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A PAIRWISE COMPARISON APPROACH WITH CONSISTENCY RATIO FOR PRIORITIZING SUSTAINABLE WASTEWATER TREATMENT TECHNOLOGIES: AN ANALYTIC HIERARCHY PROCESS-BASED FRAMEWORK

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Abstract:

The rapid expansion of population and economic activities has resulted in the generation of substantial volumes of wastewater, posing significant environmental challenges. Despite the availability of a diverse array of wastewater treatment (WWT) technologies, the selection of the most appropriate solution remains complex due to the multitude of criteria that must be simultaneously considered. This study proposes a decision-making framework based on the Analytic Hierarchy Process (AHP), employing pairwise comparisons to facilitate the sustainable selection of WWT technologies. The AHP methodology is utilized to derive the relative weights of decision criteria, with the consistency ratio serving as a measure to validate the coherence of expert judgments represented through pairwise comparison matrices. Computational results reveal that 'Composting,' with a composite weight of 0.4370, is identified as the most preferred WWT option. Future research should further investigate critical decision-making factors, including technological variability, the credibility of decision-makers, and the methodological robustness of AHP within broader conceptual frameworks.

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Introduction

Wastewater treatment (WWT) is a critical process that transforms used water into a form that can safely re-enter the natural water cycle, thereby minimize environmental harm and eliminate health risks. Wastewater typically contains human waste, food residues, and chemical by products, making effective treatment essential for maintaining water quality and ecosystem stability. WWT is formally defined as a process involving the separation, modification, removal, and destruction of undesirable substances carried by wastewater (Crini et al., 2018). The primary objective is to eliminate pollutants before the treated water is discharged back into the environment.

Proper wastewater treatment is vital for protecting rivers, streams, and other natural water bodies that communities rely on for drinking, recreation, fishing, and other daily activities. To ensure the availability of clean water, the United States enacted the Clean Water Act (CWA) in 1972. This landmark legislation aims to regulate pollutant discharges into water bodies and establish water quality standards to safeguard public health and the environment (EPA, 2004). Inadequate wastewater treatment increases the risk of waterborne disease transmission. According to EPA (2004), although some natural purification occurs, many water sources remain contaminated with various pollutants. These contaminants can adversely affect individuals who depend on such water for daily use.

With the global population continuously rising, the demand for clean water is also increasing. Wastewater treatment systems are essential for accelerating the natural purification process, ensuring that water resources remain safe and sustainable for future generations. However, despite the development of various sustainable WWT technologies, the selection of the most appropriate solution remains a challenge—especially in resource-limited settings. Therefore, this study aims to apply the Analytic Hierarchy Process (AHP) to evaluate and rank sustainable WWT technologies based on multiple decision-making criteria. This paper is structured as follows: Section 2 presents the mathematical foundations of AHP; Section 3 describes the computational procedure; Section 4 provides the ranking results; and Section 5 concludes the study.

Literature Review

Sustainable infrastructure for treated water is essential to ensure public access to high-quality water. Such infrastructure has the potential to improve the social, environmental, and economic

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well-being of communities (EPA, 2012). Traditionally, natural processes enabled water to purify itself through basic treatment mechanisms. However, with rapid population growth and industrial expansion, more advanced wastewater treatment is required to effectively manage domestic and industrial effluents.

A variety of sustainable WWT technologies are currently available, including Conventional Septic Tanks, Anaerobic Treatment Units, and Media Filters (EPA, 2004). These technologies serve as catalysts that accelerate the natural purification process of water. According to EPA (2004), over 30% of sustainable WWT systems have demonstrated enhanced treatment efficiency, resulting in cleaner effluent discharge. The growing public concern for environmental sustainability has driven industries to adopt more efficient and cost-effective wastewater treatment solutions.

