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Integrated assessment of decentralized wastewater treatment plants in a semi-arid region in Bolivia

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ABSTRACT

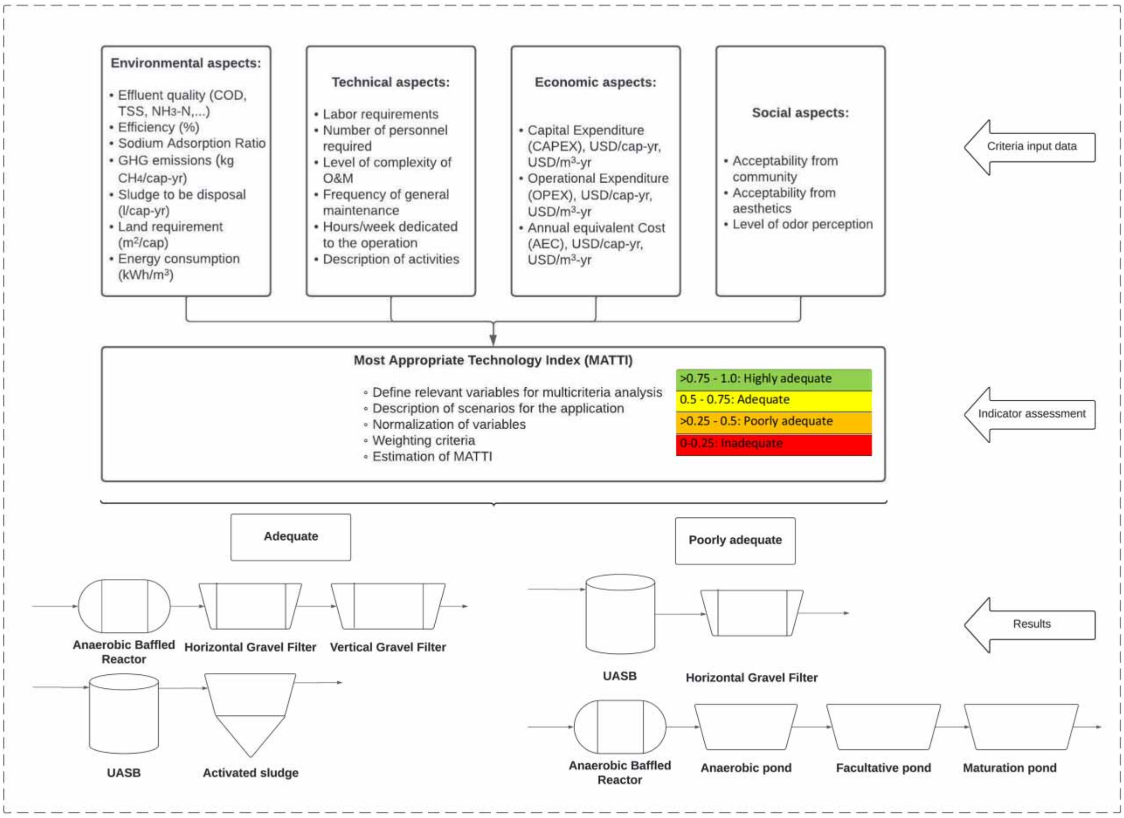
This study comprehensively evaluates four wastewater treatment plants intended for agricultural reuse in a semi-arid low-moderate temperature region. It considers environmental, technical, economic, and social perspectives. Anaerobic baffled reactors with hybrid gravel filters (ABR + HGF + VGF) proved the most efficient, with moderate requirements in space, O&M, and energy, albeit the highest treatment cost. Up-flow sludge blanket reactor with activated sludge (UASB + AS) demonstrated high efficiency and compactness, with moderate treatment costs. However, it incurred high energy demands, complex O&M, and more sludge generation. UASB with horizontal gravel filter (UASB + HGF) was among the most land-intensive systems, with moderate costs and O&M requirements, and low energy consumption. However, it fell short of meeting certain environmental criteria. ABR with stabilization ponds (ABR + PONDS) emerged as the most economical, with low energy consumption, but was also among the most land-intensive and failed to achieve adequate effluent quality. Socially, all WWTPs were well accepted for agricultural reuse benefits. In terms of odor perception, UASB + AS and ABR + HGF + VGF exhibit the lowest impact. The Most Appropriate Treatment Technology Index ranked ABR + HGF + VGF and UASB + AS as adequate technologies, while UASB + HGF and ABR + PONDS were poorly adequate. The study recommends a four-dimensional assessment for selecting the most suitable technology, considering the specific context.

Key words: comprehensive assessment, decentralized WWTP, most appropriate treatment technology index

HIGHLIGHTS

- ABR + HGF + VGF and UASB + AS are the most suitable for agricultural wastewater reuse in semi-arid low-moderate temperatures regions and socio-economic conditions similar to those of Bolivia.
- ABR + ponds is cost-effective but environmentally inefficient, while ABR + HGF + VGF is environmentally efficient but more expensive.
- The MATTI is suitable for selecting technologies for decentralized WWTPs in developing countries.

GRAPHICAL ABSTRACT



INTRODUCTION

The rapid urban and industrial growth has intensified sanitation challenges, diminishing access to water resources. This scarcity adversely impacts economic growth, living standards, and environmental sustainability. The agricultural sector, in particular, has resorted to using treated and untreated domestic or municipal wastewater to fulfill its needs (Dalezios *et al.* 2018).

Globally, around 360 km^3 of domestic wastewater is produced annually. Approximately 11.4% is treated and reused, 41.4% is treated and discharged, while 47.2% is released untreated (Jones *et al.* 2021). Effective wastewater treatment is essential for safe reuse and reducing environmental impacts (Rodriguez *et al.* 2020).

Worldwide, a variety of technologies have been implemented for the treatment of municipal wastewater. Effective wastewater management is well-established in developed countries but is still limited in developing countries. In developed countries like the USA, WWTPs generally follow a standard design comprising primary clarifiers, aeration processes, and secondary clarifiers, with slight variations (Mason *et al.* 2016). In China, the most common treatment processes include the anoxic–anaerobic–oxid (AAO) and its variants, covering 61.88% of WWTPs, followed by oxidation ditches and sequencing batch reactors (SBRs) with a share of 22.27%. The third most popular process is the SBR and its modified processes, with a share of 8.99%. Only 6.86% of WWTPs in China use other operating processes (Zhang *et al.* 2021).

Latin American WWTPs predominantly use lagoon treatments and activated sludge processes, with 38 and 26% utilization, respectively. Other methods include up-flow anaerobic sludge blanket, UASB (17%), aerated lagoons, wetlands, and trickling filters (Noyola *et al.* 2012). In Bolivia, stabilization ponds and various anaerobic processes like Imhoff tanks and septic tanks are prevalent (MMAyA 2020). Recently, trickling filters have been adopted for centralized municipal wastewater treatment.

Decentralized sanitation systems have gained traction in Bolivia's rural and peri-urban regions for populations of 2,000–20,000. In the Cochabamba department, decentralized WWTPs with anaerobic–aerobic configurations have been implemented, such as UASB followed by horizontal gravel filters (Saavedra *et al.* 2019), UASB combined by biological filters and stabilization ponds (Cossio *et al.* 2018; Mercado Guzmán *et al.* 2020), UASB-activated sludge and ABR followed by hybrid biofilters (Echeverría *et al.* 2022; Aguatuya 2023a). Similar plants are also operational in the Tarija department (Aguatuya 2023b).

