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Evaluation of Domestic Wastewater Management and the Future Potential for Diverse Technologies in Luangprabang City

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ABSTRACT

Luangprabang City is currently confronting a substantial wastewater management crisis, primarily due to the lack of an operational domestic sewage system and insufficient wastewater treatment technology. This study aimed to assess the current state of domestic wastewater management and investigate wastewater treatment technologies within a circular economic framework that is suitable for local conditions. Data were collected from local institutions encompassing local policies, legislation, wastewater treatment facilities, site visits, and observations. Secondary data were sourced from the literature reviews, technical guidelines, and related articles. Three distinct wastewater treatment technologies were evaluated to ascertain the optimal feasibility of the interventions for comparison purposes. The technical and treatment efficiencies of these technologies were also analyzed. The financial aspects were assessed, with an assumed affordability rate of 3%, a discount rate of 4.5%, and a project period of 10 years. The indicators employed included net present value and benefit-cost ratio. Based on the results of the analysis, the DEWATS Module with a constructed wetland was the most suitable option for implementation in the study area.

INTRODUCTION

The management of domestic wastewater has become a major environmental and public health problem for rapidly growing secondary cities in South East Asia, such as Luangprabang City, Laos. Under the continuous development of the city based on tourism and urban expansion, pressure on out-dated and insufficient sanitation infrastructure has increased. There is a lot of wastewater from homes that is released either untreated or undertreated into the local water supplies, polluting the water, damaging the ecosystem, and causing waterborne diseases. Luangprabang is a challenge owing to population growth, the expansion of business entities, and the burgeoning tourism sector. These developments have placed significant pressure on the urban water environment. Consequently, the existing wastewater treatment facilities are insufficient for providing the domestic wastewater generated. The treatment facilities are simple; the traditional pond system intended for treating greywater is restricted to the central area of Luangprabang and was not designed to process black water (pit latrines). Septage is introduced into ponds in wetland areas are part of the treatment system, where canals receive wastewater from households, including septic tank effluents and gray water. Sewage drainage and canals are diverted to ponds and overflow into other ponds before flowing into wetland areas, natural rivers, and streams.

Domestic wastewater is channeled through drainage systems, with some directed into ponds. Sewage settles and the adjacent wetlands absorb effluents before being discharged into the Mekong River via drainage outlets. The pond-wetland system has been studied through

several pilot projects in Luang Prabang, supported by development partners. This concept utilizes ponds and wetlands as natural treatment systems to purify city sewage to river discharge. When properly designed and maintained, these systems provide preliminary partial treatment of sewage during dry months, even though sewage overflows during rainy periods. A plan to connect all ponds and wetlands to capture and treat city sewage needs to be developed. As the city progresses towards its planning horizon, the development of wastewater treatment systems will be crucial in implementing and refining these strategies to ensure long-term water environmental sustainability. These systems did not function well because they are sewage-contaminated, and pollution poses a significant public health risk. Furthermore, there is a limited professional understanding of the aquatic environment in the context of planning and development. For example, relevant authorities have not been able to generate enough revenue to pay for the maintenance and operational expenses related to the sanitation sector's service provision.

According to estimates, Laos's poor sanitation costs \$650 million a year, or roughly 3.5% of GDP, in lost productivity and associated medical costs. For Luangprabang, this amounts to about \$10 per person. According to the World Health Organization (WHO), a \$1 investment in improved sanitation yields an economic return of \$5.50, which has a positive effect on the city. Although 94% of city residents have improved sanitation facilities, one-third of the population's sewage flows through open drains and is discharged untreated into natural water bodies or agricultural lands. Consequently, the local city government has intervened to address this issue.

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The Urban Drainage and Sewerage Systems Master Plan outlines the development of primary drainage systems to manage stormwater and wastewater, restore wetlands for stormwater preservation, and facilitate wastewater treatment. The planning horizon extends to 2037. Distinct zones encompassing 72 villages were identified, including the World Heritage Protection Area, the historic center, natural wetlands, and the section within the heritage area containing natural wetlands. The Luang Prabang World Heritage Office conducted an inventory and assessment of 106 ponds and the surrounding wetlands. Most ponds are privately owned, and regulations prohibit owners from backfilling ponds without consent from the City. In a study, Starkl *et al.* (2022) assessed the sustainability of wastewater treatment systems in developing countries. Their research examined economic, environmental, institutional, and social sustainability, which may have various objectives and audiences that require diverse approaches. This study evaluated the specific aspects of sustainability assessment that are relevant to wastewater treatment system planners. The criteria included system costs and financing; affordability for users; environmental impact; health benefits; cultural acceptance of the system and recycled products; technical performance; and administrative, political, and legal frameworks governing construction and operation. These findings suggest that a multi-criteria approach can identify the most suitable system for a given location.