Despite this progress, there is a notable lack of comprehensive performance data on the implementation and effectiveness of sustainable WWT technologies—especially in developing countries. To address this issue, various decision-making frameworks have been employed to evaluate and select appropriate WWT technologies. Common approaches include the Analytic Hierarchy Process (AHP) (Arroyo & Molinos-Senante, 2018; Fetanat et al., 2021; Muhammad Anwar et al., 2021; Wei et al., 2020), Simple Additive Weighting (Abdullah, 2015), Decision Making Trial And Evaluation Laboratory (DEMATEL) (Dursun, 2016, 2018; Štirbanović et al., 2021), Multicriteria Optimization and Compromise Solution (VIKOR, TOPSIS) (Dursun, 2016; Gichamo et al., 2021; Štirbanović et al., 2021) as well as the Analytic Network Process (ANP) (Abdullah & Rahman, 2017; Molinos-Senante et al., 2015). These methods allow researchers and policymakers to systematically assess technologies based on environmental, technical, economic, and social criteria (EPA, 2012).

Among these, AHP is recognized as a highly versatile and effective tool for addressing multi-criteria decision-making (MCDM) problems. It is especially valued for its structured pairwise comparison approach, which incorporates the judgment and experience of decision-makers to derive a ranking of alternatives (Haddad et al., 2017). The method's ability to ensure consistency and transparency in decision-making contributes to its widespread global adoption (Saaty, 1980a). AHP has been applied in diverse fields, including renewable energy—often in combination with other MCDM methods such as TOPSIS (Sedghiyan et al., 2021; Solangi et al., 2021) and VIKOR (Abdul et al., 2022)—and sustainable development, where it has been integrated with geo-spatial tools (Chavosh Nejad et al., 2021; Ramadan & Effat, 2021; Zou et al., 2021). In supplier selection research, AHP has been combined with goal programming (Khorramshahgol & Al-Husain, 2021) and TOPSIS (Marzouk & Sabbah, 2021).

Despite its demonstrated advantages, few studies have applied AHP as a standalone method in the selection of sustainable WWT technologies. Most existing research integrates AHP with other tools or focuses on sectors outside of water treatment. This indicates a research gap in the standalone application of AHP to sustainable WWT technology evaluation.

The AHP is a measurement theory used to derive ratio scales from both discrete and continuous comparisons. It structures complex decision problems into a hierarchy: the top level represents the overall goal, the intermediate levels include the relevant criteria, and the lowest level lists the available alternatives (Chuma et al., 2021). Each criterion is compared against others in a pairwise manner to derive priority weights. Due to its clarity, flexibility, and mathematical soundness, AHP is well-suited for addressing MCDM challenges where both quantitative and qualitative criteria must be considered.

Despite the increasing availability of sustainable wastewater treatment (WWT) technologies and the growing adoption of multi-criteria decision-making (MCDM) methods, several critical knowledge gaps remain. First, while various frameworks such as AHP, TOPSIS, VIKOR, and others have been widely applied, there is a scarcity of studies utilizing the Analytic Hierarchy Process (AHP) as a standalone method specifically for sustainable WWT technology selection. Second, the existing literature lacks comprehensive performance data on these technologies, particularly in developing countries, which limits evidence-based evaluation. Third, prior studies tend to adopt a limited set of decision criteria, often omitting important dimensions such as social acceptability, institutional readiness, or regulatory compliance. Furthermore, most evaluations rely on expert opinion from localized contexts, with little incorporation of diverse stakeholder perspectives or real-world implementation feedback. Lastly, many models do not account for uncertainty or dynamic changes in technological, economic, or environmental factors. These gaps highlight the need for more robust, inclusive, and context-sensitive decision frameworks to guide sustainable WWT technology prioritization.

Preliminaries

The Analytic Hierarchy Process (AHP) has gained widespread acceptance globally due to its effectiveness in addressing complex decision-making problems. It was originally developed to structure multifaceted problems into a hierarchical framework, allowing decision-makers to systematically evaluate criteria and alternatives (Saaty, 1980a). As a measurement theory, AHP calculates ratio scales and assesses consistency from both continuous and discrete pairwise comparisons.

One of the key advantages of AHP lies in its ability to handle matrix computations in a user-friendly manner, making it accessible even to those with limited knowledge of optimization theory or advanced mathematics. This simplicity, combined with its theoretical robustness, has contributed to the method's popularity across multiple disciplines.

