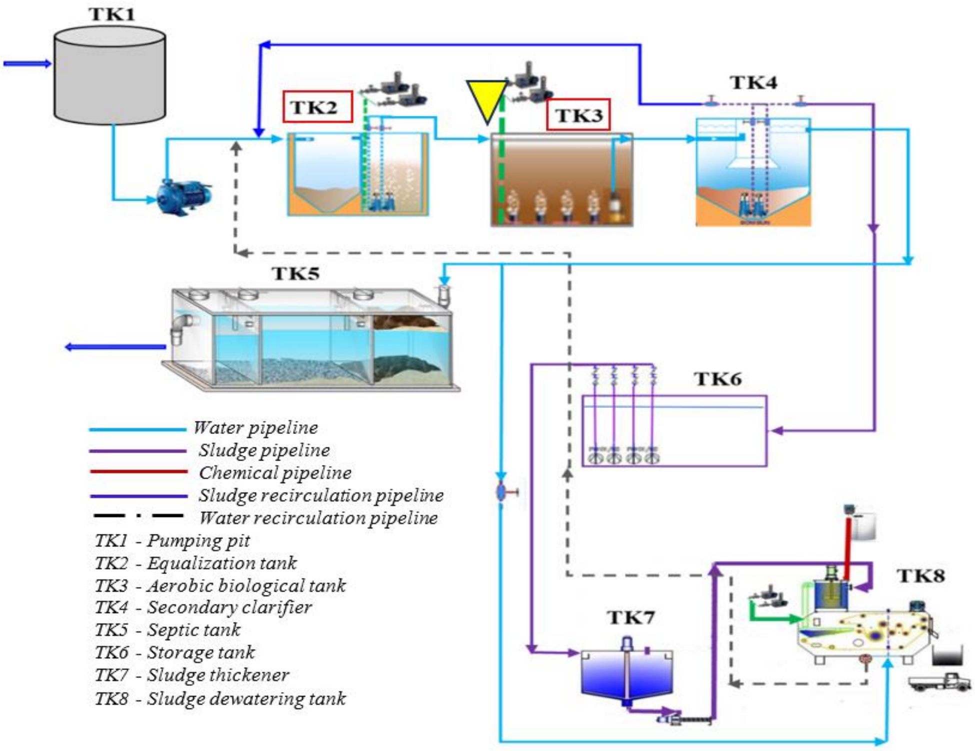
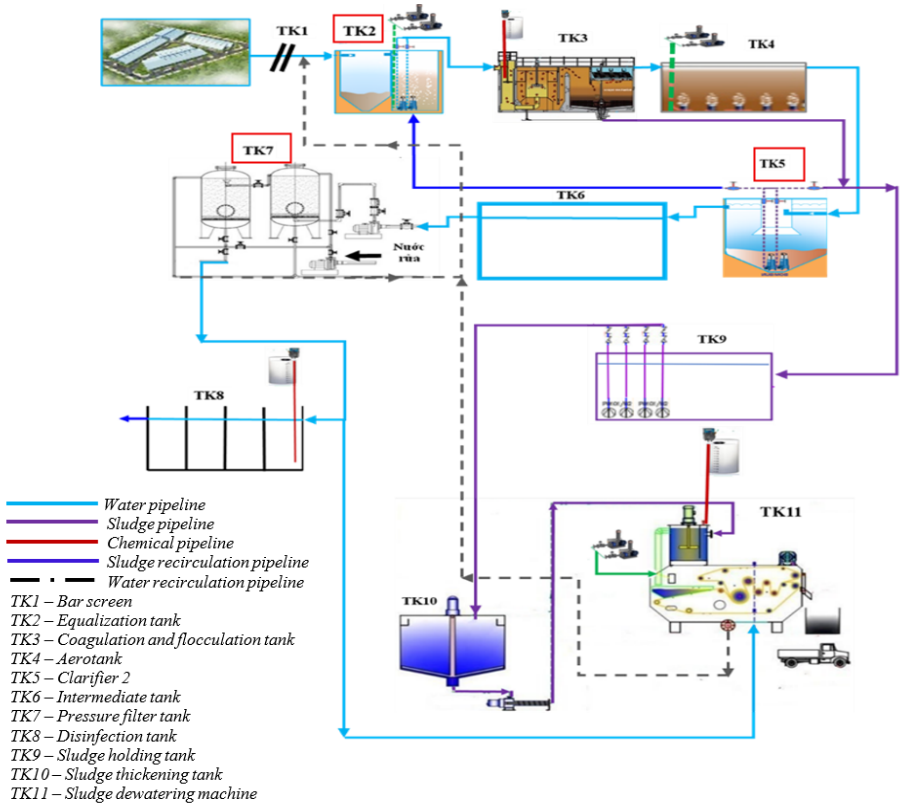