According to research, Gómez-Román *et al.* (2020) conducted a systematic review of public perceptions concerning the acceptance of decentralized wastewater treatment systems in regions not experiencing water scarcity. A focus group study was conducted to assess whether the identified factors applied to areas in which the population was unaware of water-related issues. The findings indicated that a lack of awareness regarding water issues was a significant factor affecting acceptance. It is essential to highlight features like environmental sustainability in order to highlight the usefulness of such systems. Costs, financing, affordability, technical performance, and legislation are all included in the framework for performing a cost-benefit analysis (CBA) of wastewater treatment systems. Furthermore, it considers the local context and size of the treatment facility, whereas benefits may remain relatively constant. Decision-makers can identify the most suitable and sustainable wastewater treatment system for a particular location by using this all-encompassing approach.

For constructed wetlands, decentralized wastewater treatment systems (DEWATS) usually include primary, secondary, advanced secondary, and preliminary treatments. A sedimentation tank, a primary clarifier, an aeration tank, a secondary tank, and a disinfection tank make up a conventional activated sludge system (CAS). The primary clarifier and secondary clarifier return sludge, and simultaneously control raw sludge exceeding the thickener tank and release it for sludge treatment and disposal. A sedimentation storage tank, an anaerobic

filter tank, a moving bed biofilm tank, a sedimentation tank, and a disinfection tank are all included in Johkasou. In places where conventional sewage treatment systems are impractical, this system provides an inventive wastewater solution.

The technical performances and treatment capabilities of the diverse wastewater treatment systems were evaluated. Subsequently, a financial analysis was undertaken to formulate a strategy that encompassed a comprehensive inventory of all associated costs, including those related to sewers, buildings, technical equipment, materials, and system components, all of which encompassed O&M expenses, where land was included as a government subsidy for capital costs. The analysis of net present value and benefit-cost ratio offers valuable insights into financial viability. By taking into account revenue costs as well as capital and operating expenditures. Incorporating crucial elements like household affordability and discount rates guarantees that the chosen technologies are both economically feasible and technically suitable for the city in question. The successful implementation and long-term viability of a system depend on a meticulous approach to financial planning that strikes a balance between economic viability and technological advancements.

In Luangprabang, a significant volume of untreated domestic wastewater is currently discharged into the environment, posing a risk to public health, contaminating water supplies, and harming the ecosystem. This situation is caused by a number of factors, including low community awareness, a lack of strict policy enforcement, and financial limitations that prevent the adoption of sustainable solutions. Despite these pressing concerns, empirical studies evaluating the present wastewater situation in Luangprabang. Despite these pressing concerns, there is still a noticeable lack of empirical research evaluating Luangprabang's present wastewater management procedures and investigating alternative, context-appropriate treatment technologies. In favor of an excessively large focus on urban centers, most current research overlooks the unique socio-economic, environmental, and infrastructure conditions of medium-sized cities like Luangprabang. Addressing these water-related environmental issues is essential to achieving sustainable development in the region, which necessitates the use of cutting-edge treatment technologies supported by sound research. In addition to their engineering design parameters, these technologies must be evaluated for technical efficacy, cost-effectiveness, environmental impact, and regulatory compliance. Therefore, the goal of this study is to thoroughly evaluate the state of wastewater treatment facilities today and investigate a variety of treatment technologies that are appropriate for local needs within a circular economy framework. To make sure that wastewater management plans are in line with water quality regulations and more general sustainability objectives, it looks at the technical, environmental, social, and economic aspects of current practices and suggested remedies.

Along with offering comparative analysis to guide future infrastructure planning and policy-making, the study also highlights important opportunities and challenges in putting into practice economically feasible and socially acceptable treatment systems. This research supports the sustainable development of Luangprabang and the larger regional conversation on inclusive sanitation strategies for secondary cities throughout Southeast Asia by providing practical insights into workable, affordable, and ecologically friendly wastewater solutions. This study is significant because it provides a comprehensive assessment of current domestic wastewater practices and looks at sustainable treatment options that align with the circular economy's tenets. The results can be used to find workable, reasonably priced, and environmentally friendly alternatives to assist local policymakers, urban planners, and development agencies in creating more resilient and inclusive wastewater systems that satisfy the demands of the public.

Ultimately, the study contributes to the broader regional discourse on sustainable urban sanitation by offering data that other Southeast Asian secondary cities facing similar challenges can utilize or adapt.

MATERIALS AND METHODS

The study area, known as the Ban Mano Group, encompasses 2,236 ha, 2,100 households, 12,139 inhabitants, and 30 ponds. This region is designated a World Heritage Site, as shown in Figure 1. The data-collection methodology integrates both primary and secondary data sources.