This section outlines foundational concepts and propositions established in the AHP framework, as presented in foundational literature (Chuma et al., 2021). At the core of AHP is the concept of pairwise comparison, where each criterion is compared directly to every other criterion to derive relative weights. The mathematical relationship governing these comparisons is formally introduced in Proposition 1, which provides the basis for constructing the pairwise comparison matrix and computing priority vectors.

Proposition 1 (Binary Comparison)

Let alternatives be n elements of a finite set U, and criteria are of set C with respect to U. Criteria will be refer to as elements of c. A binary comparison on elements in U with respect to criterion in C is performed.

Let $>_c$ denoted as the binary relation on U which represents 'more preferred than' with respect to a criterion $c \in C$. Let $\sim_c$ denoted as the binary relation 'indifferent to' with respect to a

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criterion $c \in C$. So, if there two elements $A_i, A_j \in A$, then, their binary relation be either $A_i >_C A_j$ or $A_j >_C A_i$ or $A_i \sim_C A_j$ or $A_j \sim_C A_i$ for all $c \in C$.

Let B be a set of mapping of $U \times U$ of a set of positive real $\Re^+$. Let $f: C \to B$ and $P_C \in f(C)$ for $c \in C$. P_C assigned as $\Re^+$ to every pair $(A_i, A_j) \in U \times U$. The basic scale mapping of items to a numerical system is then developed. A fundamental scale is applied to the triple $(U \times U, \Re^+, P_C)$ for each $c \in C$.

The basis of the AHP is a straightforward in comparison which ultimately build a strong relationship between criteria. The comparison matrix we create is made up of paired reciprocal comparisons since if one stone is five times heavier than the other, another must be one-fifth as heavy. The reciprocal axiom is provided in Proposition 2.

Proposition 2 (The reciprocal axiom)

For all $A_i, A_j \in U$ and $c \in C$.
$A_i >_C A_j$ if and only if $P_C(A_i, A_j) > 1$
$A_i \sim_C A_j$ if and only if $P_C(A_i, A_j) = 1$
If $A_i >_C A_j$, then it will be said that A_i dominates A_j with respect to $c \in C$. As a result, P_C denotes the degree to which one option is preferred over another. This proposition is applied such that $P_C(A_i, A_j) = 1 / P_C(A_i, A_j)$.

The set of objects that will be pairwise compared must be homogenous. To put it another way, the biggest object's mastery must be not exceeded 9 times that of the smallest. Items that differ by more than this range can be sorted into homogenous groups and treated with this scale. The objects are homogenous if the measurements are utilized from current scales. Homogeneity in the AHP is given in Proposition 3.

Proposition 3 (Homogeneity)

Given a hierarchy H, $x \in H$ and $x^- \subseteq L_{k+1}$ is homogenous for $k = 1, 2, \ldots, h-1$. Homogeneity is important for comparisons since the decision-makers are unable to compare aspects that are vastly dissimilar. For a positive real number $\rho \geq 1$, a nonempty set $x^- \subseteq L_{k+1}$ is said to be homogenous with respect to $x \in L_k$ if for every pair of elements $y_1, y_2 \in x^-$, $1/\rho \leq P_C(y_1, y_2) \leq \rho$. Particularly, Axiom 1 implies that $P_C(y_1, y_2) = 1$.

One criterion in decision-making is always dependent on another criteria. With this, the dependence between two criteria is presented in Proposition 4.

Proposition 4 (Dependence)

Let a fundamental scale defined on U with respect to every C. Then, U is said to be the outer dependent on C. The elements in U are said to be inner dependent with respect to $c \in C$ if for some $A \in U$, U is the outer dependent on A. Outer dependency means the connection between elements (e.g., alternatives) in one stage of the hierarchy to the components (e.g., criteria) at

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the next greater level in order to make comparisons. The stages are repeated up the hierarchy, via each pair of adjacent levels, until finally reach the top element or objective. Assume that levels $L_1, L_2, ..., L_k$ in the hierarchy H whereby all $L_k = 1, 2, ..., h-1$. Then,

L_{k+1} is the outer dependent on L_k
L_{k+1} is not inner dependent with respect to all $x \in L_k$
L_k is not outer dependent on L_{k+1}

The hierarchy in AHP can and should include all potential alternatives, criteria, and expectations (both explicit and tacit). This axiom does not take the rationality into account. People are known to have illogical expectations at times, and these expectations can be satisfied. The expectations are given in Proposition 5.

