Circular Economy and Sustainability (2026) 6:222
https://doi.org/10.1007/s43615-026-00930-2

ORIGINAL PAPER

Participative Selection of Wastewater Treatment Systems in Informal Settlements: An Innovative Tool to Address Uncertainty

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Received: 22 October 2025 / Accepted: 24 March 2026

Abstract

Peri-urban settlements are characterized by inadequate wastewater management. Decentralized wastewater management systems are promising alternatives for reducing pollution from untreated sewage entering receiving water bodies, but the social, economic, and environmental conditions in peri-urban settlements require careful technology selection to ensure sustainability. Several domestic wastewater technology selection tools exist; however, these are typically designed for either urban or rural contexts. For this reason, this work proposes a decentralized wastewater technology selection tool for the context of peri-urban settlements that includes participation of local stakeholders in decision-making. The tool includes a technical component with three stages that involve multicriteria methods based on the Analytical Hierarchy Process and Montecarlo simulation to reduce uncertainty: i) decision according to context (settlement population, settlement typology, energy availability); ii) superior decision levels (nine sub-criteria from technical, environmental and economic dimensions); iii) technical and economic feasibility (dimensioning; cost of investment, operation and maintenance; availability to pay). The tool proposes a social strategy throughout the entire process to ensure stakeholder participation, aiming to strengthen capacities and knowledge co-production for informed technology selection. The tool was validated in a peri-urban settlement of Bucaramanga (Colombia), showing robustness and soundness. This innovative approach contributes to the search for sustainable solutions by facilitating the use of systematic tools by technicians and professionals in these contexts.

Highlights

- A multi-criteria tool for the participatory selection of wastewater treatment technologies for settlements was developed.
- The tool included technical, environmental, social, and economic pre-feasibility variables under uncertain scenarios.
- Validation of the tool in a case study confirmed its robustness and relevance for use in developing countries.

Extended author information available on the last page of the article

Keywords Wastewater · Informal settlements · Circular economy · DEWATS · Valorization

Introduction

It is estimated that approximately 2.4 billion people lack access to basic sanitation [1]. Furthermore, it has been reported that 80% of wastewater is discharged untreated into water sources [2]. This facilitates the transmission of diseases associated with wastewater management and the impact of discharges on receiving water sources [3, 4]. Low- and middle-income countries are the most adversely affected by the confluence of rapid population growth, migration to urban areas, a dearth of sanitation infrastructure, and constrained economic development [5].

Informal settlements are communities established on public or private land without authorization from the authorities [6]. These settlements are characterized by precarious housing and/or lack of basic services such as access to drinking water and sanitation [7, 8]. In general, they have artisanal wastewater collection and transport systems with limited connections to conventional sewerage systems. Additionally, wastewater is often discharged directly into water sources or the soil, which impacts hydrological services. This situation has stimulated the implementation of Decentralized Wastewater Treatment Systems (DEWATS), which treat wastewater close to the place of its generation, with the aim of being: i) economically sustainable; ii) socially acceptable; and iii) environmentally and technically efficient [6, 9]. In addition, given the characteristics of informal settlements, the technologies to be implemented in these contexts should consider the environmental, social, and technical specificities of these settlements.

Studies on DEWATS are diverse and aim to improve pollutant removal efficiency [10, 11], optimize existing systems [12], explore pilot and full-scale technologies [13, 14], and study economic aspects [15, 16]. However, few studies have been conducted in low- and middle-income countries on the selection of technologies to treat domestic wastewater, considering uncertainties and involving community participation. Similarly, there is even less literature on DEWATS in informal settlements.

Considering the diversity of technological options that could be applicable in informal settlements (e.g., aerobic and anaerobic, continuous and batch flow, compact systems), the characterization and selection of technologies requires the incorporation of environmental, technical, socio-cultural, and economic factors in the decision-making processes [17, 19]. Therefore, multi-criteria decision tools are essential to identify, evaluate, and select the best option among several alternatives [7, 8, 20].

The selection of wastewater technologies is usually developed according to practical rules in guidelines [21], decision trees [22], the use of multi-criteria decision making (MCDM), as well as structured decision making (SDM) processes [23]. However, many of these tools have limitations related to poor adaptability to changing contexts, failure to consider all dimensions of sustainability, or failure to incorporate uncertainty between the treatment technology and the context. Tools based on SDM approaches have shown the most effective results in selecting sanitation options in informal settlements due to their versatility [23].

Given that SDM-based tools may have uncertainties associated with variability in expert opinion on the importance of selection criteria, it is essential to complement such tools with mathematical models. This is critical in situations where treatment alternatives have uncertainties associated with characteristics such as removal efficiencies, complexity, environmental degradation, and others. Incorporating MCDM tools such as Fuzzy Analytic Hierarchy Process (FAHP), Fuzzy Technique for Order Preference by Similarity to Ideal Solution (Fuzzy-TOPSIS), and Monte Carlo simulation can address uncertainties in the decision-making process [24, 25].

FAHP and Fuzzy-TOPSIS are used to define the importance of criteria and prioritize alternatives among a set of feasible alternatives and have demonstrated their potential application in environmental problems. In the case of Monte Carlo simulation, it is used to model and analyze uncertainty in complex processes and systems, such as domestic wastewater treatment [26]. This technique involves generating possible scenarios by randomizing input variables, each of which can have a range of possible values represented by probability distributions [27]. Both MCDM and Monte Carlo simulation tools can enhance SDM to make the decision-making process more informed and assertive.

This article proposes a participatory methodology for selecting DEWATS in informal settlements within the context of the circular economy, which accounts for uncertainty in decision-making. To the authors' knowledge, this is the first time that such a tool has been developed and validated in informal settlements in low- and middle-income countries. Existing decision-support tools for wastewater technology selection are generally context-dependent, with limited capacity for transferability across socio-environmental settings. The proposed participatory–multicriteria framework introduces a replicable structure that can be parameterized with local data while maintaining methodological consistency, allowing its adaptation to diverse peri-urban or rural contexts in developing countries. This feature enhances the approach's potential scalability beyond the Colombian case study, positioning it as a decision-support model adaptable to similar sanitation challenges worldwide.

The study provides technical-environmental, economic, and social elements for decision-makers seeking to promote sustainable wastewater treatment options with community participation in these contexts. The article consists of four sections. Sect. "Description of the Tool for Participative DEWATS Selection" presents the developed participatory decision-making tool. Section "Validation of the Participative DEWATS Selection Tool in Informal Settlements" presents the validation of the tool for the communities of three informal settlements that share an artisanal sewerage network and a domestic wastewater management problem. Sect. "Discussion" presents the study's conclusions and future perspectives.

Description of the Tool for Participative DEWATS Selection

Figure 1 illustrates the proposed tool for participative DEWATS selection, which is divided into two blocks: technical and participative. In the technical block, a systematic classification of DEWATS is conducted, considering the uncertainties associated with the technologies. In the participative block, community stakeholders, after a knowledge acquisition process, select a DEWATS using the information provided in the technical block.