Choosing the best technology for a specific context is challenging. This selection goes beyond the consideration of a cost-effective technical solution (Kalbar *et al.* 2012) requiring consideration of technical, economic, environmental, and social factors. The decision-making process also involves geographical and technological complexity aspects, with the aim of selecting a reliable technology that meets water quality standards and is socially acceptable (Leverenz & Asano 2011). Adopting a suitable WWTP requires evidence-based decisions from similar full-scale systems operating under real conditions in specific contexts.

To ensure the sustainability of treatment systems over time, it is fundamental to adopt a holistic approach in the technology selection process (Arroyo & Molinos-Senante 2018). The consensus among various scholars underscores the importance of integrating technical, economic, social, and environmental dimensions in the planning and sustainability assessment of treatment systems (Castillo *et al.* 2017). Additional dimensions like institutional robustness (Cossio *et al.* 2020), and legal considerations (Flores-Alsina *et al.* 2010) are also recognized as vital to sustainability.

Globally, numerous studies on full-scale treatment plants employ diverse approaches and metrics. For instance, Kalbar *et al.* (2012), Fighir *et al.* (2019), and Brault *et al.* (2022) analyze both technical (reliability, durability, replicability) and environmental aspects (global warming potential, eutrophication potential, land use, effluent, and sludge quality). Popovic *et al.* (2018) focus on social dimensions, including acceptability and promotion of sustainable practices among stakeholders. Economic evaluations, considering capital and operational costs, are also integral to these studies (Arroyo & Molinos-Senante 2018).

In Bolivia, technical evaluations of such systems have concentrated on efficiency and operational and climatic factors (Saavedra *et al.* 2019; Echeverría *et al.* 2022). Reports have also linked economic factors, like treatment costs, to system efficiency, particularly in management terms (Escalante *et al.* 2023). Furthermore, studies exploring the relationship between treatment system performance and operational management have been conducted (Cossio *et al.* 2018). However, comprehensive assessments of Bolivian WWTPs that encompass all these dimensions have not been reported to date.

This study aims to conduct an integrated assessment of four different WWTP configurations located in a semi-arid region with low to moderate temperatures, where untreated water reuse is common due to scarcity. These WWTPs, co-financed through international cooperation and municipal contributions, are currently operational with subsidy support. The assessment covers environmental, technical, economic, and social aspects to identify the most suitable technology for the context using the Most Appropriate Technology Index (MATTI) proposed by Soares *et al.* (2022). In addition, a hypothetical scenario was evaluated, where WWTPs operate without subsidies, with operation and maintenance (O&M) managed by water associations, and without a specific reuse destination.

METHODOLOGY

Study area context

The research was conducted in the high valley of Cochabamba, situated 30–40 km from the city of Cochabamba, in Bolivia (Figure 1). Characterized as a semi-arid zone, the area experiences dry and cold winters, and hot and rainy summers (GAMC 2016). The average annual temperature is approximately 15.7 °C, coupled with a mean annual precipitation of 400 mm (SENAMHI 2021). Spanning five provinces and 16 autonomous municipalities, this region is home to 151,369 inhabitants, primarily engaged in agricultural activities (INE 2012). The most commonly produced crops in this area are corn, peaches, alfalfa, and potatoes. Due to limited natural water sources, the area faces significant water scarcity, resulting in reliance on groundwater and rainfall, thereby constraining agricultural production to rain-fed crops (GAMC 2016). Consequently, treated wastewater is emerging as a highly valuable resource in the region.

The focus of this study encompasses four distinct wastewater treatment plants located in the provinces of Germán Jordán and Punata, each featuring a unique configuration, as detailed in the following.

Tolata wastewater treatment plant

Positioned at 17°32′19.21″S, 65°58′6.79″W, the Tolata WWTP channels effluent into a sump, followed by a rotary screen capable of retaining solids up to 3 mm. Subsequently, the flow is directed to a degreaser and then divided between two treatment modules, each consisting of a three-compartment anaerobic baffled reactor

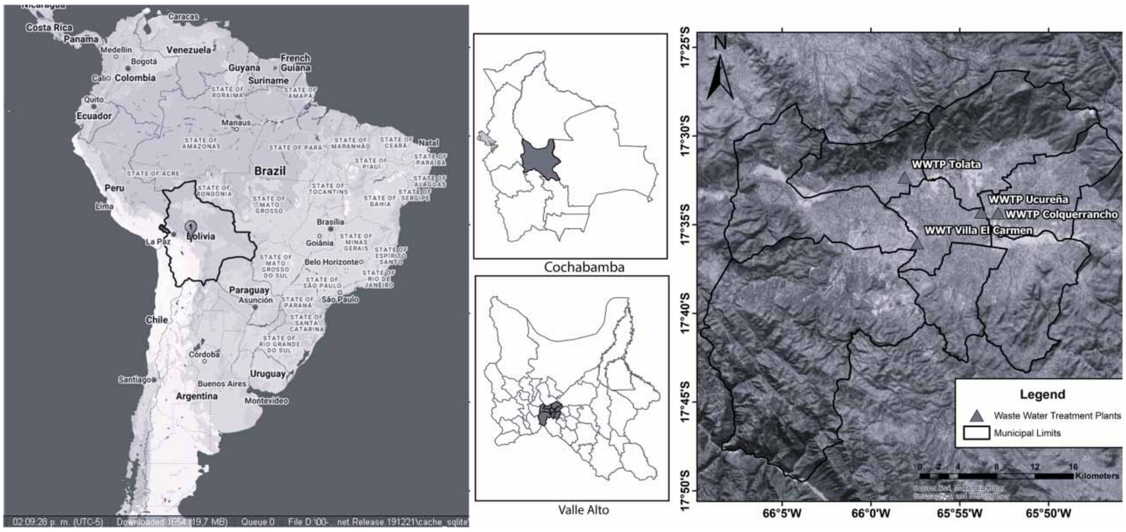


Figure 1 | Location of WWTPs in the Valle Alto region of Cochabamba, Bolivia.

and a series of horizontal and vertical gravel filters (ABR + HGF + VGF). Post-treatment, the effluent from each module is gathered in a chamber leading to a chlorine contact tank, and then pumped to a storage tank equipped with a sand filter at the inlet, facilitating water reuse for crop irrigation. The plant's design caters to a treatment capacity of 325.7 m^3/day. A schematic representation of the WWTP is provided in Figure 2.

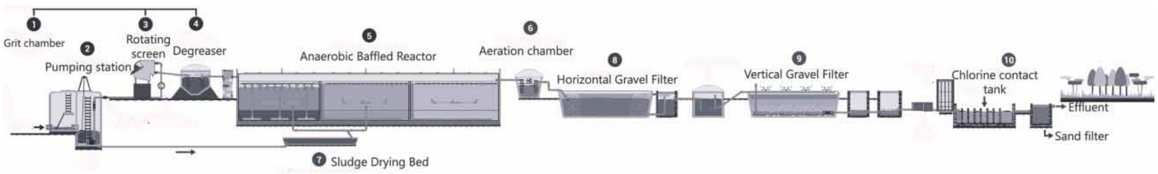


Figure 2 | Schematic representation of the Tolata WWTP.