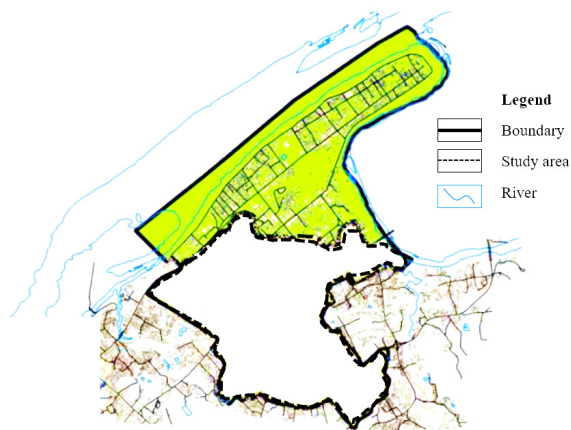


Figure 1: Map of the Study Area

Data Collection

Data collection was conducted with strict adherence to ethical and legal standards, transparency and accountability throughout the study. The acquisition of official permission from local authorities facilitated by a university-issued letter enabled the execution of survey interviews and site visits in compliance with local regulations. Furthermore, all secondary data sources were reviewed, cited, and acknowledged, thus supporting the credibility and integrity of the study methodology.

Primary data were collected through direct interviews and group discussions with the local authorities of key

officials in charge of domestic wastewater management and development, namely, the Department of Public Works and Transport, Luang Prabang City Office of Management and Service, and Water Supply State Enterprise, focusing on local policies related to wastewater development initiatives, legislation for wastewater management, wastewater treatment facilities, and associated issues in wastewater management. Interviews were conducted with 20 stakeholders. Furthermore, the study included site visits to the study area where observations were conducted to gather existing phenomena for data analysis, specifically in terms of comparing diverse wastewater treatment technology plans conducted in November 2023. These interviews explored perspectives on current practices, awareness of wastewater issues, and willingness to adopt alternative treatment options. An interview guide was used to ensure consistency while allowing flexibility to explore emerging topics.

Secondary sources included project reports, academic papers, and relevant articles, which provided a broader context and theoretical foundation for the study. By synthesizing information from these diverse sources, this study presents a comprehensive analysis of the current sanitation landscape and proposes recommendations for future development and policy enhancement. Statistical data from municipal records were also analyzed to understand population growth, sanitation coverage, and financial allocations for wastewater services.

By exploring these factors, the study offers a thorough assessment of the state of sanitation today, points out possible areas for development, and adds to the continuing discussion about appropriate wastewater treatment techniques. A thorough examination of practices and policies within the local context, supported by primary data obtained from direct interviews with authorities and policymakers, provides valuable insight into the current state of wastewater management. This method makes it easier to comprehend the difficulties and tactics used for local wastewater management.

Data Analysis

To find recurring issues and stakeholder perceptions, qualitative data from field observations and interviews were subjected to thematic analysis. Quantitative information was compared between various technologies, including treatment capacity and cost estimates. A multi-criteria assessment framework that considered technical feasibility, environmental impact, cost-effectiveness, and social acceptance was used to evaluate treatment options. The Lao National Standard for Wastewater Quality Control, which lists the eight main parameters, is displayed in Table 1. The purpose of this standard was to control the wastewater quality that domestic households released into the environment. Potential of hydrogen (pH), chemical oxygen demand (COD), biochemical oxygen demand (BOD5), total suspended solids (TSS), total nitrogen, phenol (C6H5OH), fat, oil, and grease (FOG), and total dissolved solids (TDS) were among these parameters. To guarantee proper wastewater

treatment prior to discharge into watercourses, these parameters must be regularly monitored.

Table 1: Lao PDR's standard limits for the quality parameters of domestic wastewater

Symbol	Standard Value	Unit
pH	6-9	Not defined
BOD ₅	30	mg/L
COD	125	mg/L
TSS	50	mg/L
TN	10	mg/L
C ₆ H ₅ OH	2	mg/L
FOG	5	mg/L
TDS	400	MPN/ml

Table 2 lists the key factors that have a major impact on water quality and human health: total suspended solids (TSS), total Kjeldahl nitrogen (TKN), chemical oxygen demand (COD), bio-chemical oxygen demand (BOD₅), and total phosphorus (TP). Different wastewater treatment systems in the study area are compared using the estimated pollution load per capita. These parameters are important markers of possible health hazards and water quality. Elevated levels of BOD₅, COD, TSS, TN, and TP can cause eutrophication, algal blooms, decreased light penetration, and oxygen depletion, all of which are harmful to aquatic ecosystems and human health.