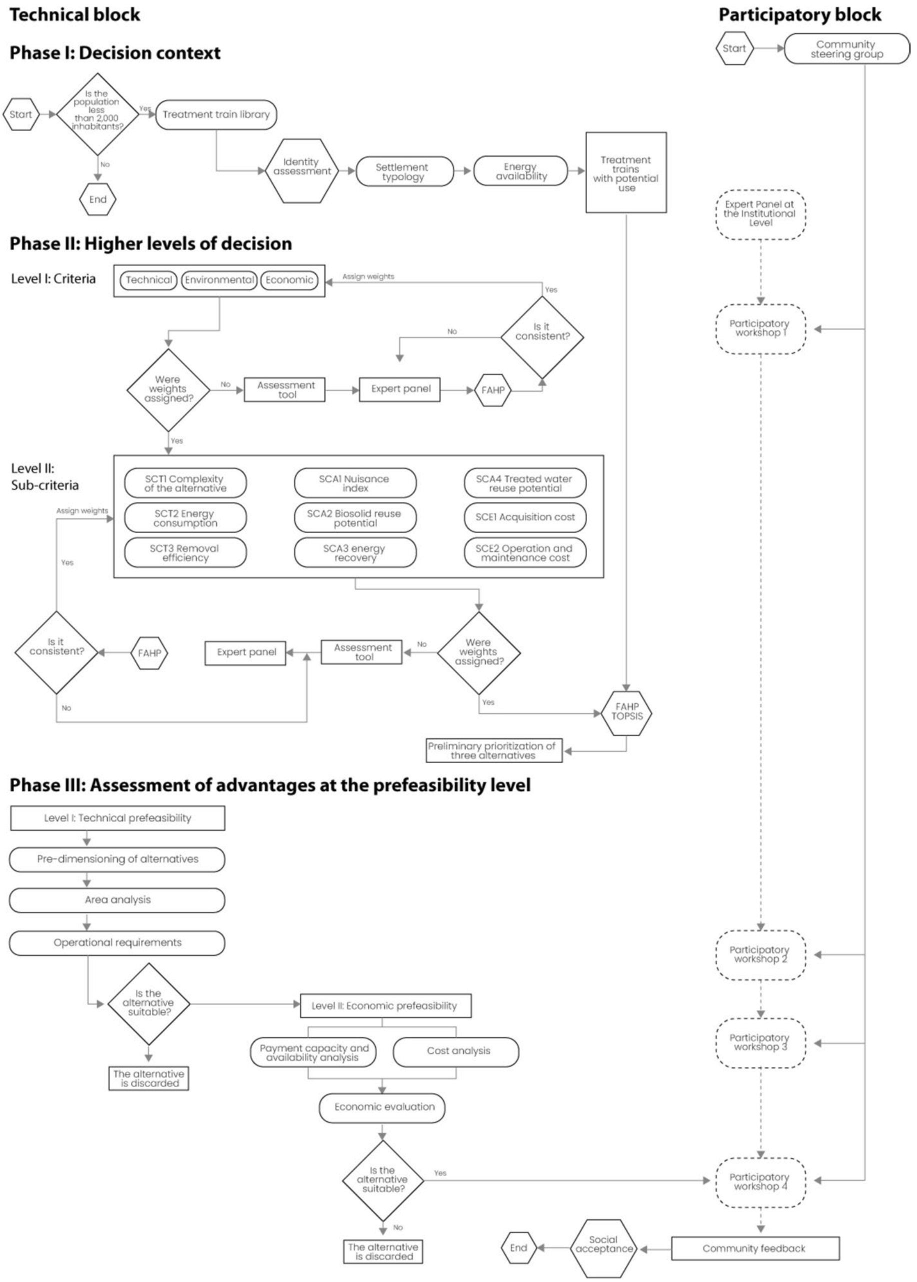

Fig. 1 Tool for the participative selection of DEWATS in informal settlements

Technical Block: Preliminary Assessment of Decentralized Wastewater Treatment Systems

The DEWATS assessment block consists of a set of technical elements that allow to determine which technologies are appropriate according to the context. The block consists of three phases: i) decision context, ii) higher decision levels, and iii) pre-feasibility studies of benefits and implications.

Phase I: Decision Context

Phase I considers the characteristics of the informal settlement and aims to filter the 48 DEWATS presented in Tables S1 and S2 of Supplementary Material S1 by applying the joint elimination method [28]. Technological options and treatment systems potentially applicable to informal settlements were identified through a comprehensive and systematic literature review. First, the settlement typology is defined as small (i.e., 100 to 550 inhabitants), medium (i.e., 550 to 1,100 inhabitants), or large (i.e., 1,100 to 20,000 inhabitants) by projecting the current population to a planning period defined by government agencies (in the case of Colombia, 25 years). The DEWATS for each type are presented in Table S3 of Supplementary Material S1. Once the informal settlement typology is defined, the DEWATS are evaluated in terms of the available area to determine the feasibility of extensive (i.e., high area requirement and lower operational complexity) or intensive (i.e., low area requirement and higher operational complexity) alternatives.

The available area is determined by the analysis of digital shapefile datasets that include: i) land use, ii) areas with environmental or legal restrictions, iii) areas with hazards, vulnerability, or risk of landslides and floods, iv) geological faults, v) water table, and vi) topography. The shapefiles are overlaid in a geographic information software to identify possible areas where the DEWATS could be located (see Supplementary Material S2). These generated areas should be discussed with territorial and environmental planning authorities. Once the possibility of the area for installing DEWATS has been agreed upon, an indicator is included that relates the projected population of the settlement to the available area for the DEWATS. The area indicator is shown in Eq. 1. The value of the Ia index is used to compare the area requirement with the area required for an extensive DEWATS (area > 1.5 m^2/inhabitant). If Ia is less than 1.5 m^2/inhabitant, intensive systems are recommended; if it is higher, both extensive and intensive systems are viable. Table S4 (see Supplementary Material S1) shows the intensive and extensive DEWATS based on the required area per inhabitant for each operational unit of the treatment system.

$$Ia = \frac{Aa}{HA} \tag{1}$$

where Ia is the area indicator [m2/inhabitant], Aa is the area available for DEWATS [m2], HA is the projected number of inhabitants in the settlement [Inhab].

The filtered DEWATS are evaluated for power availability. DEWATS that depend on electricity are discarded when there is no electricity in the informal settlement or when there are interruptions. The information needed to apply this criterion is obtained from a diagnosis of the water and sanitation conditions of the settlement. Table S5 shows the DEWATS with and without energy requirements (see Supplementary Material S1). The DEWATS that meet the requirements are referred to as "Treatment Alternatives with Potential Use" and are the input data for Phase II of the Technical Block.

Phase II: Higher Levels of Decision-Making

The treatment alternatives with potential use in the informal settlement are preliminarily compared and ranked using the FUZZY-AHP and FUZZY-TOPSIS tools. Through a systematic literature review, the project team identified and analyzed a set of criteria and sub-criteria, which were then filtered to develop the methodology (Table S6 in Supplementary Material S1). The weights for the criteria and sub-criteria were provided by a panel of experts from academia, institutions and industry from different parts of the world. A total of 29 experts participated, which exceeds the recommended number when they possess high expertise in a topic of interest [29]. Table 1 shows the consolidated criteria and sub-criteria used in the methodology. Table S6 in Supplementary Material S1 contains their description, desirability function (i.e., the objective from their description), typology, and measurement scale. It should be noted that, according to the experts' judgment, the environmental and technical criteria have the greatest uncertainty in the selection; however, in all cases, a Consistency Index (CI) of less than 0.1 was achieved, a value considered adequate for assigning

Table 1 Criteria and sub-criteria considered for the selection of DEWATS in informal settlements

Criterion	Sub-criterion	Definition	Diffuse weight (%)	Weight (%)
Technical (33.9%)	SCT1. Technical complexity of the DEWATS	Indicator of the ease of operation and maintenance of the technology as a function of skilled labor requirements	[33.0–40.0–47.0]	39.7
	SCT2. Energy consumption	Electrical energy consumption during the operation of the technology is related to its various components	[27.0–31.0–37.0]	31.5
	SCT3. Efficiency of the removal of pollutants	Removal efficiency of pollutants such as organic matter, nitrogen, phosphorus, and fecal coliforms as a function of concentration reduction	[24.0–29.0–34.0]	28.9
Environmental (38.7%)	SCA1. Environmental impact index with direct repercussions for inhabitants	Impact of DEWATS operations on local residents in terms of odors, noise, greenhouse gases and visual impact	[16.0–20.0–27.0]	20.5
	SCA2. Biosolids Reuse Potential	Possibility of recovering biosolids generated during the treatment process	[22.0–29.0–36.0]	28.5
	SCA3. Energy Recovery Potential	Possibility of using the biogas produced during treatment	[18.0–24.0–30.0]	23.7
	SCA4. Wastewater Reuse Potential	Possibility of reclaiming the DEWATS effluent	[21.0–27.0–35.0]	27.3
Economical (27.4%)	SCE1. Capital Expenditures (CAPEX)	The financial resources required for the procurement of equipment, infrastructure and the undertaking of a range of activities associated with the construction and implementation of the DEWATS	[35.1–41.8–50.2]	41.9
	SCE2. Operational expenditures (OPEX)	Expenses related to the operation of DEWATS	[48.5–58.2–69.4]	58.1

weights to the criteria and sub-criteria [30]. This result also demonstrated the importance of using fuzzy tools to address uncertainty in decision-making processes, minimizing the subjectivity associated with human judgments in processes such as pairwise comparisons.