Figure 5. Wastewater treatment systems and solutions for troubleshooting

(b) Centralized industrial WWTS



(c) Seafood processing WWTS

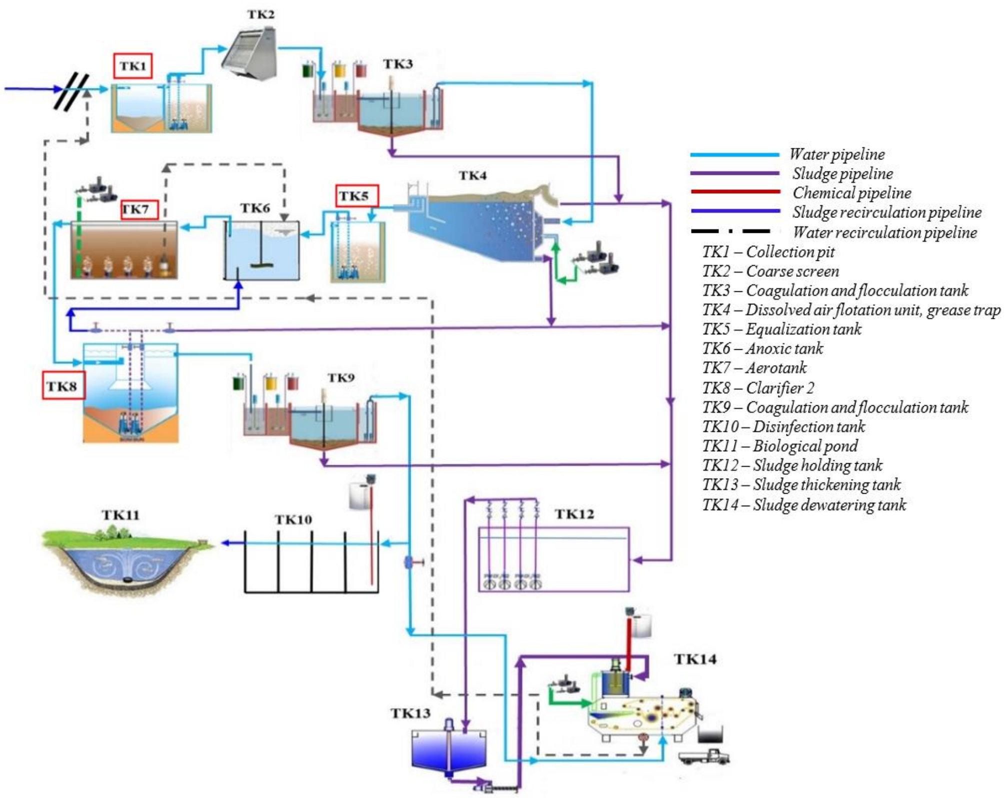
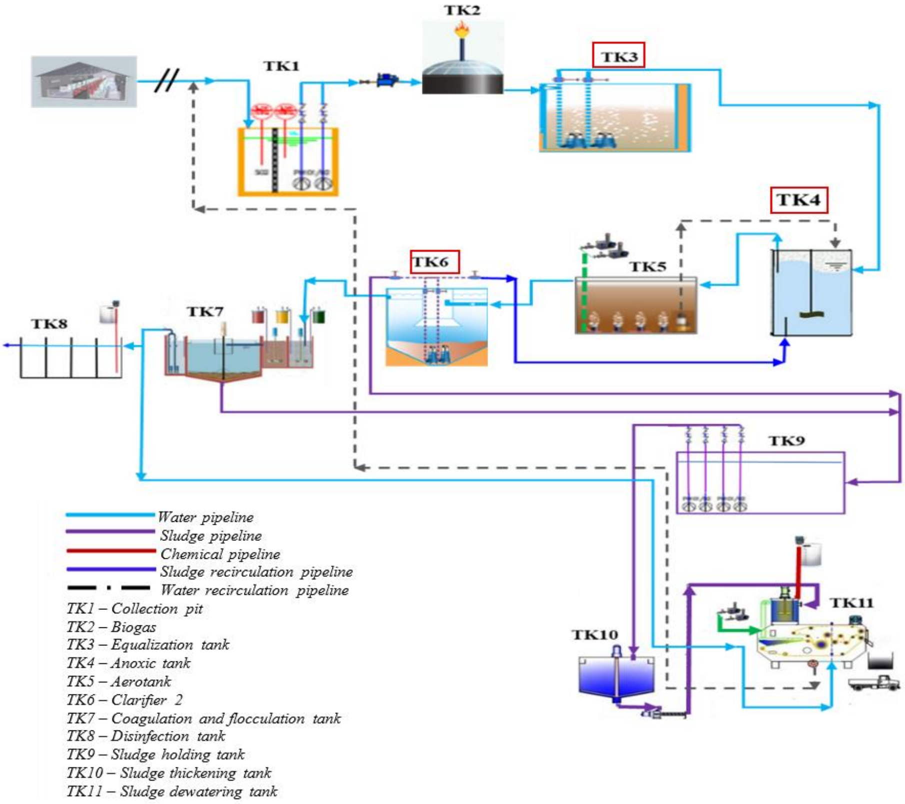


Figure 5. Wastewater treatment systems and solutions for troubleshooting (cont.)