Ucureña wastewater treatment plant

Located at 17°34′18.38″S, 65°53′47.19″W, the Ucureña WWTP begins with a pumping station that transfers wastewater to two treatment modules. Each module integrates a pretreatment system with a degreaser, a UASB reactor, and an activated sludge reactor (UASB + AS). The facility is designed to handle a treatment capacity of 677.5 m^3/day. Figure 3 depicts a schematic of the WWTP.

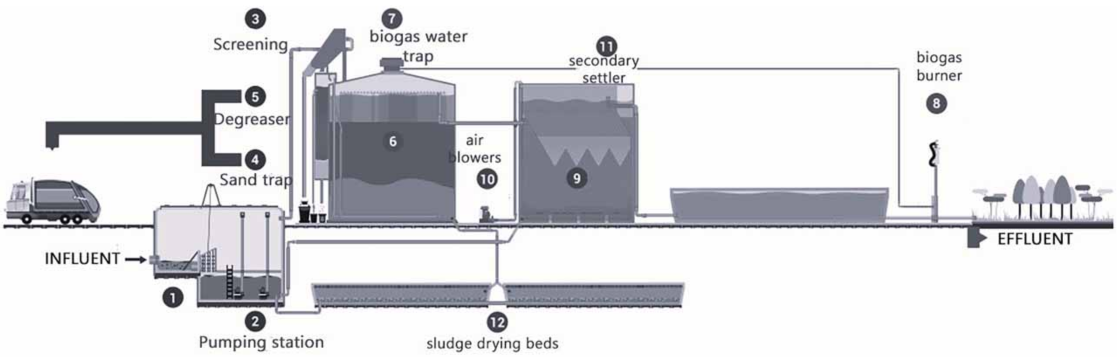


Figure 3 | Schematic representation of the Ucureña WWTP.

Villa El carmen, cliza wastewater treatment plant

Situated at 17°35′59.99″S, 65°57′23.96″W, this WWTP features a mechanized pretreatment system and a flow distribution chamber leading to five modules. Each module includes a degreasing chamber, two anaerobic up-flow sludge blanket reactors, and a horizontal flow gravel filter (UASB + HGF). Additionally, the plant contains five sludge drying beds for UASB sludge. The effluent from each biofilter is channeled outside the WWTP for crop irrigation reuse. Designed for a treatment capacity of 568 m^3 /day, the layout of the WWTP modules is illustrated in Figure 4.

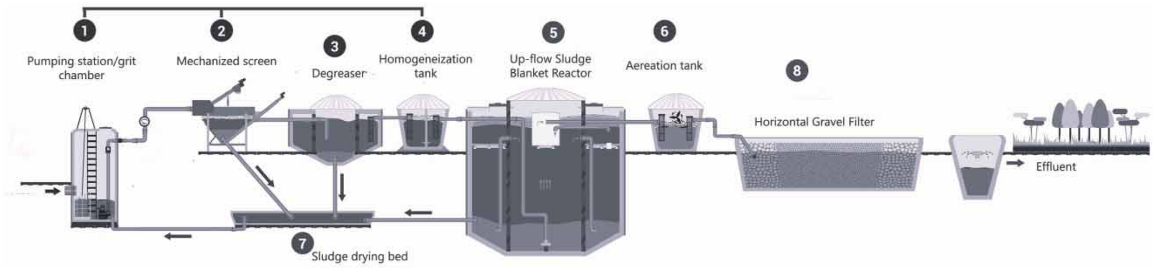


Figure 4 | Schematic representation of the Villa El Carmen WWTP.

Colquerrancho wastewater treatment plant

The Colquerrancho WWTP, positioned at 17°34′20.84″S, 65°52′50.35″W, combines an ABR reactor with waste stabilization ponds (ABR + PONDS). Wastewater enters through a channel with coarse-solids screens, followed by an auger-type screen for finer solids. The plant also includes a sand trap and degreaser for pretreatment. After degreasing, wastewater is pumped to a six-compartment anaerobic reactor, distributed in two lines, and then flows into three anaerobic ponds, two facultative ponds, and three serially connected maturation ponds. The facility is designed to treat 2,531.5 m^3/day. A schematic of the WWTP is presented in Figure 5.

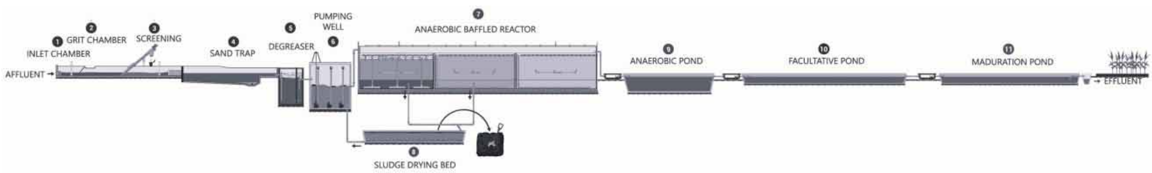


Figure 5 | Schematic representation of the Colquerrancho WWTP.

Comprehensive assessment context

This study adopts a holistic approach to assess four critical dimensions of WWTPs: environmental, technical, economic, and social. Recognizing the significance of all-encompassing project planning, a multi-criteria decision analysis method is implemented to determine the 'best technology available'. This involves including additional indicators to those proposed by Soares *et al.* (2022) for calculating the MATTI. The methodology is applied to two distinct scenarios: the current operational context supported by international cooperation, and reuse destinations; and a hypothetical situation lacking financial arrangements, where local municipalities or water associations manage the WWTPs without a predetermined reuse destination for the treated wastewater. The methodological framework is illustrated in Figure 6 which details the selected variables for each of the criteria.

For the ABR + HGF + VGF, UASB + HGF, and ABR + PONDS systems, efficiency and effluent quality data were sourced from existing literature (Saavedra *et al.* 2019; Echeverría *et al.* 2021, 2022). The UASB + AS system underwent nine monitoring campaigns to evaluate its efficiency and effluent quality concerning chemical oxygen demand (COD), total suspended solids (TSS), ammonia nitrogen (NH_3-N), and phosphorus (P). In all instances, influent and effluent samples were analyzed for anions and cations to calculate the sodium adsorption ratio (SAR), a critical parameter in evaluating irrigation water quality, particularly for soil sodium accumulation risks.