The data for the treatment alternatives (i.e., DEWATS) should be characterized in the field or compiled from secondary information based on documented experience in the country of study. The information for each alternative is represented by a triangular fuzzy number *Rk* with membership function μ_{Rk} (x). The fuzzy numbers used (x_{ij}) are given by Eqs. 234. They are compared with respect to the fuzzy weight of the set of criteria $w_{ijk} = w_{jk1} \ldots w_{ijkn}$, forming a fuzzy matrix D as shown in Eq. 5 [25].

$$a = \frac{min}{k} \{a_k\} \tag{2}$$

$$b = \frac{1}{k} \sum_{k=1}^{k} b_k \tag{3}$$

$$c = \frac{max}{k} \{c_k\} \tag{4}$$

$$D = \begin{bmatrix} x_{1,1} \ldots x_{1,2} \ldots x_{1,n} \\ x_{2,1} \ldots x_{2,2} \ldots x_{2,n} \\ x_{m,1} \ldots x_{m,2} \ldots x_{m,n} \end{bmatrix} \tag{5}$$

where a, b and c are fuzzy numbers and D is the fuzzy matrix. Due to the dimensional heterogeneity of the attributes in each sub-criterion, the matrix D was normalized by a linear transformation that preserves the properties of fuzzy numbers, thus obtaining the normalized fuzzy matrix $R = [r_{ij}]_{mxn}$ through Eqs. 6 and 7, where $a^{-}{}_{j} = \frac{min}{k} a_j$ and $c^{*}{}_{j} = \frac{max}{k} c_{ij}$.

$$r_{ij} = \left(\frac{a_{ij}}{c^{*}{}_{j}}, \frac{b_{ij}}{c^{*}{}_{j}}, \frac{c_{ij}}{c^{*}{}_{j}} \right) \tag{6}$$

$$r_{ij} = \left(\frac{a^{-}{}_{j}}{c^{*}{}_{j}}, \frac{a^{-}{}_{j}}{c^{*}{}_{j}}, \frac{a^{-}{}_{j}}{c^{*}{}_{j}} \right) \tag{7}$$

where r_{ij}: the normalized fuzzified value of each attribute belonging to a subcriterion; a, b, c: is the rank of each attribute in the subcriterion.

With the fuzzy relative importance of each criterion, sub-criterion and the values of each alternative with fuzzy numbers, a normalized and weighted fuzzy decision matrix was formed considering that $V = [v_{ij}]_{mxn}$ where $v_{ij} = r_{ij} (.) w_j$. Then, the ideal positive (FPIS, A^{+}) and negative (FPIS, A^{-}) fuzzy solution is calculated considering the Eqs. 8 and 9.

$$A^{+} = v_1{}^{+}, v_2{}^{+} \ldots v_n{}^{+}, v_j{}^{+} = max \{v_{ij}\} \tag{8}$$

$$A^{-} = v_1{}^{-}, v_2{}^{-} \ldots v_n{}^{-}, v_j{}^{-} = min \{v_{ij}\} \tag{9}$$

where A^{+}: is the positive ideal fuzzy solution, A^{-}: is the negative ideal fuzzy solution, v_{ij}: is the product of the normalized matrix weighted by the sub-criteria weight.

Based on the fuzzy solutions, the ideal positive and negative fuzzy distances were determined (Eqs. 10 and 11), where d_v is the distance measure between two fuzzy numbers.

$$d^{+} = \sum_{j=1}^{n} d_v \left(v_{ij}, {v_j}^{+}\right) \tag{10}$$

$$d^{-} = \sum_{j=1}^{n} d_v \left(v_{ij}, {v_j}^{-}\right) \tag{11}$$

where d^{+} corresponds to a positive diffuse ideal distance, d^{-} corresponds to a negative diffuse ideal distance.

Finally, the proximity coefficient was calculated to determine the order of all possible alternatives. The proximity coefficient (CCi) simultaneously represents the distances to the positive fuzzy ideal solution (A^{+}) and to the negative fuzzy ideal solution (A^{-}). The CCi of each alternative was calculated using Eq. 12. After processing the information, the results of the FAHP-TOPSIS were obtained, which were used to rank the DEWATS.

$$CCi = \frac{d^{-}}{d^{+} + d^{-}} \tag{12}$$

Based on the results of the FAHP-TOPSIS, the most appropriate alternatives for potential use in the informal settlement are ranked from a technical, environmental and social perspective.

Phase III: Pre-Feasibility Studies of Benefits and Implications

Phase III of the screening tool consists of two levels, in which technical and economic pre-feasibility studies are carried out for the alternatives classified in Phase II. In the first level, the location of the DEWATS site is selected using a geographic information system (GIS), following the recommendations of [31]. This is done by characterizing criteria related to terrain vulnerability, soil, distance to water sources, urban centers and roads, and topography, which are accepted attributes for the location of a treatment system [32, 34]. Table 2 shows the criteria, sub-criteria and indicators for the selection of a site near a settlement. The selection of alternatives is performed using the suitability index (I_j), which ranks the location options (Eq. 13). The calculation of I_j is based on the weighted sum multicriteria method, using a Likert scale from 1 to 5, where 1 is the least favourable condition and 5 is the most favourable according to the normative criteria.

$$I_j = \sum_{i=1}^{m} W_i * C_{ij} \tag{13}$$

Table 2 Values for the reclassification of the raster for the selection of the DEWATS site

Criterion	Sub-criterion	Values assigned
Vulnerability	Flood Vulnerability	High = 1 Medium = 3 Low = 5
	Mass movement vulnerability	High = 1 Medium = 3 Low = 5
	Torrential Flood Vulnerability	High = 1 Medium = 3 Low = 5
Land	Land use	Agriculture = 3 Agroforestry = 3 Livestock = 5 Forestry = 3 Conservation = 1 Settlement = 1 Infrastructure = 1 Mining = 3 Waste Material Disposal Sites = 1 Natural Water Bodies = 1
Proximity to water sources, populated areas and roads	Proximity water source	Less than 50 m = 1 More than 50 m = 5
	Proximity to populated areas	Less than 200 m = 1 More than 200 m = 5
	Proximity to railroads	Less than 20 m = 1 More than 20 m = 5
Topography	Slope	Level, 0–1% (a) = 5 Slightly flat, 1–3% (a) = 4.5 Slightly sloped, 3–7% = 4 Moderately sloped, 7–12% = 3.5 Steeply sloped, 12–25% = 3 Slightly Steep, 25–50% = 2.5 Moderately steep, 50–75% = 2 Very steep, 75–100% = 1.5 Completely steep, > 100% = 1
	Altitude	500 a. s. l.m. – 720 a. s. l.m. = 5 720 a. s. l.m. – 740 a. s. l.m. = 4 740 a. s. l.m. – 760 a. s. l.m. = 3 760 a. s. l.m. – 780 a. s. l.m. = 2 780 a. s. l.m. – 1800 a. s. l.m. = 1

where I_j is the suitability index for alternative j, W_i is the weighted weight of criterion i, C_i is the performance value assigned to alternative *j* with respect to criterion *i*.

Once the location of the DEWATS is determined, the design flows and required areas for each alternative are estimated, considering the preliminary, primary, secondary, and tertiary treatment levels, as appropriate. The area where DEWATS is to be located is then compared to the area required for each treatment system. In this case, DEWATS, with a smaller required area than the available one, continue in the technical prefeasibility process.

$$\text{Area required}_{ai} < \ \text{Area available} \therefore \textit{The alternative is accepted} \tag{14}$$

The dimensioned DEWATS are then compared with respect to the effect of the terrain slope. In this case, the alternatives with potential for use according to the topography of the defined area for the DEWATS are filtered, taking into account the information presented in Table S7 (see Supplementary Material S1). The technical prefeasibility concludes with the analysis of the construction and operational requirements of the DEWATS, using the index of construction, operation and maintenance (ICO&M), according to Eq. 15. The ICO&M considers variables such as: i) regional/local supply of materials and equipment; ii) supply of inputs for maintenance and operation; iii) generation of waste requiring special management. A DEWATS with an ICO&M≥0.45 was considered acceptable for the economic pre-feasibility study; otherwise, it was discarded.

$$ICO\&M = \frac{OM\&E + I\&M + GW}{\sum n} \tag{15}$$

where $OM\&E$ is the regional/local supply of materials and equipment necessary for the construction of the alternative, $I\&M$ is the local and regional supply of inputs, parts, and materials for maintenance and operation of the alternative, GW is the generation of waste requiring special disposal or management, and n corresponds to the sum of points for each variable.