Table 2: Parameters Pollution Load Assumptions

Parameters	Units	Average	Range
BOD ₅	g/cap/d	60	40-60
COD	g/cap/d	130	25-200
TSS	g/cap/d	50	35-70
TN	g/cap/d	14	2-15
TP	g/cap/d	2.4	1-3

Table 3 shows the main parameters used to estimate the design capacity of wastewater treatment technologies derived from the national socio-economic statistics of the province. Water usage per capita was obtained from the Water Supply State Enterprise Report. And wastewater was estimated according to the guideline. Three diverse wastewater treatment systems were assumed to have equal capacities of 1,000 m³/d.

Table 3: Main Parameters for Design Capacity

Indicators	Unit	Values
No. of Household	Unit	2,100
Household Size	Persons	6
Population	Persons	12,139
Assumed water usage per capita	Liter/day	150
Assumed wastewater produced	%	60%
Total daily water usage amount	Liter/ca	1,820,850
Total daily wastewater produced	Liter/ca	1,092,510
Assume the total design capacity	m ³ /d	1,000

Table 4 shows the annual income per capita of Luang Prabang people, as referred to by the local government in 202510. The assumed wastewater fee was derived from the Decree on Water Policy Guidelines, which mandates that service providers establish water tariffs or fees for 3-5% of households for affordability of annual income (11). This study uses 3% of the assumed wastewater fee as the estimated operating revenue.

Table 4: Household socioeconomic data

Socioeconomic data	(USD)
Income per capita	1,752
Income per household	
(Average 6 persons)	10,512
The annual income of a household in the study area	22,075,200
Affordability of wastewater fee (3%)	662,256
Operating revenue for evaluation	662,256

Equation for Financial Aspects Evaluation

The net present value measures the viability of projects by calculating the difference between discounted benefits and costs (12).

$$NPV = \sum_{t=1}^n ((Bt - Ct) / ((1+r)^t))$$

NPV = Net Present Value; Bt = amount of net benefit in year t; Ct = operating costs, including O&M costs; r = discount rate; n = project period.

The benefit-cost ratio is the ratio of the sum of the present value of the project benefits to the total project costs (12).

$$BCR = \sum_{t=1}^n Bt / (1+r)^t \div \sum_{t=1}^n Ct / (1+r)^t$$

Where BCR Benefit Cost Ratio (BCR), Bt = amount of net benefits in year t, Ct = operating cost including O & M cost interest rate, and n project period.

Figure 2 presents the DEWATS with constructed wetlands encompassing preliminary, primary, secondary, and tertiary advanced treatment processes. In the primary treatment phase, a settler, specifically a septic tank, was used. The majority of solids were processed in the initial chamber, whereas the second chamber facilitated the smooth flow of water. This system incorporates mechanical treatment via sedimentation and biological treatment via sludge digestion. Anaerobic baffled reactors and anaerobic filters are commonly used as backup

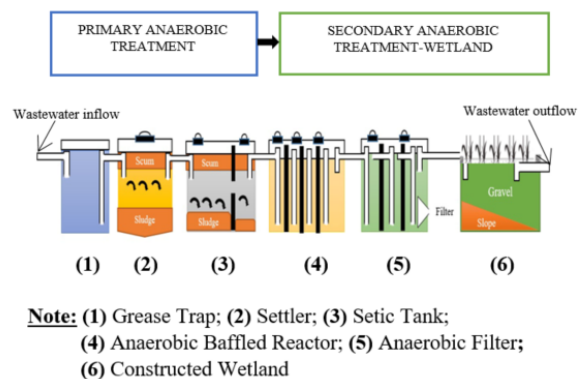


Figure 2: Schematic of DEWATS with constructed wetlands treatment process

treatments. Constructed wetlands use soil, vegetation, and microorganisms to remove pollutants naturally. Both the secondary (post-initial) and tertiary (post-polishing) treatments use these systems. Wastewater traverses wetlands, where plants, soil, and microorganisms remove contaminants, such as organic matter, nutrients (nitrogen and phosphorus), and pathogens. Constructed wetlands represent a low-energy and 1 operationally demanding alternative to conventional treatment systems. The systems demonstrated efficiency in pollutant removal, achieving reductions exceeding 70% for BOD₅, 46% for COD, 46% for TSS, and 45% for both TN and TP¹³. Figure 3 shows that the conventional activated sludge process is fundamental to the activated sludge processes. A Conventional Activated Sludge system (CAS) comprises a sedimentation tank, primary clarifier, aeration tank, secondary tank, and disinfection tank. The primary and secondary clarifiers return sludge, allowing the raw sludge to exceed the thickener tank for treatment and disposal. However, this requires strict operating conditions, the outputs are affected by load fluctuations, and the nitrogen and phosphorus removal ratios are low. Other processes have been developed to solve these problems and improve the conventional activated sludge processes. A sedimentation tank treats the initial wastewater by removing the grit and garbage through settling. The primary clarifier settles small particles that cannot be removed from a sedimentation tank. The primary sludge was placed in a sludge thickener tank with excess sludge. The activated sludge multiplied as the wastewater received oxygen from the aeration tank. By breaking down organic materials in wastewater, this activated sludge purifies the water. The secondary clarifier was activated sludge, which became lump-shaped and heavier than the water. After settling, the clean water was removed from the top layer. The settled sludge was treated after being transported to a thickener tank. Some of the precipitated activated sludge was returned to the aeration tank. The disinfection facility sterilizes the water removed from the secondary clarifier before discharge into the receiving water-course. The systems demonstrated treatment efficiencies exceeding 80% for removing pollutants such as BOD₅, COD, and TSS, while achieving over 70% efficiency for removing TN and TP.