Proposition 5 (Expectations)

The axiom of expectations $C \subset H - L_k$, $A - L_h$. The hierarchy in AHP can and should include all potential alternatives, criteria, and expectations (both explicit and tacit).

The above propositions are related to the computational procedure that is given in the following section.

Computational Procedures

The Analytic Hierarchy Process (AHP) is designed to facilitate decision-making in various contexts by structuring problems based on several independent variables. Typically, the decision problem is decomposed hierarchically into multiple sub-problems across different levels. The top level of the hierarchy represents the overall goal of the decision, the intermediate level consists of the criteria relevant to achieving that goal, and the bottom level comprises the set of alternatives or options under consideration (Saaty, 1980a, 2003; Vargas, 1990).

A fundamental requirement of AHP is that the criteria must be pairwise comparable in terms of their relative importance with respect to their influence on the decision outcome. The objective is to evaluate how significantly each criterion contributes toward achieving the goal, which ultimately affects the ranking of the alternatives

This section outlines the computational steps involved in determining the weights of alternatives. There are three fundamental principles that guide the AHP computational procedure: (i) decomposition of the problem into a hierarchy, (ii) pairwise comparisons of the decision elements (criteria or alternatives), and (iii) synthesis of priorities to derive the final ranking. These principles are illustrated in Figure 1.

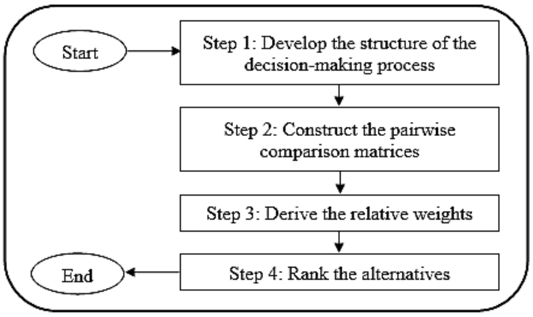

Figure 1: Conceptual Illustration of Proposed Work

According to Figure 1, the computational procedure of the Analytic Hierarchy Process (AHP) can be described as follows:

Step 1: Development of the Decision-Making Framework

The decision problem is first structured into a hierarchical framework. This involves decomposing the problem into several levels with unidirectional relationships between them. The hierarchy starts at the top with the overall goal, proceeds to the intermediate level with the relevant criteria, and concludes at the bottom with the set of alternatives—i.e., the possible options for achieving the objective.

Step 2: Construction of Pairwise Comparison Matrices

The next step involves assessing the relative importance of the criteria using pairwise comparisons. Decision-makers are required to evaluate two elements at a time in terms of their contribution to a specific criterion at the higher level. These comparisons generate a numerical judgment for each pair of criteria, resulting in the construction of a pairwise comparison matrix. The general structure of this matrix is shown as follows:

$$
\begin{array}{c}
 \\ C_1 \\ C_2 \\ \vdots \\ C_n
\end{array}
\begin{array}{c}
\begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array} \\
\begin{bmatrix}
1 & w_1/w_2 & \cdots & w_1/w_n \\
w_2/w_1 & 1 & \cdots & w_2/w_n \\
\vdots & \vdots & \vdots & \vdots \\
w_n/w_1 & w_n/w_2 & \cdots & 1
\end{bmatrix}
\end{array}
=
\begin{array}{c}
A_{ij} \\
\begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix}
\end{array}
$$

where $C_1, C_2, \ldots C_n$ are the criteria, A_{ij} are the alternatives and $w_1, w_2, \ldots w_n$ are the weight to represent the strength of importance.

The 1-9 scale in Table 1 was applied to determine the relative importance of criteria.