The second level of economic prefeasibility is applied to DEWATS that meet the OM&E index. The Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) were estimated for each DEWATS. The CAPEX is calculated from Eq. 16, while the OPEX is calculated from Eq. 18.

$$CAPEX = CM + CHE + CMC + CT + CAIU + CA \tag{16}$$

$$CAIU = \frac{AIU}{100} * CD \tag{17}$$

$$OPEX = CMO + CM\&R + CIQ + CM\&C + CEE + CTTr \tag{18}$$

where CM is the cost of materials required for the design of alternative *ij,* CHE is the cost of tools and equipment required for the design of alternative *ij,* CMC is the cost of labor for the construction of alternative *ij;* CT is the cost of land acquisition and/or adequacy; $CAIU$ is the cost of contingencies, administration, and utilities; CD are direct costs of the alternative; CA are additional costs; CMO are labor costs associated with the operation of alternative *ij,* $CM\&R$ are costs associated with the maintenance and repair of equipment for alternative *ij,* $CM\&C$ are costs associated with the purchase of chemical inputs for alternative *ij,* $CM\&C$ are costs associated with process control and water quality; CEE are costs associated with energy consumption; and $CTTr$ are costs associated with the retributive rate charge.

To estimate the potential income, the willingness to pay (WTP) of the inhabitants of the settlement is first assessed using logit or probit econometric models (Eqs. 19 and 20) and goodness-of-fit tests such as pseudo-R^2, percentage ranking and the Lemeshow-Hosmer test. These models include variables such as the current situation of the settlement (discharge of WW to water sources) and the impact of DEWATS. Table S8 details the variables used to estimate WTP (see Supplementary Material S1). Once the parameters are estimated, WTP is calculated as the expected value using the Zi=$X_i\beta$ index and the price coefficient (Eq. 21).

$$Prob(Y_i = 1/X_i) = \Lambda(X_i\beta) = \frac{1}{1+e^{X_i\beta}} = P_i \tag{19}$$

$$Prob(Y_i = 1/X_i) = \Phi(X_i\beta) = \int_{-\infty}^{X_i\beta} \frac{1}{2}\frac{1}{1+e^{X_i\beta}} = P_i \tag{20}$$

$$E_u(WTP/X_iB) = \frac{X_i\beta}{B_{precio}} \tag{21}$$

where $E_u(WTP/X_iB)$ is the ability to pay, X_i is the average value of each of the significant independent variables of the model, β: coefficient of the model corresponding to the independent variable, B_{precio} is the coefficient of the supply price variable.

To estimate the potential income generated by the implementation of the wastewater treatment project, the number of potential users of the service in the settlement and the WTP value of treatment per user per month are considered, as shown in Eqs. 222324.

$$Users_{ser} = \#users * P_{WTP} \tag{22}$$

$$Income_{month} = WTP * Users_{ser} \tag{23}$$

$$Income_{year} = income_{month} * 12 \tag{24}$$

where $Users_{ser}$ is the number of potential users of the service, $\#users$ is the number of users present in the settlement, P_{WTP}: probability of WTP and WTP average willingness to pay.

Once the possible revenues and service operator have been defined, the economic viability of each DEWATS is assessed through an economic evaluation using indicators such as net present value (NPV), cost benefit ratio (CBR), and annual equivalent cost (AEC). For this, the tool considers the country's average inflation and discount rate (i.e., 3.7% and 12.76% respectively, in the case of Colombia). To analyze the uncertainty of the economic level, Monte Carlo Simulation is used, taking as input data the cash flow and the variations of inflation and discount rate of the country of study (i.e., inflation between 1.8 and 9.0% in Colombia and discount rate between 2.5 and 12.8%) for those DEWATS that have a NPV greater than or equal to zero. The simulation included 10,000 iterations, with NPV as the response variable, which allowed defining the level of risk associated with each DEWATS and the range of fluctuation of NPV.

Participative Block of the DEWATS Selection Tool

The participative block is an essential element of the tool. This block involves the formation of a driving group with members of the settlement who voluntarily wish to participate in the process at three stages: i) appropriation of knowledge; ii) participatory selection; and iii) sharing of the results of the decision process.

The knowledge appropriation stage focuses on the formation of the driving group and the acquisition of skills that will enable its members to make informed decisions. This level begins at the end of Phase III of the technical block, where several DEWATS with potential application in the settlement have been identified. At this stage, the driving group is expected to learn about sanitation, wastewater, wastewater collection infrastructure and decentralized wastewater systems, wastewater treatment technologies with potential for use in settlement, possible by-products, environmental impacts and costs. The proposed pedagogical strategy is detailed in Supplementary Material S3.

The individual DEWATS selection is made using a choice card given to each member of the driving group (see Fig. 2). The card provides information on the performance of each DEWATS with respect to each of the weighted criteria listed above. Driving group members are asked to rate the nuisance index, COPEX, operational complexity, and effluent quality for each DEWATS on a qualitative scale of good, fair, and poor. The individual results are collected, processed and weighted by the technical team to identify DEWATS with the highest scores. While this process is taking place, the driving group, accompanied by a facilitator, performs the collective selection of the DEWATS. The same selection card is used, but printed in a large size. Each member of the driving group records their scores publicly. The facilitator encourages a collective discussion of the results and highlights the DEWATS that emerged from the exercise.

At the time of the final decision, the technical team presents the result of the individual evaluation to the driving group and asks them to compare it with the collective evaluation. If both agree, the resulting decision is approved. If there is disagreement, group discussion is encouraged to reach a new collective decision by consensus. If consensus cannot be reached, a vote is taken, and the DEWATS with the most votes is selected. The results of the decision-making process are disseminated by the driving team in the settlement.

CHOICE CARD **NAME:_______________** **COMMUNITY:_______________**

DEWATS	Potential environmental impacts	Environmental benignity	Associated costs	Affordability	Operational complexity	Ease of operation and maintenance	Removal of pollutants	Effluent quality
DEWATS 1 Preliminary treatment + UASB reactor	**Noise:** Low **Odors:** Medium **Visual Impact:** Low		**Initial investment:** COP$1,096'182.900 **Operation and maintenance:** COP$7.700		Personnel with technical knowledge		**Suspended solids:** High **Organic Matter:** Medium **Pathogenic microorganisms:** Low	
DEWATS 2 Preliminary treatment + UASB Reactor + UAF	**Noise:** Low **Odors:** High **Visual Impact:** **Low**		**Initial investment:** COP$2.561'221.800 **Operation and maintenance:** $8,100		Personnel with technical knowledge		**Suspended solids:** High **Organic Matter:** High **Pathogenic microorganisms:** Low	
DEWATS 3 Preliminary treatment + UASB Reactor + UAF + Chlorination	**Noise:** Medium **Odors:** High **Visual Impact:** Low		**Initial investment:** COP$2.634'829.700 **Operation and maintenance:** COP $ 10.400		Personnel with technical knowledge Handling of chemical supplies		**Suspended solids:** High **Organic Matter:** High **Pathogenic microorganisms:** Low	

Fig. 2 Example of a selection card for selecting DEWATS. Source: Author's elaboration

Validation of the Participative DEWATS Selection Tool in Informal Settlements

Context of the Informal Settlements

There is an increasing trend of migration to peri-urban areas in Colombia. The Bucaramanga Metropolitan Area (AMB), which includes the municipalities of Bucaramanga, Girón, Floridablanca and Piedecuesta in the department of Santander (see Fig. 3), had 251 informal settlements and approximately 230,000 inhabitants in 2013. It is estimated that by 2023, these settlements will exceed 350. These communities, lacking formal recognition, have inadequate sanitation infrastructure that can affect the ecosystem services of the Río Alto Lebrija watershed due to untreated domestic wastewater discharges. This watershed is crucial as it provides essential hydrological services of water supply [35].