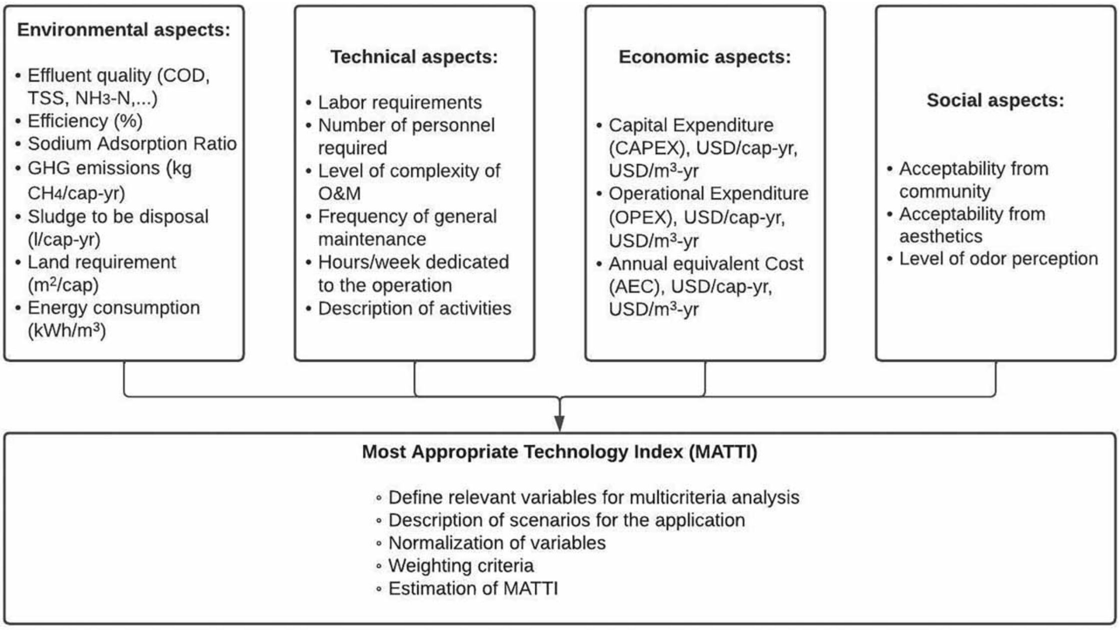


Figure 6 | Methodological scheme of integrated assessment of WWTPs.

SAR index was estimated as shown in the following equation:

$$\mathrm{SAR} = \frac{\mathrm{Na}}{\sqrt{\frac{\mathrm{Ca}+\mathrm{Mg}}{2}}} \tag{1}$$

Quantifying the amount of biogas released into the environment can be challenging due to the lack of appropriate gas collection and transport facilities. For this study, the estimation of direct greenhouse gas (GHG) emissions was based on the relations proposed by the Intergovernmental Panel on Climate Change (IPCC 2019) as indicated in the following equation:

$$\mathrm{EF}_j = B_0 \cdot \mathrm{MCF}_j \tag{2}$$

where EF_j = emission factor, kg-CH_4/kg COD, j is the each treatment/discharge pathway or system, B_0 is the maximum CH_4 producing capacity, kg-CH_4/kg COD, MCF_j is the methane correction factor (fraction), B_0 has a value of 0.25 kg-CH_4/kg COD, and the methane conversion factor used is 1.0, within a recommended range of 0.8–1.0 for anaerobic reactors.

For the estimation of the amount of sludge produced in the four configurations studied, reference values from Brault *et al.* (2022) and Soares *et al.* (2022) were used. The land requirement was measured based on the current area occupied by the WWTPs, excluding potential expansion space.

From a technical perspective, the assessment included operational characteristics, specialized labor requirements, and the complexity level of O&M. The complexity level was rated by WWTP operators on a scale from 1 to 5, with 1 being the most complex and 5 the simplest.

Economically, the study considered investment costs, O&M costs, and the cost of wastewater treatment.

Social impacts were evaluated through semi-structured interviews with operators, focusing on odor perception at each WWTP. Odor levels were rated on a scale from 1 to 5, with 1 indicating the strongest and 5 the weakest odor perception.

The decision-making process for selecting the most suitable technology involves defining the wastewater technologies to be evaluated, characterizing the performance criteria of the WWTPs, and normalizing and weighting variables. Normalization results are essential for making accurate comparisons, with scales with variable values between 0 and 1, where 0 represents the lowest value and 1 the highest value. This process is executed using the following equation:

$$\text{Normalized}_{ij} = \frac{X_{ij} - \min(j)}{\max(j) - \min(j)} \quad (3)$$

where Normalized_{ij} is the normalized value of technology i for parameter j, X_{ij} is the numerical value of technology i for parameter j, $\min(j)$ is the lowest value of parameter j observed, and $\max(j)$ is the highest value of parameter j observed.

When the analyzed characteristics become less desirable with increasing numerical values, such as implementation costs, the values are subtracted from 1, expressed as (1-normalized value). This approach serves to minimize the impact of negative characteristics (Soares *et al.* 2022).

The variables selected for evaluating the MATTI include COD removal efficiency, NH_3-N removal efficiency, GHG emissions, sludge production, land requirements, power consumption, capital expenditures (CAPEX), operational expenditures (OPEX), simplicity of O&M, and esthetics.

The MATTI quantifies the level of criteria compliance on a scale from 0 to 1, with increasing values indicating greater suitability in meeting local demands. The levels of suitability are classified as follows:

Greater than 0.75 to 1.0: Highly recommended
Greater than 0.5 to 0.75: Adequate
Greater than 0.25 to 0.5: Poorly adequate
0 to 0.25: Inadequate

This index is calculated by adding the normalized results of the analyzed characteristics, each multiplied by its respective weight as indicated in the following equation:

$$\text{MATTI}_{\text{technology } i} = \frac{\sum NR_J(i) \times w_j(i)}{\sum w_i} \quad (4)$$

where i is the compared technology, j is the analyzed parameter, $NR_J(i)$ is the result of parameter j, normalized to technology i, $w_j(i)$ is the weight attributed to the analyzed parameter and $\sum w_i$ is the sum of the assigned weights (Soares *et al.* 2022).

Weights are generally assigned by expert judgment.

Application of MATTI additionally requires the definition of the scenarios where it is applied. Two scenarios were considered for this assessment and are described below.

Scenario 1 description

This scenario reflects the current state of the wastewater treatment systems in the studied region. WWTP construction has been partially funded through international cooperation, and a foundation manages, operates, and maintains these facilities with subsidies. As a result, the significance of CAPEX and operational (OPEX) costs is diminished. In addition, the complexity of operations is not a major concern because trained personnel ensure proper O&M. Furthermore since the treated water is primarily intended for crop irrigation, nutrient removal becomes a secondary consideration.

Scenario 2 description

In this scenario, it is anticipated that water associations will eventually manage the WWTPs. Given Bolivia's status as a medium- to low-income country, treatment costs assume greater importance. The complexity of O&M also becomes crucial to ensuring the effective functioning of the WWTPs. Moreover, in different contexts where these systems might discharge into natural water bodies, more efficient nutrient removal becomes essential.

RESULTS AND DISCUSSION

This section details the outcomes of the evaluation, focusing on various critical aspects of the WWTPs.

Environmental dimension

Figure 7 presents the overall efficiencies and contributions of each of the processes that make up the different WWTPs, specifically in terms of COD, TSS, and NH_3-N.