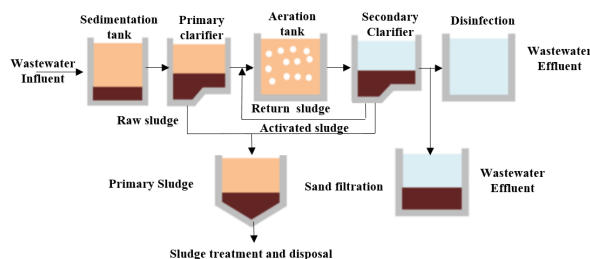


Figure 3: Systematic of the Conventional Activation Sludge Process

Figure 4 shows the Johkasou (an advanced Septic Tank). The Johkasou system comprises a sedimentation storage tank, an anaerobic filter tank, a moving bed biofilm

tank, a sedimentation tank, and a disinfection tank. During the treatment process, influents are stored in a sedimentation tank, large amounts of solid matter are separated, and the sludge is stored. The solid matter was separated when the wastewater flowed through the filter. Anaerobic bacteria decompose organic matter and remove nitrogen via denitrification. Aerobic bacteria decompose organic matter. Ammonia was oxidized, and nitrification proceeded. The suspended matter was precipitated in the treated water, a clean supernatant was sent to the disinfection tank, and the effluent was discharged after disinfection with chlorine. The Johkasou Module integrates domestic wastewater treatment with an efficiency rate of 90%, achieving BOD₅ concentrations below 60 mg/L, COD at 20 mg/L, and a TSS removal ratio of 90%. The TN and TP concentrations were less than 20 mg/L or a removal ratio of 70%^{(14), (15)}.

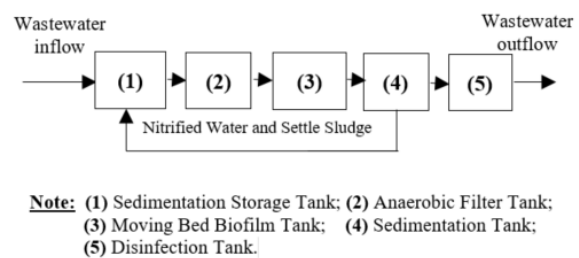


Figure 4: Systematic of the Johkasou Process

Table 5 presents a comparative analysis that offers valuable insight into the performance of the three wastewater treatment technologies. By utilizing standardized metrics and drawing from established research, this study provides a robust framework for evaluating and comparing these systems. Quantifiable data on removal efficiencies and rates enable stakeholders to make informed decisions when selecting appropriate wastewater treatment solutions. This approach not only facilitates a clear understanding of each technology's strengths but also contributes to the broader goal of improving water quality management.

Table 5: Parameters of Comparison

Pollution Removal (%)	Unit	DEWATS	CAS	Johkasou
BOD ₅	mg/cap/d	73.6	80	90
COD	mg/cap/d	46.10	80	80
TSS	mg/cap/d	75.20	90	90
TN	mg/cap/d	45	70	90
TP	mg/cap/d	45	70	90

Statistical Analysis

To evaluate and contrast wastewater treatment performance and financial viability, the study mostly used descriptive statistical techniques. Important parameters, such as the removal efficiencies of BOD₅, COD,

TSS, TN, and TP, were summarized using percentage reduction values. The Bene-fit-Cost Ratio (BCR) and Net Present Value (NPV) were computed as part of financial analyses to evaluate the economic feasibility of each treat-ment system. Design capacities were estimated us-ing population, water use, and wastewater genera-tion data. Since the study concentrated on compar-ative and economic evaluation using primary and secondary data, no inferential statistical tests were conducted.

During the data collection process, local authorities were unable to provide a complete set of technical and financial data. Limited availability of technical and financial data from local authorities impedes the analysis of wastewater treatment options. Previous research on the Lao PDR constrains the under-standing of suitable technologies in the study area. The absence of specific data and insufficient tech-nical information complicates the development of effective solutions. Consequently, inadequate local data and narrow research scope restrict the identi-fication of cost-effective treatment options for cit-ies.