Informal settlements in the AMB include Miradores de la UIS, El Porvenir- Los Cuadros and Los Santos Bajo, near the Suratá River (Fig. 3). The temperature in these settlements ranges between 22.7 °C and 23.4 °C, and they have two periods of high rainfall per year and two dry periods [35]. The population in 2023 was 2,160 inhabitants for Miradores de la UIS, 1,728 inhabitants for El Provenir-Los Cuadros and 1,144 inhabitants for Los Santos Bajo. In all cases, the population is expected to increase in the years to come. In Miradores de la UIS, 98% of the population has access to drinking water, with an availability of 4 to 7 h per day. In El Porvenir-Los Cuadros, 90% of the population has access to drinking water, which

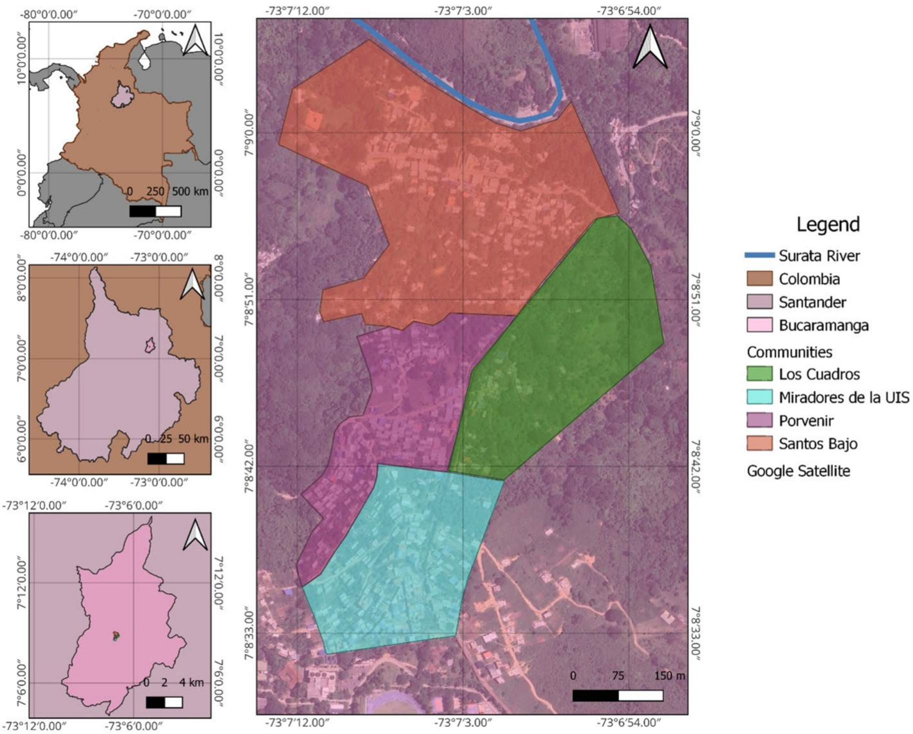

Fig. 3 Location of the settlements under study

is supplied through pipelines (public water supply), cisterns and water trucks. Of these, 50% have daily access to water (the majority less than 1 h per day). In contrast, most of the sectors in Los Santos Bajo are supplied by a cistern, although others are connected to the El Porvenir-Los Cuadros water system or receive water from a water truck.

Regarding wastewater management, 84%, 70% and 90% of the settlements (i.e., Miradores de la UIS, El Porvenir-Los Cuadros, and Los Santos Bajo, respectively) are connected to the same artisanal sewerage system (i.e., no conventional system). This system suffers from a series of limitations due to difficult hydraulic conditions, collector blockages, vector presence, and unpleasant odours. These conditions affect the community's quality of life and the environment, as the system discharges untreated wastewater directly into the Suratá River.

Application of the DEWATS Pre-Selection Technical Block

Decision Context

It is estimated that in 25 years the population of Miradores de la UIS, El Porvenir-Los Cuadros and Los Santos Bajo will grow significantly, reaching 6,448, 3,132 and 4,012 inhabitants respectively. These data place the settlements within the population range of 1,100 to 20,000 inhabitants, classifying them as large settlements (i.e., three settlements forming a single case study with a DEWATS selection that will serve all settlements). Due to the proximity of the settlements, the topography of the terrain and the limited space available in Miradores de la UIS and El Porvenir, it was considered that the DEWATS should be located in Los Santos Bajo to serve all three informal settlements. Table 3 shows the DEWATS with potential applications in the settlements.

Regarding the requirements for the implementation of a DEWATS, the settlements have the following characteristics: i) they have prepaid electricity, which would allow the installation of a DEWATS with an appropriate agreement with the supplying energy company; ii) the reuse of wastewater is limited due to the topography, which hinders the necessary infrastructure, although the community is interested in using the water for irrigation; and iii) there is an area of 1.5 Ha that could accommodate a DEWATS. On the other hand, the possibility of using extensive technologies is limited (area > 1.5 Hab/m^2) because the area indicator (Ia) was equivalent to 0.33, 0.18 and 0.24 Hab/m^2 for each settlement. This result demonstrates that 10 intensive DEWATS are viable for implementation and aligns with the technological offer, as presented in Table 3, considering the availability of electric power.

Table 3 Suggested DEWATS by typology for large settlements and suggested according to the area index

Type of settlement	SDTAR
large settlements	TPS1, TPS2, TPS3, TPS4, TPS5, TPS6, TPS7, TPS8, TPS9, TPS10, TPS11, TPS12, TPS13, TPS14, TPS15, TPS16, TPS17, TPS18, TPS19, TPS20, TPS21, TPS22, TPS23, TPST1, TPST2, TPST3, TPST4, TPST5, TPST6, TPST7, TPST8, TPST9, TPST10, TPST11, TPST12, TPST13, TPST14, TPST15, TPST16, TPST17, TPST18, TPST19, TPST20, TPST21, TPST22, TPST23, TPST24
Intensive systems	TPS1, TPS2, TPS6, TPS11, TPS15, TPS16, TPS17, TPS18, TPS19, TPS20, TPST4, TPST17, TPST18, TPST19

TPS treatment system with preliminary, primary and secondary treatment level (does not allow reuse). *TPST* Treatment system with preliminary, primary, secondary and tertiary treatment level (allows reuse)

Higher Levels of Decision Making

Table 4 shows the results of the multicriteria analysis with the FUZZY-AHP-TOPSIS tools. The five best DEWATS from the technical, environmental and economic dimensions corresponded to the alternatives TPST16, TPS17, TPS18, TPST18 and TPS19 in descending order according to the proximity coefficient (CCi). These systems are highly efficient for removing organic matter, with significant potential for energy generation and improved effluent quality. It should be noted that DEWATS with tertiary treatment have a higher potential for inactivating microorganisms and a greater reuse potential. The result is consistent with the objective of prioritizing DEWATS that maximizes the valorization of by-products within the circular economy. It is highlighted that the five DEWATS are the ones classified for evaluation in Phase III of the tool.

The first position (CCi 82.7) was occupied by the UASB reactor due to its operational versatility, lower costs (CAPEX and OPEX), low complexity, and the potential to produce by-products, such as methane and stabilized sludge, which can be used for agricultural purposes. The DEWATS consisting of two anaerobic systems, such as the UASB reactor and FAFA (i.e., system up to the secondary treatment level), was ranked second (69.6); this configuration was affected by the increase in CAPEX and OPEX costs compared to the first alternative (i.e., UASB). In third position (56.8) was the DEWATS with tertiary treatment level UASB, FAFA and chlorination, while the DEWATS consisting of UASB and FP occupied the fourth position (CCi 50.1). The latter was in this position due to the energy requirement of the aerobic unit operation and, therefore, the lower energy generation potential.