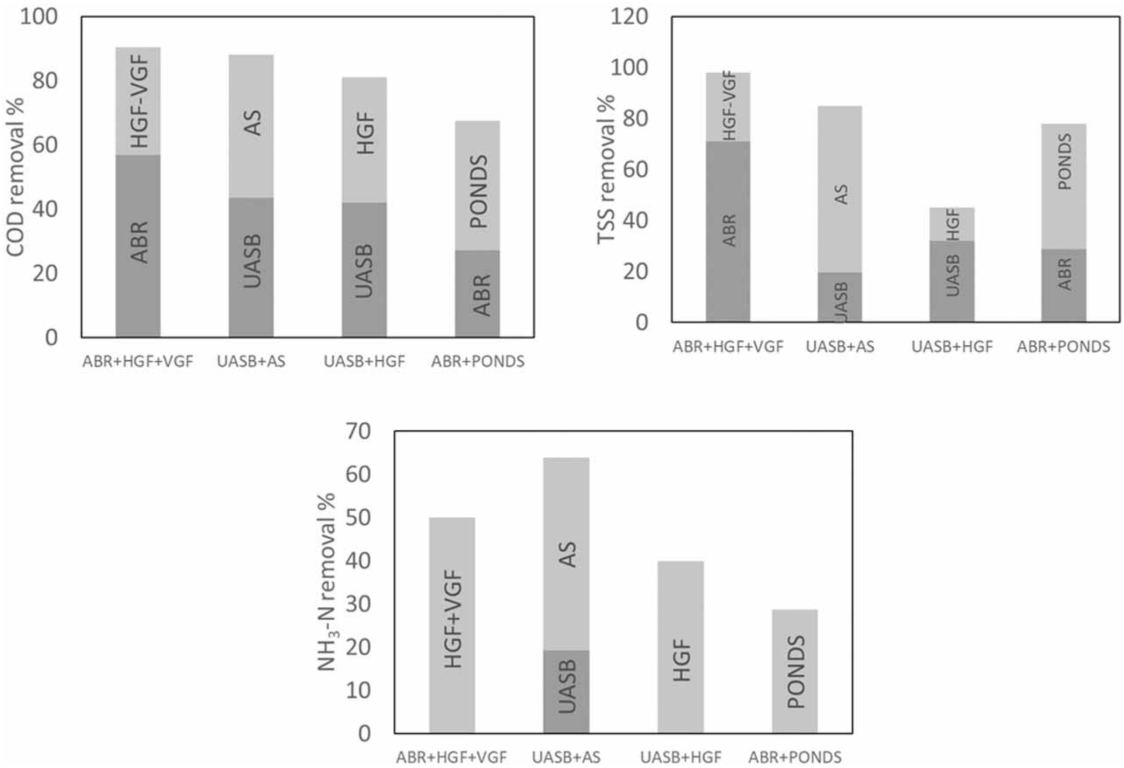


Figure 7 | Comparative efficiency of WWTPs.

The analysis of the efficiency shows that the UASB + AS and ABR + HGF + VGF configurations achieve higher COD removal efficiencies. As can be seen, the UASB in this evaluation achieves a removal rate of nearly 45%, and the overall efficiency reached in combination with the AS is 88%. This coincides with the results of various researchers who indicate that the UASB + AS combination is very effective, as the anaerobic stage proficiently removes a large amount of organic matter, and the activated sludge facilitates the removal of the remaining organic matter and suspended solids while aiding in nitrification (Von Sperling *et al.* 2001). Research indicates that integrating an up-flow anaerobic reactor with an activated sludge reactor can result in COD removal efficiencies of up to 87% (Von Sperling *et al.* 2001; Díaz-Gómez *et al.* 2022).

Furthermore, the ABR + HGF + VGF system is also recognized as a robust alternative, addressing certain drawbacks of up-flow anaerobic sludge blankets, such as fluidized bed expansion and biomass loss (Manariotis & Grigoropoulos 2006). In this study, this combination achieves a removal efficiency of 90% of total COD, with more than 50% occurring in the anaerobic stage. This combination is also efficient for suspended solids removal thanks to the addition of the hybrid biofilter, which effectively complements the removal of organic matter and suspended solids (Echeverría *et al.* 2022).

In comparison, the UASB + HGF and ABR + PONDS systems attain lower efficiencies of 81 and 68%, respectively. These disparities are largely due to the distinct treatment methodologies implemented.

Regarding the removal of ammonia nitrogen, the highest efficiencies are achieved with the UASB + AS combination, around 60%. However, none of these WWTPs have been designed for nutrient removal since the final destination of these effluents is agricultural irrigation reuse.

Table 1 compares the effluent characteristics of the four evaluated WWTPs against national and international standards pertinent to agricultural reuse.

Globally, different countries have set varied COD thresholds for wastewater reuse in agriculture. For instance, Italy and Israel mandate a maximum COD value of 100 (Jeong *et al.* 2016), while France stipulates a limit of 60 for irrigation, except in the case of raw-consumed crops (Paranychianakis *et al.* 2016). In the local Bolivian context, although specific COD standards for agricultural reuse are absent, environmental regulations (Law 1333) prescribe stringent discharge criteria at the WWTP outlet. The UASB + AS and ABR + HGF + VGF systems align with these international standards, unlike UASB + HGF and ABR + PONDS. Notably, ABR + PONDS

Table 1 | Comparison of wastewater treatment plants effluent characteristics with standards for agricultural reuse

WWTP Technology	TOLATA ABR + HGF + VGF	UCUREÑA UASB + AS	VILLA EL CARMEN UASB + HGF	COLQUERRANCHO ABR + PONDS	Agricultural reuse standard	References
COD (mg/L)	95	93	249	333	<60 <100	UNESCO (2017) Jeong *et al.* (2016)
TSS (mg/L)	18	34	460	78	<30 (processed food crops) <60	U.S. Environmental Protection Agency (EPA) and U.S. Agency for International Development (USAID) 2012 do Monte (2007)
NH_3–N (mg/L)	41.7	43	46	74	<30 as total nitrogen (TN)	MMAyA (2013)
P (mg/L)	8	16	16	9		–
pH	7.4	7.1	7.2	7.46	6–8.5	FAO/Unesco (1973)
Electrical conductivity (EC) (mS/cm)	2.35	1.67	1.78	1.47	0.7–3.0	Ayers & Westcot (1987)
$(SO_4)^{2-}$ (mg/L)	132.00	252.00	190.00	190.00		
$(Cl)^{-1}$ (mg/L)	336.70	107.04	145.12	168.34	142–355 For surface irrigation	Ayers & Westcot (1987)
$(NO)^{-3}$ (mg/L)	37.80	27.30	17.80	32.40	–	–
$(HCO_3)^{-1}$ (mg/L)	299.7	603.50	826.2	526.5	90–500	Ayers & Westcot (1987)
Na^{+1} (meq/L)	17.60	11.80	16.50	13.50	3–9 For surface irrigation	Ayers & Westcot (1987)
Ca^{+2} (meq/L)	5	4.6	2	4.2	–	–
Mg^{+2} (meq/L)	6.2	6.6	7.6	7	–	–
SAR	2.85	3.49	4.02	2.49	0–10 Low risk	Mohammadi-Moghadam *et al.* (2015)

fails to meet even the local discharge requirements, likely due to its expansion beyond the designed capacity in 2020.

Typical recommendation values for irrigation water according to the SAR index as sodium hazard to soil are 0–10 (low risk), 10–18 (medium risk), 18–26 (high risk), and >26 (very high risk) (Mohammadi-Moghadam *et al.* 2015). The effluents of the WWTPs evaluated according to their SAR index represent a low risk to the soil.

The results of estimating GHG emissions, sludge production, land requirements, and specific energy consumption are presented in Figure 8.

GHG emissions were relatively uniform across all systems, while sludge production was notably higher in the UASB + AS configuration.

The ABR + PONDS system demands the largest area per capita for wastewater treatment. Traditional waste stabilization ponds and constructed wetlands generally require substantial land, with standard pond systems needing about 4 m^2 per capita. In contrast, UASB combined with waste stabilization ponds reduces this demand to approximately 1.5 m^2 per capita (Brault *et al.* 2022). The results obtained from this evaluation suggest that a combined ABR + PONDS system can further reduce the area requirement to 1 m^2/cap.