RESULTS AND DISCUSSION

Local Authorities

Local municipal organizations have reported that the existing wastewater treatment facilities are in-adequate for processing domestic wastewater. This region is prone to natural disasters, which worsen residents' lack of access to sanitation facilities and hinder basic needs. The sanitation sector requires cost recovery strategies that consider residents' low-income status and willingness to pay for im-provements. Sanitation services fail to adequately serve urban populations, leading to poor health, a reduced quality of life, and impeded economic de-velopment. Failure to implement master plans has resulted in a lack of urbanization benefits. The city employs strategies to guide investment and sanita-tion infrastructure expansion, influenced by social, cultural, economic, and environmental factors. Defective sewer systems that link pipes to septic tanks have been found during site inspections, re-sulting in wastewater being released into wetlands, rivers, and streams. There are two kinds of sewage collection systems: separate systems that collect sewage and stormwater separately, and combined systems that collect both. This indicates the need for individual water flow systems, as stormwater must be diverted during rainfalls. The three primary sewerage collection systems were conventional sewerage with centrally installed sewer pipes, sim-pled sewerage with pipes installed at the rear and sides of the properties requiring the owner's consent for maintenance, and established systems of gravity collection networks with interceptor septic tanks and small-diameter pipelines. Settled effluent wastewater enters small-diameter pipes for treat-ment. Septic tanks near wetlands are connected to these areas through discharge pipes. Individual wa-ter-flow systems are essential for stormwater man-agement during rainfall events. However, popula-tion growth and

tourism have increased wastewater beyond the capacity of existing wetlands, which are affected by excessive wastewater inflow. Addition-ally, authorities have been deficient in maintenance, resulting in noncompliance with LENS standards. Authorities cannot generate sufficient revenue from user charges to cover O&M costs because of low wastewater tariffs, high technical standards, commercial losses, and poor collection efforts.

Site and Observations

Luang Prabang lacks centralized sewage, with residences that use individual on-site treatment systems with septic tanks. However, domestic wastewater has only been partially treated. Before entering the Nam and Mekong Rivers, septic tank effluents and household wastewater from kitchens, bathrooms, laundry, and cleaning (gray water) exit through drainage canals or pond-wetland systems. This presents health hazards, especially during rainy seasons when floodwater tainted with sewerage overflows drainage systems, ponds, and wetlands. Recent comprehensive studies on urban sewage systems are lacking. Current efforts have focused on decentralized systems and pond rehabilitation for preliminary treatment. Local authorities, initially hesitant about centralized wastewater systems be-cause of spatial constraints, now prioritize city cleanliness and aesthetics, particularly in tourist areas. The existing decentralized wastewater treatment system demonstrates a typical non-mechanized treatment flow. Similar low-cost systems globally have reduced organic pollution from domestic wastewater, but show limited ca-pacity to remove nutrients and coliforms from sewage.

Comparison of Technical Aspects

Table 6 presents the results of wastewater treatment systems that vary in effectiveness in eliminating pollutants, such as BOD₅, COD, TSS, TN, and TP. Decentralized wastewater module combustion showed less than ideal results, remov-ing only 73.6% of BOD₅ and 46.1% of COD, with BOD₅ levels of 60 mg per capita per day, and a 46.10% increase in COD. The TSS and TP removal rates were 75.2% and 45%, respectively. However, conventional activated sludge systems performed better, efficiently reducing BOD, COD, TSS, TN, and TP to meet the discharge standards. The Johkasou system has emerged as the most effective treatment method, surpassing other technologies in terms of all the parameters. Different treatment methods have shown varying efficiencies for spe-cific pollutants, which has implications for water quality management and environmental protection. The poor performance of the decentralized wastewater module combination highlights the need for improvements to meet the acceptable dis-charge standards. In contrast, the superior perfor-mance of conventional activated sludge systems and the Johkasou system suggests their potential as the preferred methods for wastewater treatment. These findings emphasize the importance of selecting appropriate treatment

technologies based on pollutant removal capabilities to ensure optimal water quality. The effectiveness of wastewater treatment systems varies across technologies. While the de-centralized wastewater module showed suboptimal performance, conventional activated sludge

systems demonstrated superior efficiency. Johkasou systems have emerged as one of the most effective methods. These findings highlight the importance of selecting appropriate treatment technologies based on pollutant removal capabilities.