The DEWATS ranked in the first four positions have been evaluated in different scales and contexts, demonstrating their feasibility of application [13, 36, 37]. In the case of informal settlements, Ferreira et al. [6] conducted a literature review of decentralized systems in Brazil between 1991 and 2021, highlighting that technological alternatives such as septic tanks, biological filters, and anaerobic reactors are appropriate in this context due to their social acceptability and environmental benefits. This is in line with the report by Rodrigues Mesquita [11], who indicate that these systems are a viable and effective option for treating wastewater and meeting water quality standards. However, as highlighted by

Table 4 DEWATS classification with potential applicability in settlements

DEWATS	Alternative	CCi	Rank
TPS17	UASB	82.7	1
TPS18	UASB + UAF	69.6	2
TPST17	UASB + UAF + chlorination	56.8	3
TPS19	UASB + TF	50.1	4
TPS2	AUF	46.9	5
TPST18	UASB + TF + chlorination	44.1	6
TPS1	ST + UAF	40.8	7
TPS16	ABR + UAF	39.5	8
TPS6	IT + UAF	35.6	9
TPS15	PS + FP	34.0	10
TPS17	SBR	32.4	11
TPST4	ABR + UAF + chlorination	32.2	12
TPS19	UASB + RBC	29.3	13
TPST19	UASB + RBC + chlorination	22.1	14

ST is septic tank, *UAF* is upflow anaerbic filter, *IT* is imhoff tank, *SBR* is sequential batch reactor, *SP* is primary sedimentation, *TF* is trickling filter, *UASB* is upflow anaerobic sludge blanket reactor, *y RBC* is rotatory biological contactor

Bernal et al. [17], there is a need to deepen the selection process for DEWATS to be efficient, sustainable and accepted by the community.

For DEWATS ranked above 4, the lower Cci index value (below 50) is associated with higher operational complexity, energy requirements, or limited energy recovery. The FAFA and the UASB, FP, and Chlorination DEWATS ranked fifth and sixth, respectively. In the first case, the low energy production of the FAFA compared to what could be achieved with a UASB affected its CCi; similarly, for the UASB, FP, and Chlorination DEWATS, the energy and area requirements of the FP affected their rating. In seventh and eighth place were the DEWATS septic tank with FAFA and the ABR with FAFA. Although these systems are widely used in rural communities, they were affected by producing less stabilized sludges compared to other systems (e.g., UASB or FAFA); moreover, the energy production is also low [36], so the utilization of by-products is limited. This aspect negatively affected the evaluation of the alternatives. Similarly, the DEWATS of TI and FAFA have low operational complexity and low energy generation. In addition, Mikelonis et al. [38] highlights that these systems require frequent monitoring so that the efficiency of pollutant removal is not compromised, an aspect that may limit their applicability in unplanned human settlements [39]. On the other hand, DEWATS between the ninth and fourteenth positions are the least appropriate systems according to the decision context and settlement conditions.

- Benefit and Impact Pre-Feasibility Study *Technical Prefeasibility*

The methodology presented in Supplementary Material S2 was used to select the implementation site. By applying the site selection methodology, a site with an area of approximately 1.5 ha was selected (see Supplementary Material S4). To evaluate the feasibility of implementing DEWATS classified by fuzzy TOPSIS, Table 5 shows the area required for each treatment system. The sizing of the DEWATS was performed according to the criteria established by the Colombian Resolution 0330 of 2017. In all cases, the required area is less than 1.5 hectares, which is less than the available area for DEWATS installation. In addition, given the region's topographic characteristics, with slopes ranging from 0 to 1%, all DEWATS are suitable for implementation in this location.

For the construction and operational requirements of DEWATS, all materials for their construction can be found locally and regionally. Therefore, the ICO&M Index for the DEWATS pretreatment-UASB was 1, while for the others it was 0.86 (i.e., pretreatment-UASB-FAFA, pretreatment-UASB-FAFA-chlorination, pretreatment-UASB-FP). Table S10 presents the values of the indices that constitute the ICO&M in more detail (See supplementary material S1).

- *Economic Prefeasibility*

Table 5 DEWATS Area Requirement

DEWATS	Alternative	DEWATS area (m^2)	Total area required (m^2)
TPS17	UASB	434.0	564.2
TPS18	UASB + UAF	979.0	1272.7
TPST18	UASB + UAF + Chlorination	1174.8	1527.2
TPS19	UASB + TF	1389.2	1805.9

ST is septic tank, *UAF* is upflow anaerobic filter, *TF* is trickling filter, *UASB* is upflow anerobic sludge blanket reactor

Table 6 shows the CAPEX and COPEX for the DEWATS. The treatment systems with FAFA (i.e., TPS18 and TPST18) have the highest investment costs, with the chlorination alternative being the most expensive option. The implementation of a chlorination unit at the tertiary level results in additional costs of 2.7% and 16.88% in the treatment trains compared to trains without this component. As far as COPEX is concerned, DEWATS with tertiary treatment have the highest costs due to the need to monitor each treatment unit. On the other hand, trains with individual technologies have similar monitoring costs because they do not require specific controls such as activated sludge systems. In terms of energy consumption, DEWATS TPS19 requires electricity for mechanical equipment, lighting and administrative operations. Anaerobic DEWATS only consider consumption for lighting and administrative activities. Finally, it is estimated that the COPEX of the DEWATS, considering the total number of users (i.e., 1,226 dwellings in the informal settlements), ranges between US$1.0 and US$2.3 per month. In terms of WTP, the three settlements had a payment probability of more than 90%, and the econometric models for each case are presented in Table S11, Table S12, and Table S13. Overall, the WTP for the three settlements was US$2.6 per month, which can cover the COPEX of the DEWATS, except for the system that includes FP (i.e., TPS19). According to the results, the communities of the three informal settlements could generate a monthly income of $US 3,185 and an annual income of $US 8,220.42, which could be used for operation and maintenance. In this case, the sale of biogas or digestate was not considered, as there is currently no market for these by-products.

The DEWATS TPS17 and TPS18 were demonstrated to be cost-effective, as evidenced by their NPV and AEC values being greater than zero; they also had a CBR greater than 1, indicating that the benefits outweighed the costs of implementing a DEWATS. In contrast, the TPST18 and TPS19 systems are discarded due to their lack of economic viability (i.e., NPV values less than 0). Figure 4 shows the Monte Carlo simulation results for the economically viable DEWATS, based on 10,000 iterations. In general, at low discount rates (i.e., 2.5 to 4.7 percent) and inflation rates (i.e., 4.5 to 6.0 percent), a range between $70,000 and $100,000 can be achieved. The increase in inflation, while resulting in higher net present values, implies a higher cost of living that could make it difficult for communities to pay the tariff. On the other hand, since the discount rate is higher than 5.8%, the present net value is reduced regardless of the assumed inflation rate. It should be noted that DEWATS TPS17 has the highest feasibility, with an average NPV of $110,184.7 and values ranging from $123,857 to $142,150.4, corresponding to a confidence interval of 80% to 90%. This is consistent with Medeiros et al. [40] and Pereira Silva et al., [41] who reported on the feasibility of using UASB for wastewater treatment. TPS18 presented the lowest NPV values

Table 6 Investment costs for the different treatment systems studied

DEWATS	Alternative	CAPEX US $	OPEX $US Year^{-1}	NPV $US	CBR	AEC $US
TPS17	UASB	277,518.9	31,153.3	58,030.1	1.2	8,144.3
TPS18	UASB+UAF	648,420.4	34,960.1	7,146.7	1.1	1007.9
TPST18	UASB+UAF+Chlorination	667,055.6	37,722.0	−34,564.0	1.0	−3,951.8
TPS19	UASB+TF	682,719.3	45,266.3	−129,032.2	0.84	−18,103.8

The estimated CAPEX includes pre-treatment and assumes that the investment will be made by a government entity. The results correspond to an inflation rate of 3.7% and a discount rate of 12.76%. *CAPEX: OPEX: NPV* net present values, *CBR* cost benefit ratio, *AEC* Annual Equivalent Cost