The UASB and ABR systems are often categorized as intermediate-level treatment technologies, given their requirement for subsequent treatment stages, such as filters or ponds, to achieve optimal efficiency. These additional steps are important in removing residual contaminants, thereby producing high-quality effluent. UASB and ABR systems, as standalone processes, typically require a moderate amount of land, ranging from 0.1 to 0.4 m^2 per capita. Besides, processes like constructed and hybrid wetlands (both horizontal and vertical flow) demand considerably more space, approximately 2–4 m^2 per capita (Brault *et al.* 2022). In this evaluation,

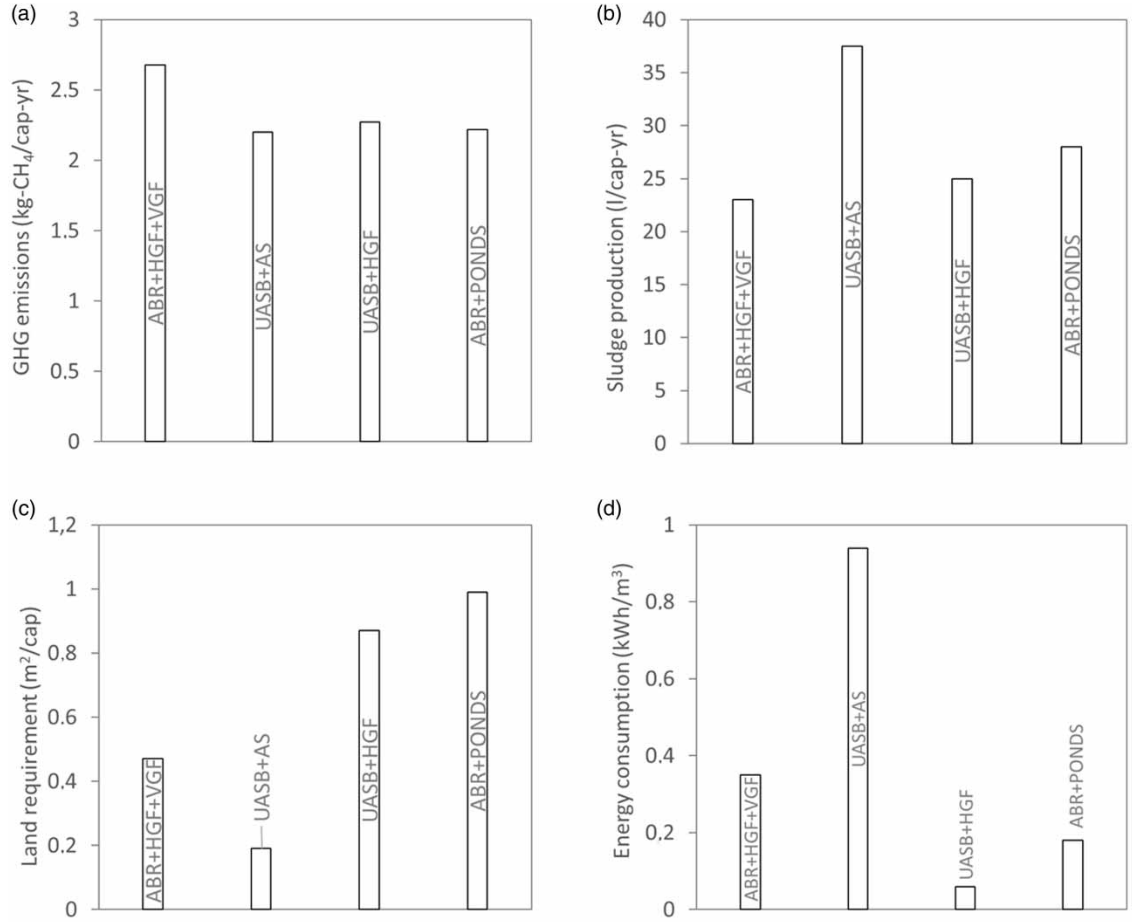


Figure 8 | (a) GHG emissions, (b) sludge production*, (c) land requirements, and (d) energy consumption. *Typical sludge quantities for these WWTPs configurations or similar from Brault *et al.* (2022) and Soares *et al.* (2022).

the combined UASB + HGF system occupies 0.87 m^2 per capita, while the ABR + HGF + VGF setup requires 0.47 m^2 per capita. These findings suggest that integrating compact anaerobic pretreatment with these systems can significantly reduce the area typically needed for processes like wetlands. Moreover, activated sludge technology, known for its space efficiency in wastewater treatment, further exemplifies this efficiency. For instance, extended aeration systems generally demand about 0.2 m^2 per capita (Brault *et al.* 2022). The UASB + AS combination in this study aligns with these standards, requiring only 0.19 m^2 per capita, underscoring its effectiveness in space utilization.

The energy consumption ranges from 0.06 to 0.94 kWh/m^3 of treated water. Energy consumption is not only one of the most critical factors to consider in the operational cost of wastewater treatment, which accounts for 15–50% of total operating costs (Buchauer *et al.* 2015) but also constitutes a significant concern in terms of environmental impacts due to its association with GHG emissions. In fact, there are several studies that classify this as an environmental indicator rather than an economic one, even though they are directly related (Popovic *et al.* 2013; Arroyo & Molinos-Senante 2018). The energy needed to operate a treatment plant can vary significantly, depending on various factors such as the energy efficiency of the devices, the quality of the raw water, and the size of the plant, among others.

Among the treatment configurations analyzed, the UASB + AS system exhibits the highest energy consumption, largely due to the energy-intensive nature of the secondary treatment processes such as aeration, sludge mixing, and recirculation. Aeration, which is essential for supplying oxygen to microorganisms, is particularly energy-demanding. Furthermore, the mixing and recirculation of activated sludge are essential for maintaining microbial populations but also contribute to energy use. Average energy consumption for conventional activated sludge plants varies internationally: 0.46 kWh/m^3 in Australia, 0.269 kWh/m^3 in China, 0.33–0.60 kWh/m^3 in the United States, 0.30–1.89 kWh/m^3 in Japan (Bodík & Kubaská 2013), and 1.02 kWh/m^3 in Italy (Ranieri *et al.* 2021). Decentralized plants similar in scale to those assessed in this study have energy consumptions ranging from 0.35 to 0.65 kWh/m^3 (Gu *et al.* 2017). The UASB + AS system evaluated here records a higher consumption of 0.94 kWh/m^3, suggesting potential areas for optimization to reduce energy use.

UASB and ABR systems, known for their anaerobic processes, are typically more energy-efficient than aerobic systems. This efficiency stems from their ability to decompose organic matter without the need for energy-intensive air blowers, thereby reducing operational costs (Mainardis *et al.* 2020). For instance, full-scale anaerobic systems in Italy report an average energy consumption of 0.43 kWh/m^3 of treated wastewater (Ranieri *et al.* 2021). The UASB + HGF system evaluated in this study demonstrated notably low energy consumption at 0.06 kWh/m^3. However, the ABR + HGF + VGF system exhibited a higher energy consumption of 0.48 kWh/m^3, despite a lower treatment capacity, which can be attributed to the energy required for pumping in the hybrid wetland system, particularly for the horizontal biofilter.

Waste stabilization ponds are another energy-efficient treatment option, often operating without energy input by utilizing gravity for flow between process units. The ABR + PONDS system in this study recorded an energy consumption of 0.21 kWh/m^3, primarily due to the energy required for pumping wastewater from the pretreatment stage to the ABR and the size of the facility.