Table 6: Comparison of pollution removal efficiency

Pollution Removal (%)			DEWATS		CAS		Johkasou	
Parameters	Unit	Pollution (10 ³) Load/ca/d	(%)	(10 ³)	(%)	(10 ³)	(%)	(10 ³)
BOD ₅	mg/cap/d	728	73.6	536	80	582	90	655
COD	mg/cap/d	1,578	46.10	727	80	1,262	80	1,262
TSS	mg/cap/d	606	75.20	456	90	546	90	546
TN	mg/cap/d	169	45	76	70	118	90	152
TP	mg/cap/d	29	45	13	70	20	90	26

Comparison of the Financial Aspects

Table 7 presents the primary values for comparison within the wastewater treatment system encompassing both capital expenditure (CAPEX) and operational expenditure (OPEX). OPEX includes the costs related to administration and maintenance. Revenue costs were evaluated by examining household contributions to wastewater fees. By the Decree on Water Supply Tariffs Policy 11), service providers are authorized to receive 3-5% of household income. This study utilized

a conservative estimate of 3% for household income contribution. Affordability is the principal factor that influences household contributions to wastewater fees. The assessment methodology balances system costs by considering household affordability. This study advocates a prudent approach to revenue projections. The system prioritizes affordability while also aiming for financial sustainability. The balance between cost and affordability may influence the treatment service quality and long-term system sustainability.

Table 7: Result of CAPEX, OPEX, and Revenue

Type of Technologies	Unit	Data	Total (10 ³ USD)
DEWATS			
CAPEX/cap (USD)	150	12,139	1,820
OPEX /cap (USD)	5.16	12,139	62
Affordability to pay	3%	21,267,528	638
CAS			
CAPEX/cap (USD)	100	12,139	1,213
OPEX /cap (USD)	9.78	12,139	118
Affordability to pay	3%	21,267,528	638
Johkasou			
CAPEX/cap (USD)	800	12,139	9,711
OPEX /cap (USD)	98	12,139	1,189
Affordability to pay	3%	21,267,528	638

Table 8 provides a comparative analysis of the various wastewater treatment technologies. Under the constraints of a specified project duration of 10 years, discount rate of 4.5% based on the wastewater treatment project in Lao PDR16), and capacity, it was assumed that the operational and benefit costs remained constant throughout the project. The results indicate that the net present value (NPV) of the benefits is uniform across technologies. However, because each wastewater treatment technology has different operating and maintenance costs, differences in the net present value (NPV) of the costs were noted. Critical values, like those found in cost-benefit

analyses, must be taken into account. The analysis demonstrates that the benefit-cost ratio of the DEWATS Module Combination yields the highest benefits, followed by the CAS, whereas the Johkasou case does not achieve a benefit-cost ratio of one. According to economic theory, a benefit-cost ratio below one suggests that the project is unlikely to be profitable because of elevated operational costs and insufficient benefits. Specifically, the Johkasou technology's benefit-cost ratio falling below one indicates potential economic unsustainability in the long term. These findings can guide policymakers and project planners in prioritizing

and allocating resources towards more cost-effective and sustainable wastewater treatment technologies, thereby potentially enhancing sanitation outcomes and optimizing the use of public funds.

Table 8: Results of Net Present Value and Net Benefit

Year	CAPEX & OPEX (10 ³ USD)	Benefit (10 ³ USD)	Discount Factor (4.5%)	Net Value Benefit (10 ³ USD)	Net Present Value Cost (10 ³ USD)
1) DEWATS Module Combination					
0	(1,820)	-	1	-	(1,820)
1	62	638	0.96	610	59
15	62	638	0.63	410	40
Benefit Cost Ratio				10.25	
2) Conventional Activated Sludge					
0	(1,213)	-	1	-	-
1	118	638	0.96	610	113
15	118	638	0.63	410	76
Benefit Cost Ratio				5.39	
3) Johkasou					
0	(9,711)	-	1	-	-
1	1,189	638	0.96	610	1,138
15	1,189	638	0.63	410	766
Benefit Cost Ratio (BCR)				0.53	

Decentralized Wastewater Treatment Systems (DEWATS) that use constructed wetlands offer cost-effective solutions. The system provides advantages such as low construction and operational cost and the possibility of resource recovery. However, these methods require sufficient space, pose odor issues, and require optimal treatment. The treated effluent can be used for irrigation or aquaculture, and nutrients can be recovered. The system adapts to various scales using local materials and labor for community participation. Constructed wetlands improve water quality and reduce flood risk. However, they require large areas, which limits their use in densely populated areas. Treatment effectiveness varies with the wastewater composition, climate, and wetland design. Maintenance included solid removal and water quality monitoring. Conventional activated sludge (CAS) systems have the advantages of low installation cost and high effluent quality. However, they have high operational costs, require space for sludge disposal, and require skilled supervision. Effluent quality can be inconsistent. These systems handle various wastewater loads with lower energy demands for aeration than Johkasou systems. However, aeration, sludge recycling, and maintenance costs are also high. The effluent quality varied and did not meet the clarity levels. This process is time-consuming and sensitive to fluctuations in wastewater. Therefore, CAS systems may be unsuitable for wastewater with high pollutant concentrations. The Johkasou system offers an alternative that balances cost-effectiveness and environmental benefits. Despite their high initial costs and maintenance needs, their long-term benefits often outweigh their drawbacks. Their adaptability, pollutant removal efficiency, and water reuse potential