Table 1: The Pairwise Comparison Scale

Strength of Importance	Definition	Explanation
1	Equal Importance	Two criteria each contribute equally to the goal.
3	Moderate Importance	Experience and opinion favour one criterion over others.
5	Strong Importance	Experience and opinion favour one criterion over others.
7	Very Strong Importance	The criterion is strongly favoured, and its importance is established in practice
9	Extremely Importance	The information that favours one over the other is of the maximum possible validity.
2,4,6,8	Intermediate Values	When a compromise is required
Reciprocals	If any value between 1-9 assigned to it when compared with j, then j has its reciprocal value when compare with i	
Rational	Ratio arising from scale	If consistency was enforced by acquiring numerical values spanned the matrix

Then, construct the pairwise comparison matrix for the alternatives with respect to each criterion. Compute the eigenvector and the consistency ratio. The relative weights of the alternatives are defined as follows:

$$w_i = \sum A_i K_{ij} \qquad (1)$$

where w_i is the overall relative weight for criteria *i*, A_i is the average normalized weight for criteria *i*, and K_{ij} is the average normalized weight for alternatives *j* with respect to factor *i*.

Step 3: Derivation of the Relative Weights

To obtain this weight, the adjacent upper level is computed as components of the normalized eigenvector. In fact, there are numerous ways in deriving the vector priorities from the matrix form. But, since AHP emphasis on consistency, hence this leads to an Eigenvalue formulation (Saaty, 1987).

Eigenvector, $A_{ij} =$

$$\frac{\left[\sum_{i=1}^{n}\left(w_1/w_1 \times w_1/w_2 \times \ldots \times w_1/w_n\right)^{1/n}\right]}{\sum\left[\sum_{i=1}^{n}\left(w_1/w_1 \times w_1/w_2 \times \ldots \times w_1/w_n\right)^{1/n}\right]} \qquad (2)$$

$$\text{Eigenvalue, } \lambda_i = \frac{\sum_{j}^{n}\left(\sum_{i=1}^{n} A_{ij}\right) w_j}{A_{ij}} \tag{3}$$

$$\text{Consistency test, } CI = \frac{\lambda_{\max} - n}{n-1} \tag{4}$$

$$\text{Consistency Ratio, } CR = \frac{CI}{RI} \tag{5}$$

Table 2 describes the random indices of sizes of matrices to calculate the consistency ratio of the matrix judgement.

Table 2: Random Indices of Sizes of Matrices

N	1-2	3	4	5	6	7	8	9
RI	0.0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

Consistency ratio (*CR*) is acceptable if it does not higher than 0.10. If the *CR* of *CI* is greater than 0.10, the judgment matrix should be seen as contradictory. Thus, the comparison should be repeated.

$$A_x = \lambda_{\max} x \tag{6}$$

where A is the matrix of the pairwise comparison of size $n \times n$ for n criteria, x is the calculated eigenvector of size $n \times 1$, and $\lambda_{\max}$ is the eigenvalue.

$$\text{Eigenvector, } A_{ij} = \frac{\left[\sum_{i=1}^{n}\left(w_1 / w_1 \times w_1 / w_2 \times \ldots \times w_1 / w_n\right)^{1/n}\right]}{\sum\left[\sum_{i=1}^{n}\left(w_1 / w_1 \times w_1 / w_2 \times \ldots \times w_1 / w_n\right)^{1/n}\right]} \tag{7}$$

$$Eigenvalue = \lambda_{\max} = \frac{\sum_{j}^{n}\left(n \sum_{i=1} A_{ij}\right) w_j}{A_{ij}} \tag{8}$$

Normalizing the principal eigenvector produce a unique estimate of ratio scale underlying the judgment. The Consistency Index of a matrix comparison is given by

Next, Consistency Ratio (*CR*) is calculated in (4) in order to measure how far the judgments have been relatively consistent to the large samples of a purely random judgment. Here, if the calculated *CR* is greater than 0.1, then the decision maker needs to revise their judgment (Bottero et al., 2011).

In the formulation of *CR* in (5), the *RI* means the random consistency index of the reciprocal matrix from 9-scale, with forced reciprocal. Saaty (1980b) has derived the average of consistency index from a sample of randomly selected reciprocal matrices for a sample size of 500.