Technical dimension

Operational characteristics of the WWTPs, such as staffing requirements, operational hours, frequency of various maintenance activities, and complexity of operations as assessed by the operators, are detailed in Supplementary material (Table S1). Key findings reveal that the UASB + AS system is the most operationally complex, while the UASB + HGF is less complex but still requires consistent attention due to its high flow rate, which may generate suspended solids washout from the anaerobic reactors to the filters, as reported by Saavedra *et al.* (2019). In all the WWTPs, routine operational activities predominantly focus on cleaning the pretreatment units to prevent clogging and ensure efficiency. Despite its larger treatment capacity, the ABR + PONDS system is simpler in terms of O&M.

Economic dimension

Understanding the financial aspects of water treatment facilities, including investment, operational and maintenance costs, and capital replacement over the lifecycle, is fundamental for assessing economic sustainability. The annual costs for the evaluated plants are divided into operational expenditures (OPEX), CAPEX, and the annual equivalent cost (AEC), which combines CAPEX and OPEX. The results based on design flow rates are presented in Figure 9.

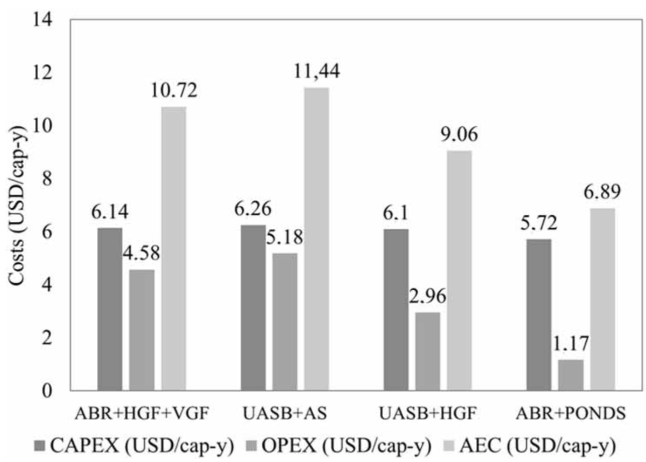


Figure 9 | CAPEX, OPEX and AEC of WWTPs.

According to Brault *et al.* (2022), treatment costs are categorized into high (above 20 USD/cap-yr), moderate (approximately 3–20 USD/cap-yr), or low (less than 3 USD/cap-yr) operating costs. The ABR + HGF + VGF and UASB + AS systems incur the highest operating and maintenance costs, falling within the moderate range at around 5 USD/cap-yr. In contrast, the UASB + HGF and ABR + PONDS systems demonstrate lower operational and maintenance costs, ranging from 1 to 3 USD/cap-yr. Furthermore, the AEC per volume of treated wastewater estimated for design flow were as follows: 0.33, 0.26, 0.32, and 0.13 USD/m^3 for ABR + HGF + VGF, UASB + AS, UASB + HGF, and ABR + PONDS, respectively.

Social dimension

When deploying a WWTP, several critical factors come into play, such as the size of the population served, public engagement, esthetic considerations like noise and odor, and the overall benefit to the community. In the rural areas surrounding the evaluated WWTPs, agriculture is the primary livelihood, with about 60% of the residents, or approximately 27,528 individuals, relying on it. The provision of treated water for crop irrigation by these WWTPs has been a significant boon, especially in a region grappling with resource scarcity. This support has been instrumental in bolstering the economic sustainability of these communities.

A key aspect of WWTPs' acceptability relates to esthetics, particularly odor management. Odor perception was evaluated on a scale of 1–5, with 1 representing the strongest odor and 5 the weakest. The ABR + HGF + VGF system received a score of 4, indicating relatively low odor perception, while UASB + AS was rated 5. Both the UASB + HGF and ABR + PONDS systems were rated 2, suggesting stronger odor emissions.

Application of MATTI

Utilizing the gathered information, the MATTI methodology was applied to identify the most suitable technology among the four configurations under review, particularly for regions in Bolivia or globally with similar socio-economic, climatic, and environmental contexts.

Table 2 outlines the variables selected for the MATTI calculation across all dimensions. These data come from the comprehensive assessment of the WWTPs discussed in the preceding sections. The column 'Direction' indicates that a variable with a positive direction (increasing) means that it is better the higher its value (e.g., treatment efficiency), while a variable with a negative direction (decreasing) means that it is better the lower its value (e.g., implementation costs). For ordinal values, the direction depends on the established scale. For example, in the case of odor perception, a higher odor perception is rated as 1 on a scale of 1–5, while a lower odor perception is rated as 5, making the direction of this variable positive.

Table 2 | Variables for the estimation of MATTI

	Technology	Direction	ABR + HGF + VGF	UASB + AS	UASB + HGF	ABR + PONDS
Technical dimension	Simplicity of O&M[a]	Positive	4	2	3	4
Environmental dimension	COD removal efficiency %	Positive	0.90	0.88	0.81	0.68
	GHG (kg-CH_4/cap-yr)	Negative	2.68	2.2	2.27	2.22
	Sludge to be disposal (l/cap-yr)	Negative	23	37.5	25	28
	Land requirement	Negative	0.47	0.19	0.87	0.99
	Power consumption (kWh/m^3)	Negative	0.35	0.94	0.06	0.18
Economic dimension	CAPEX (USD/cap-yr)	Negative	6.14	6.26	6.1	5.72
	OPEX (USD/cap-yr)	Negative	4.58	5.18	2.96	1.17
Social dimension	Odor perception[b]	Positive	4	5	2	2

[a]In a 1–5 scale, where: 1 is complex and 5 is simple.
[b]In a 1–5 scale, where: 1 is the major odor perception and 5 is the lowest odor perception.

Since the variables selected for the estimation of the MATTI are of different natures, both quantitative and qualitative, normalization was performed based on Equation (1). The results of the normalized values are provided as Supplementary material (SM-1 and SM-2). Subsequently, the estimation of the MATTI requires calculating the product of the normalized value by the weight assigned to the variable in question, as specified in Equation (2).

The weight assignment for these methods is generally based on the expertise of those involved in decision-making for WWTP implementation, and the criteria can vary by region. In this study, the work of Cossio *et al.* (2020), a local study, was used as a reference, gathering opinions from technical experts. According to their results, the importance of the four evaluation criteria follows this order: Social > Technical > Economic > Environmental. This indicates that the social factor is essential for the selection and sustainability of a technology, while the environmental factor is considered less important. However, in the present study, based on the authors' own judgment, greater weight was given to the environmental factor, considering that an effluent of adequate quality is more visually and esthetically acceptable, directly influencing the social acceptance of WWTPs.

Under these criteria, weights were assigned values from 1 to 5, where 1 represents the least importance and 5 is the greatest. For example, the importance of CAPEX is assigned a value of 3 when there are economic subsidies for the installation of WWTPs (Scenario 1). However, when the municipality relies on its own resources, CAPEX becomes more important, and a weight of 5 is assigned (Scenario 2).

The values of the assigned weight, the product of normalized values by the weight of each variable for each scenario, and the results of the estimation of MATTI are presented in Table 3. Additional details regarding the calculations for estimating MATTI are provided in the Supplementary material (SM-1 and SM-2). This information is presented in an Excel spreadsheet and has been customized for the purpose of a comprehensive evaluation, based on the original tool proposed by Soares *et al.* (2022).