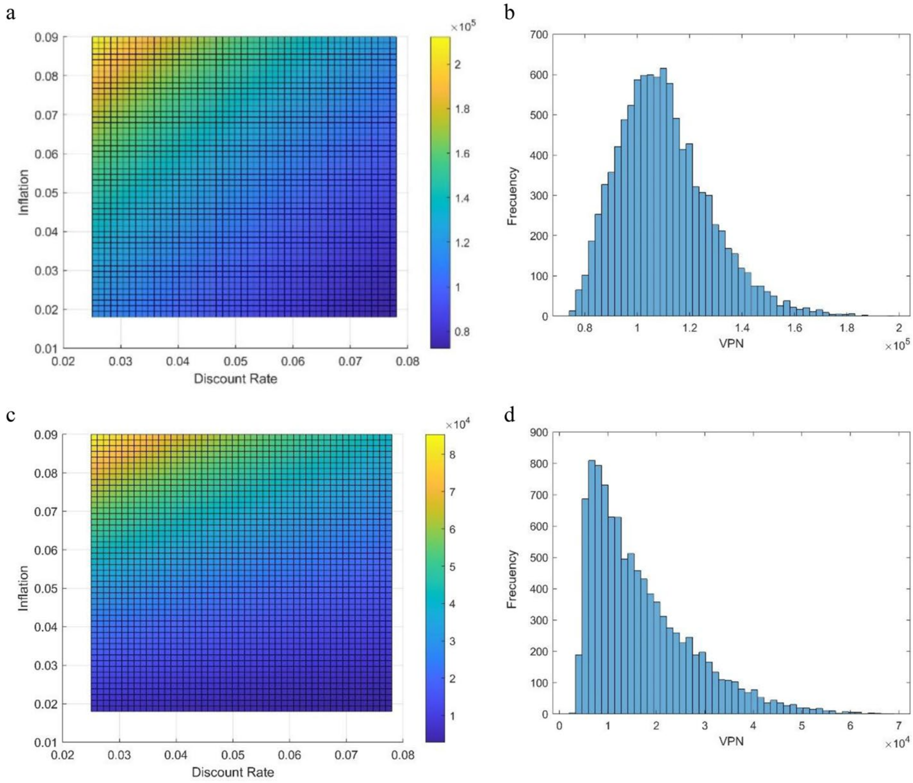

Fig. 4 Monte Carlo simulation results **a** Simulation for TPS17. **b** Histogram of the simulated NPV for TPS17. **c** Simulation for TPS18. **d** Histogram of simulated NPV for TPS18

(i.e., mean NPV of $US 16,921.7) and has the highest risk among the economically viable DEWATS.

Participative Block of Selection of the Wastewater Treatment System

A driving group was formed in each community, comprising 26 participants across the three settlements. Critical case sampling was employed to purposively select local leaders with extensive knowledge of local conditions, to incorporate their perspectives and experiences into the participatory block. The inclusion criteria for participant selection were: (i) being at least 18 years of age; (ii) having permanent residence in the settlement; (iii) having lived in the settlement for no less than one year; and (iv) willingness to participate voluntarily, without financial compensation. The driving groups were involved in the stages of knowledge appropriation, participatory selection, and shared decision-making described above. Their level of participation varied throughout the process; on average, approximately 18,75 leaders attended the group meetings. Following a training process (see Supplementary Material S3), 17 members of the driving groups ranked the selection criteria and conducted both individual and collective evaluations of the DEWATS alternatives TPS17 and TPS18. A final decision was reached through a participatory forum and subsequently shared with their respective communities. In total, 82 residents participated in these subsequent community meetings, during which the results of the decision-making process were shared. Attendance was voluntary and resulted from an open call to all settlement residents.

Table 7 presents the weightings obtained, while Table 8 details the results of both individual and collective evaluations. The latter shows consistency in the classification and evaluation of the criteria, both at the individual and group levels.

DEWATS TPS17 ranked first due to the impact of the nuisance index and affordability on the system's sustainability. Among the reasons given by the community for selecting this system were: i) lower nuisance index due to less landscape degradation; ii) less odor generation; iii) lower operation and maintenance costs compared to other DEWATS; iv) possibility of using biogas for energy purposes and recovery of digestate with potential agricultural use. Although this system can meet discharge quality standards, its use is currently limited to the reuse of treated wastewater, thereby contributing to the circular economy. Finally, the DEWATS TPST18 had second position because the community considered that this system, besides being the most expensive, is the one that generates the highest level of nuisances, such as odor generation if the system is not operated properly, and due to the area, that the FAFA can occupy, there would be greater landscape degradation.

The consistency between the individual and collective results facilitated the process of dynamizing the group discussion before the final decision was made. During the discussion, it became clear that for some participants, reducing the environmental impact of their wastewater discharges was essential. For this reason, they defended the selection of TPST17. However, they did not reach a collective consensus. After a voting process, the preference for TPS18 persisted, and this alternative was finally selected.

Discussion

The selection of DEWATS is crucial for overcoming the challenges in informal settlements in low- and middle-income countries. The application of the proposed selection methodology can lead to more effective targeting by considering multiple criteria and their associated uncertainties. A major challenge in implementing decision support tools (DSS) is the effective translation of problems into clear objectives [42]. The proposed tool addresses this challenge through a protocol that translates the problems identified during the diagnostic phase into specific technical and environmental objectives, such as effluent quality and by-product utilization opportunities (i.e., treated wastewater, energy production from methane, biosolids). This enables the prioritization of alternatives based on the application context.

Comparable applications of multi-criteria and participatory approaches in the water sector confirm the robustness of these findings.Beutler et al. [43] developed a participatory MCDA framework for wastewater management in OECD countries, highlighting that Monte Carlo-based uncertainty treatment improves transparency and robustness. While this work operated at the policy level, this study provides empirical field validation through

Table 7 Community-driven prioritization of criteria

Criteria	Weight
C1 -Nuisance index	34.60%
C2 - OPEX	21.9 0%
C3- Operational complexity	17.20%
C4- Effluent quality	26.30%

Table 8 Results of the MDCM conducted with the community

		Individual assessment					Collective assessment					
SDTAR	Alternative	C1	C2	C3	C4	Total	C1	C2	C3	C4	Total	Classification
TPS17	UASB	0.35	0.22	0.17	0.12	0.86	0.29	0.20	0.14	0.13	0.77	1
TPS18	UASB + UAF	0.07	0.22	0.17	0.16	0.62	0.09	0.16	0.14	0.17	0.56	2

participatory workshops, demonstrating that combining probabilistic modeling with stakeholder weighting can yield transparent, actionable results even under resource-constrained conditions. Similarly, Villalba et al.et [44] introduced a hybrid Fuzzy DEMATELDANP–TOPSIS approach emphasizing causal dependencies among sustainability dimensions. This comparison highlights that the proposed tool provides a simpler yet transferable framework that strikes a balance between methodological rigor and practical feasibility, thereby ensuring its applicability across diverse contexts.

The results of the participatory validation workshops confirm the model's capacity to integrate technical, environmental, and social considerations into a coherent decision-making process. Stakeholders consistently prioritized systems combining low operational costs, environmental safety, and adaptability to space and infrastructure limitations—criteria consistent with sustainability dimensions identified in earlier MCDA studies [45]. Furthermore, the tool can be used in different phases of the project cycle, for example, in the formulation and analysis of alternatives, facilitating the definition of concise objectives, which are fundamental for effective decision-making [46, 47]. However, it is important to consider that different stakeholders may propose additional objectives, as these depend not only on the problems identified, but also on the principles of the stakeholders[23] or legal requirements. Therefore, future versions of the tool should integrate different stakeholder perspectives to define coherent and concise objectives, which will be crucial to formulate robust goals and ensure effective implementation [9, 23].

The technical and environmental criteria have the highest uncertainty in the DEWATS ranking, with ranges of 15%–35% and 24%–47%, respectively, according to the experts' judgment. This uncertainty affects the ranking of the alternatives. In economics, Monte Carlo simulation has proven to be a robust tool for handling uncertainty, particularly in variables such as inflation and the discount rate. It is therefore essential to integrate the opinions of experts and local stakeholders to select the most appropriate alternative in each specific context.