(d) Livestock WWTS



(e) Hospital WWTS

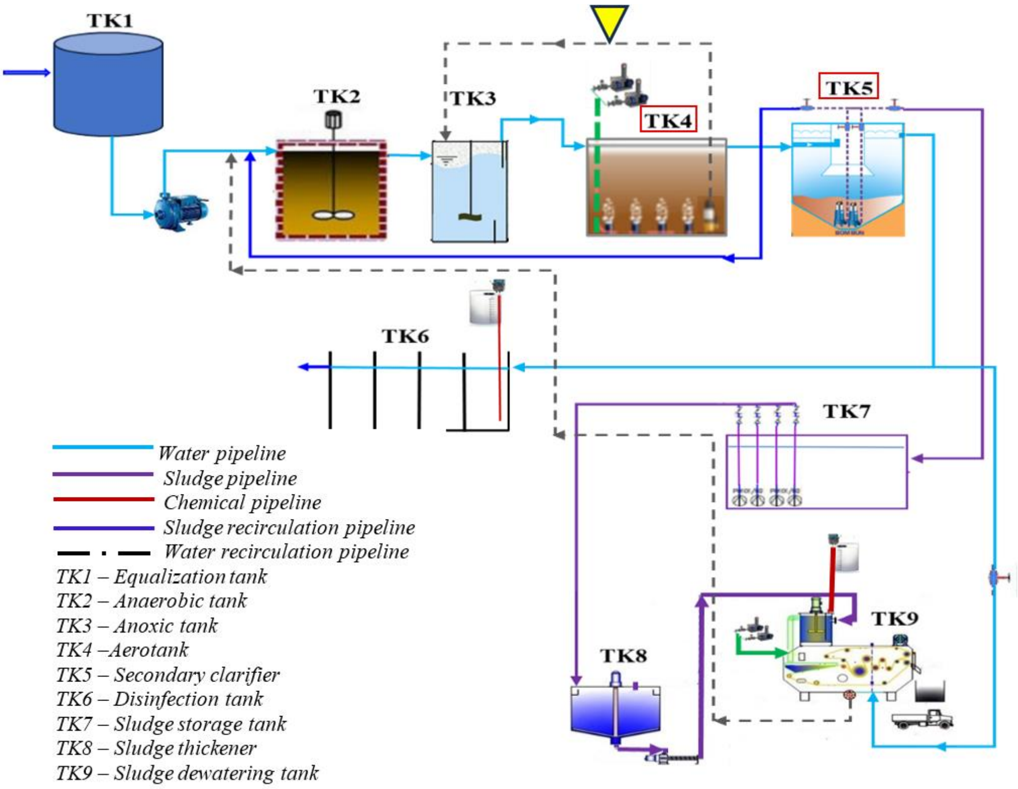


Figure 5. Wastewater treatment systems and solutions for troubleshooting (cont.)

4. CONCLUSION

This study represents the first application of a multi-criteria analysis (MCA) framework to systematically evaluate the suitability of existing wastewater treatment systems (WWTSs) in the former Binh Thuan Province, Vietnam. Using 22 sub-criteria grouped into four sustainability dimensions, the assessment revealed that domestic and centralized industrial WWTSs achieved the highest overall scores (75/100 and 73.1/100, respectively), reflecting stable technical performance and relatively balanced economic and social outcomes. In contrast, seafood processing WWTSs obtained the lowest score (50.6/100), with particularly weak results in environmental (9.4/30) and economic (6.3/16.3) aspects, underscoring their high operational costs and unstable treatment efficiency. Livestock and hospital WWTSs scored moderately (64.4/100 and 68.8/100), performing well in technical criteria but constrained by high energy consumption, gas emissions, and investment costs. Across all five systems, recurrent operational incidents, such as aeration failures, sludge flotation, and odor generation were identified, yet most had feasible technical remedies, with seafood processing and industrial systems prioritized for urgent rehabilitation due to their significant environmental and community impacts. These findings provide essential baseline data for selecting and adapting treatment technologies to local conditions, while offering a decision-support tool for regulatory agencies to enhance wastewater management and safeguard water resources in Vietnam’s river basins. Further studies are strongly recommended to expand the MCA framework in order to better capture the long-term impacts of wastewater treatment technologies. In addition, applying this assessment framework to other regions and validating it through post-rehabilitation performance monitoring would enhance the applicability and reliability of the method.

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AUTHOR CONTRIBUTIONS

Conceptualization, H.P., T.T.M.H. and N.T.H.; Methodology, H.P., T.T.M.H. and N.T.H.; Validation, H.P., T.T.M.H. and N.T.H.; Formal Analysis, H.P., T.T.M.H.; Investigation, H.P., T.T.M.H.; Resources, H.P., T.T.M.H.; Data Curation, H.P., T.T.M.H.; Writing-Original Draft Preparation, H.P. and T.T.M.H.; Writing-Review and Editing, H.P., T.T.M.H. and N.T.H.; Visualization, H.P., T.T.M.H. and N.T.H.; Supervision, H.P.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

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