render them suitable for dense areas. In recent years, wastewater management has changed. Johkasou systems are a sustainable solution, but in order to optimize their efficacy, local conditions must be taken into account. A wastewater treatment system's selection is influenced by a number of variables, including local conditions, environmental impact, and cost effectiveness. DEWATS with artificial wetlands provide an inexpensive, natural solution, but they need a large amount of land and careful planning. Even though they are well-known and efficient, conventional activated sludge systems have problems with consistency and operating costs. Johkasou systems have become viable substitutes for balancing environmental advantages with cost-effectiveness. Despite their high initial costs, they are appropriate for densely populated areas due to their long-term benefits, adaptability, and efficacy in pollutant removal. To ensure sustainable wastewater management, local conditions and requirements must be taken into account when choosing treatment systems.

In order to achieve environmental sustainability, community involvement in wastewater treatment systems is essential. Focusing on a number of important areas is necessary for effective community involvement, such as the effects of wastewater management on environmental quality, public health, and economic stability, as these factors can raise community members' awareness and interest. Communities can gain a better understanding of their role in supporting sustainable wastewater treatment systems by educating the public. The many advantages of sustainable methods for involving the community in wastewater treatment systems must be emphasized. Presenting wastewater treatment as a crucial component

of sustainable urban development and circular economy principles can encourage participation in decision-making and support creative, environmentally friendly solutions by emphasizing the economic and environmental benefits, such as the mitigation of water pollution and the preservation of ecosystems.

Based on these results, we draw the conclusion that decentralized wastewater treatment systems provide significant benefits, such as lower pollution and better investment costs, in local economic and environmental contexts. These systems offer benefits through lower investment and operating expenses than centralized systems. However, comparing these systems is complicated by the diverse contexts and priorities under varying circular economic conditions.

Comparative analyses of wastewater treatment systems have significantly contributed to water management and sustainability. Such methodologies are essential for the selection of suitable treatment technologies. These approaches evaluate sustainability across economic, environmental, social, and technical dimensions and offer a comprehensive assessment of options. There is an increasing focus on decentralized strategies and natural systems such as constructed wetlands. These systems are often favored over conventional activated sludge treatments and Johkasou systems, owing to their lower energy use and environmental impact. However, an analysis of land suitability is required to identify appropriate locations. This highlights the need to consider the technological and geographical factors when selecting treatment systems. The comparative evaluation of wastewater treatment systems facilitates informed decisions, promotes sustainable solutions, and addresses water management challenges. This approach supports the development of efficient strategies that can contribute to improved public health and environmental protection.

A significant limitation of this study was the absence of standardized monitoring protocols for wastewater treatment systems. Current systems focus on conventional pollutants and lack effective standards for monitoring the pollution loads from household sources. This deficiency complicates the assessment of decentralized systems. Decentralized wastewater treatment systems can contribute to optimal household wastewater fees. Limitations in data collection, standardization, and context-specific factors impede comprehensive comparison. Future research should prioritize the development of cost-effective technologies tailored to site-specific conditions to facilitate accurate comparisons.

Practical Implications

For policymakers looking to enhance wastewater management in Luang Prabang, this study offers several practical insights. According to a comparative study of treatment technologies, integrating low-energy, decentralized systems like DEWATS with artificial wetlands may provide sustainable and affordable solutions.

Taking into account local socioeconomic conditions and affordability, policymakers should give capacity-building top priority and offer incentives to promote the adoption of such technologies. Additionally, improved data collection and financial and technical information transparency will facilitate long-term planning and better informed decision-making. These actions are essential to improving the region's public health, environmental protection, and sanitation coverage.

CONCLUSION

This study looked into the current wastewater facilities in Luang Prabang and compared three different treatment technologies to see which would work best locally. The evaluation took into account technical needs, site characteristics, what households can afford, and national water quality standards. Key factors analyzed included wastewater volume, treatment efficiency, and economic feasibility—covering everything from initial investment to operational and maintenance costs—within the context of local policies.

The findings indicated that the DEWATS system combined with a constructed wetland stands out as the optimal choice for larger areas, thanks to its low operating costs, sustainability, and eco-friendliness, making it well-suited to local budgets and land availability. Although Johkasou comes with higher setup and running expenses, it's a good option for areas at high risk for organic waste, like factories or hospitals. On the other hand, the conventional activated sludge system could still be an option in some cases, despite its higher operational costs. This thorough evaluation lays a strong groundwork for picking the right wastewater treatment technologies that strike a balance between technical efficiency, economic soundness, and policy needs for sustainable wastewater management in Luang Prabang City.

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