The validation of the tool demonstrated its effectiveness in selecting DEWATS for specific contexts. In the case of the informal settlements evaluated, the UASB reactor proved to be the most economically viable option, with a net present value (NPV) ranging from $ 87,592.20 to $ 94,445.90, at confidence levels of 80% and 90%, respectively. However, the tool has limitations, as its applicability depends on external factors such as political, environmental, or economic changes, which require periodic adjustments to the criteria's weightings. It is necessary to validate its use in different contexts and to expand the technical and environmental sub-criteria, especially in the presence of emerging contaminants such as endocrine disruptors and metals, which may influence the selection of technologies.

The outcomes of the FAHP and Monte Carlo analysis not only provide numerical validation of the most viable DEWATS configurations but also reveal underlying dynamics in stakeholder preferences and trade-offs between criteria. The relatively higher uncertainty observed in the technical and environmental dimensions suggests that expert judgments are influenced by local experience and perceived implementation risks, rather than by a quantitative data availability pattern consistent with the findings by Haag et al. [46] on the role of cognitive framing in participatory MCDA. This highlights the importance of integrating iterative feedback loops within the decision-support process to progressively refine weights and reduce subjective bias. Moreover, the close alignment between simulated rankings and stakeholder evaluations indicates that probabilistic modeling can act as a boundary object, facilitating dialogue between technical experts and community representatives. Such alignment between empirical outcomes and participatory insights reinforces the tool's dual value: as a practical instrument for technology selection and as a social interface for collaborative sanitation planning.

However, the tool's applicability depends on external factors, such as political, environmental, and economic changes, which may require periodic adjustments to the weighting parameters. Future versions should integrate evolving legal frameworks and emerging environmental challenges, such as endocrine disruptors and heavy metals, that may influence technology selection. Furthermore, as different stakeholders can introduce new objectives depending on their principles, roles, or institutional mandates [23], future development should include multi-stakeholder rounds to refine objectives and ensure coherent and implementable goals.

Finally, the tool provides sanitation professionals with a starting point for identifying decentralized wastewater treatment alternatives tailored to the specific needs of informal settlements in developing countries. Likewise, the application of the tool highlights the challenges of implementing systems for the reuse of treated wastewater and by-products in this type of settlement, characterized by limited areas and small-scale productive activities. To ensure transferability, the decision-support framework was designed with modular input layers, allowing for easy customization and adaptation. The weighting matrices, fuzzy membership functions, and uncertainty distributions can be recalibrated using context-specific socio-economic or environmental datasets. For instance, the environmental sub-criteria can be adjusted to reflect local legislation on effluent quality, while the economic block can incorporate national discount rates or inflation ranges. This modular design enables replication in diverse geographies from Latin American peri-urban areas to African or Asian informal settlements without altering the core algorithmic logic.

Limitations and Future Research

The current tool simplifies the dynamic interdependencies between criteria by assuming partial independence within the FAHP weighting structure. Integrating approaches such as Fuzzy DEMATEL or network-based MCDM methods could better capture causal relationships among technical, environmental, and social dimensions. In addition, the framework does not explicitly consider emerging contaminants (e.g., endocrine disruptors, microplastics, and heavy metals), which may influence technology rankings in future wastewater management scenarios.

Another important limitation relates to spatial constraints and the volatility of land availability. Land suitability is currently incorporated through GIS-based screening that compares available areas with the spatial requirements of candidate technologies. Nevertheless, the present implementation treats land availability as relatively static. In peri-urban informal settlements, land conditions may change rapidly due to informal expansion, competing land uses, tenure uncertainty, and exposure to hazards. These dynamics can modify the set of technically viable technologies over time. Future research could therefore incorporate multi-scenario and time-varying spatial assessments (e.g., optimistic, constrained, and highly constrained land-availability scenarios). Such analyses should explicitly account for land tenure risks, location acceptability, and land-related transaction or suitability costs as either decision criteria or binding constraints. Coupling the proposed tool with scenario-based GIS suitability mapping would enable periodic reassessment and reclassification of alternatives under realistic spatial volatility conditions.

Economic pre-feasibility is currently assessed through cash-flow analysis using indicators such as net present value (NPV), benefit–cost ratio (BCR), and annual equivalent cost (AEC). However, in resource-constrained peri-urban environments, the affordability and feasibility of implementation may be strongly influenced by external subsidies from public or private entities, fluctuations in household income, tariff collection capacity, operation and maintenance capabilities, and variations in input costs (e.g., materials, energy, and institutional changes). Expanding the treatment of uncertainty beyond macroeconomic parameters would strengthen the framework. This could include probability distributions for household income and expenditure dynamics, heterogeneity in willingness to pay and payment compliance, and potential institutional or market shocks. Robustness-oriented indicators such as affordability-constrained feasibility metrics and percentile-based risk measures—could improve decision-making under conditions of high uncertainty and enhance the transferability of the framework to volatile contexts.

Based on these limitations, several priority directions for future research emerge: i) incorporating statistical measures of stakeholder consensus and sensitivity analyses to improve the reliability of participatory inputs; ii) extending validation to peri-urban or rural contexts in other regions of Latin America, Africa, and Asia; iii) developing an open-source computational module to operationalize the tool and facilitate reproducibility; iv) integrating dynamic or adaptive weighting mechanisms that can evolve with changing socio-environmental conditions and policy frameworks; and v) strengthening the spatial and economic modules through scenario-based analyses of land availability and affordability that explicitly reflect peri-urban volatility.

Conclusions

The conclusions of this study are:

- The use of the proposed wastewater treatment technology selection methodology contributes to a more holistic selection process that considers multiple criteria, their uncertainty, and involves the community in the final decision-making process.
- Forty-eight DEWATS were proposed for the unplanned settlements. The trains were proposed based on guidelines provided in the literature, such as synergies between intensive and extensive technologies, ease of operation and maintenance, and operating costs. Likewise, 48 of the proposed trains were characterized in terms of their potential for implementing circular economy schemes and the possible usable by-products generated were determined.
- The application of the Fuzzy AHP multicriteria method allowed us to determine the relative importance of the technical, environmental, and economic criteria with weighted weights of 33.9%, 38.7% and 27.4%, respectively. Similarly, the sub-criteria with the highest relative importance were the technical complexity of the DEWATS and the operational expenditure (OPEX), with a weighted weight of 14.97% and 14.40%, respectively.

- The tool proved to be effective and practical in the selection of DEWATS for this specific context, with the UASB reactor being the best option in terms of economic feasibility, with an NPV ranging from $87,592.2 to $94,445.9.
- The participative block is a key component of the tool, enabling the creation of a driving group composed of settlement members who voluntarily engage in the process through three stages: knowledge appropriation, participatory selection, and sharing of results of the decision process.
- The validated tool is effective in selecting DEWATS for these specific contexts, although its applicability is limited by external factors and requires periodic adjustment of the criteria. It is recommended to validate its use in different contexts and to expand the technical and environmental sub-criteria to address issues such as the removal of emerging contaminants.

The proposed participatory multicriteria framework serves not only as a context-specific solution for Colombian informal settlements but also as a transferable decision architecture for decentralized wastewater management in data-limited environments. Its modular design allows recalibration of criteria weights, uncertainty parameters, and stakeholder preferences, ensuring methodological consistency and adaptability across various socio-environmental contexts. Future research will focus on testing the tool in contrasting scenarios, such as flood-prone settlements in Southeast Asia or semi-arid regions in Africa, to further validate its global applicability.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s43615-026-00930-2.

Author Contributions All authors contributed to the conception and design of the study. Material preparation, data collection, and analysis were performed by Jesús Álvarez, Ricardo Oviedo, Isabel Dominguez, Carlos Aceros, and Jonathan Soto. The first draft of the manuscript was written by Jesús Álvarez, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding Open Access funding provided by Colombia Consortium. The authors would like to thank the "Ministerio de Ciencia, Tecnología e Innovación" for financing the project "Desarrollo de estrategias para el manejo de aguas residuales en asentamientos periurbanos, con enfoques de sostenibilidad y economía circular, en la cuenca del río Alto Lebrija" (BPIN 2021000100536), carried out by the Universidad Industrial de Santander and the Acueducto Metropolitano de Bucaramanga S.A. E.S.P.

Data Availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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