The outcomes of the MATTI methodology indicate that both the ABR + HGF + VGF and UASB + AS configurations are considered adequate technologies for both scenarios, as they achieved the highest scores. Conversely, the UASB + HGF and ABR + PONDS sequences were rated as poorly adequate, scoring the lowest in both scenarios.

The empirical application of composite multi-criteria indicators for comparing the sustainability or suitability of WWTPs is still limited. The analytical hierarchy process (AHP) methods are possibly the most suitable for developing a multi-criteria indicator for decision-making purposes. There are some specific examples where these indicators have been applied. For instance, Soares *et al.* (2022) proposed the MATTI, a tool developed from AHP concepts as a composite indicator tailored to regional needs and the criteria of its users. Soares employed technical, economic, and environmental evaluation criteria in assessing seven treatment technologies across different scenarios in Brazil. The study found that UASB combined with high-rate plastic media percolating filters and UASB combined with biological aerated filters are the most suitable technologies for wastewater treatment, particularly in scenarios where the majority of the population resides in metropolitan areas with space constraints, stringent quality standards, and adequate tariffs to cover construction, operation, and maintenance costs. Conversely, rock media percolating filters and anaerobic ponds combined with percolating filters were found to be the most suitable technologies for small municipalities with fewer than 50,000 inhabitants, where ample space is available for WWTP implementation.

These findings contrast somewhat with those of this study, as the study area encompasses intermediate cities combining rural and urban activities, where space has become a limiting factor despite having municipalities with populations ranging from 2,000 to 20,000 inhabitants.

Another study conducted by Molinos Senante *et al.* (2014) focused on evaluating the sustainability of small WWTPs serving 1,500 inhabitants. This research assessed seven secondary treatment technologies commonly applied in small WWTPs. The study describes a hypothetical but typical context where the sewerage system is mixed, including both wastewater and stormwater, resulting in standard effluent concentrations, and where wastewater is discharged into non-sensitive areas without reuse. Up to seven scenarios were considered for weighting the dimensions evaluated in the study – technical, economic, and social. In the scenario where weights were assigned by experts, extended aeration emerged as the most sustainable technology for small communities. When equal weights were assigned to each dimension, constructed wetlands were found to be the most sustainable technology. Depending on the weight allocation in the other scenarios, the most sustainable technologies varied between constructed wetlands and extended aeration. However, lagoons also scored highly in all scenarios.

There are only a few examples of applying multi-criteria analysis for selecting the best treatment alternative or evaluating the most sustainable option in a specific scenario. These include studies by Castillo *et al.* (2017) for selecting the best technology for industrial effluent treatment and Bringer *et al.* (2018) for optimizing water quality in watersheds under management principles, in addition to the aforementioned studies by Soares *et al.* (2022) and Molinos Senante *et al.* (2014); Soares *et al.* (2022) and Molinos Senante *et al*. (2014).

Since selecting the best technology depends on specific contexts, gathering evidence-based information is essential.

Table 3 | Results for MATTI assessment in Scenarios 1 and 2

Parameter	Land requirement (m^2/cap)		GHG emissions (kg-CH_4/cap-yr)		Sludge to be disposal (l/cap-yr)		Power consumption (kWh/m^3)		Odor presence		Simplicity O&M		COD removal (%)		NH_3-N removal (%)		CAPEX (USD/cap-yr)		OPEX (USD/cap-yr)		MATTI $\frac{\sum NR_j(i) \times w_j(i)}{\sum w_i}$	
Scenario[a]	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**
Weights	4	4	2	2	3	4	3	4	5	5	3	5	3	5	2	5	3	5	3	5		
Normalized value × weight: $NR_j(i) \times w_j$																						
ABR + HGF + VGF	2.60	2.60	0.00	0.00	0.00	0.00	2.01	2.68	3.33	3.33	3.00	5.00	3.00	5.00	1.37	3.43	0.67	5.00	0.45	0.75	**0.53**	**0.54**
UASB + AS	4.00	4.00	2.00	2.00	3.00	4.00	0.00	0.00	5.00	5.00	0.00	0.00	2.73	4.55	2.00	5.00	0.00	4.55	0.00	0.00	**0.60**	**0.56**
UASB + HGF	0.60	0.60	1.70	1.70	0.41	0.55	3.00	4.00	0.00	0.00	1.50	2.50	1.77	2.95	1.41	3.53	0.89	2.95	1.66	2.77	**0.42**	**0.46**
ABR + PONDS	0.00	0.00	1.91	1.91	1.03	1.38	2.59	3.45	0.00	0.00	3.00	5.00	0.00	0.00	0.00	0.00	3.00	0.00	3.00	5.00	**0.47**	**0.49**

[a]Scenario 1: with subsidies, with effluent reuse; Scenario 2: without subsidies and no effluent reuse.

CONCLUSIONS

This comprehensive assessment of four decentralized WWTPs in a similar geographical and social context encompassed technical, environmental, economic, and social aspects.

Environmental aspect

The ABR + HGF + VGF and UASB + AS configurations exhibited very good performance, with COD removal efficiencies exceeding 87% and TSS removal over 85%. The UASB + HGF system showed reasonable efficiency in COD and TSS removal, but less than the aforementioned technologies. ABR + PONDS, while adequate in TSS removal, was less efficient in COD removal. UASB + AS and ABR + HGF + VGF achieved superior effluent quality (<85 mg-COD/L and <35 mg-TSS/L), aligning with agricultural reuse standards. In terms of the SAR index, all WWTPs presented a low risk, indicating suitability for irrigation purposes. UASB + AS was the most space-efficient with a land usage of 0.19 m^2/cap, and UASB + HGF and ABR + PONDS were more energy-efficient. GHG emissions and sludge production were also considered, with UASB + AS having the highest sludge disposal requirements.

Technical aspect

ABR + HGF + VGF and ABR + PONDS were noted for their ease of O&M. The UASB + AS system, despite being more complex operationally, justified this with its high efficiency. UASB + HGF, due to its larger size, had greater operational complexity.

Economic aspect

CAPEX was fairly uniform across all WWTPs ranging from 6.2 to 6.8 USD/cap-yr. However, OPEX varied, with ABR + PONDS having the lowest (1.17 USD/cap-yr), followed by UASB + HGF (2.96 USD/cap-yr). ABR + HGF + VGF and UASB + AS had slightly higher OPEX, 4.58 and 5.18 USD/cap-yr, respectively. The treatment costs per volume of water treated also followed this trend: ABR + PONDS (0.13 USD/m^3) < UASB + AS (0.26 USD/m^3) < UASB + HGF (0.32 USD/m^3) < ABR + HGF + VGF (0.33 USD/m^3).

Social aspect

The reuse of treated water for irrigation was significant, especially considering the agricultural dependency of about 60% of the population (27,528 inhabitants). The esthetic factor related to the acceptability of WWTPs in terms of odors reflects that these are more noticeable in ABR + PONDS and UASB + HGF.

The application of the MATTI in two scenarios – with and without economic subsidies, and with and without agricultural reuse as the end goal – showed that ABR + HGF + VGF and UASB + AS are adequate technologies. In contrast, UASB + HGF and ABR + PONDS were rated as poorly adequate. The selection of technology should consider local criteria and the specific context.

In short, the methodology used in this study is highly recommended for selecting appropriate technology for decentralized WWTPs in developing countries with similar climatic, geographic, and social conditions.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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