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Table 3: The Random Consistency Indexes

N	1-2	3	4	5	6	7	8	9
RI	0.0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

Step 4: Ranking of the Alternatives

The alternatives were ranked by computing the composite weights. Composite weight is computed by aggregating the weights throughout the hierarchy. It is calculated one-by-one, beginning from the criteria (the top of the hierarchy) down-path to the alternatives (the lowest stage of the hierarchy), and then for each weight calculated, they were multiplied along each segment of the path.

Normalize the calculation, and then the overall weights of the alternatives were produced. Rank was determined from the overall weight. The highest value of weight is the most preferred one (Saaty, 1980).

Application to WWT Technology Prioritization

Generally, the primary components of a decision-making problem are known as alternatives, criteria, and sub-criteria. Dependencies often exist between groups of criteria and alternatives, which must be thoroughly analyzed. In the case of wastewater treatment (WWT), it is crucial to recognize the interrelationships among groups of criteria and alternatives in the context of sustainable WWT technology prioritization.

This research proposes an experiment that employs the Analytic Hierarchy Process (AHP) to identify the optimal solution for selecting sustainable WWT technologies, based on the relative importance of the alternatives. Structured interviews were conducted to obtain linguistic data from three decision-makers (DMs), whose evaluations reflect the sustainability requirements for WWT in the Malaysian state of Terengganu, as measured using AHP's 1–9 scale. Explanations of this scale are provided by Saaty (1987). A distinctive feature of AHP is the use of reciprocal values: if a value between 1 and 9 is assigned to a comparison, its reciprocal is used in the reverse comparison.

The alternatives and criteria applied in this experiment were adopted from (Bottero et al., 2011). Using AHP, this study aims to determine a ranking of the most suitable sustainable WWT technologies.

In this section, the AHP method is used to rank three sustainable WWT alternatives. Three DMs were asked to provide linguistic evaluations based on the AHP scale. These evaluations include both the importance of the criteria and the performance of each alternative with respect to each criterion. The selected criteria include the economic aspect (C1), technological aspect (C2), and environmental aspect (C3). The alternatives considered are Anaerobic Digestion (A1), Phytoremediation (A2), and Composting (A3). Linguistic variables are defined to facilitate the evaluation of both the importance of criteria and the rating of alternatives against those criteria (see Table 2).

Step 1: Identify the Hierarchical Structure of the Problem

The goal, alternatives, and criteria are identified and structured hierarchically. Figure 2 illustrates the hierarchical structure of the decision problem.

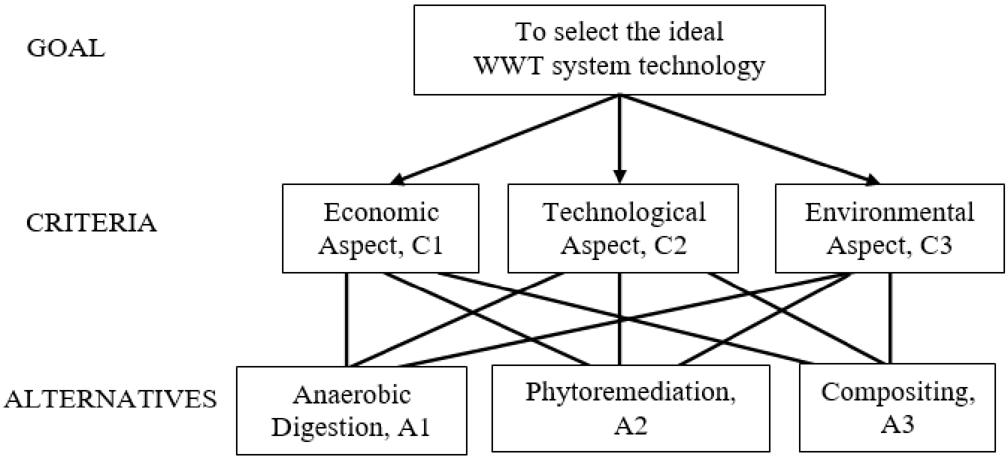

Figure 2: Hierarchy Structure of The Sustainable WWT Technology Prioritization

Step 2: Construct the Pairwise Comparison Matrices

There are four different pairwise comparisons are made at this step. Pairwise comparison of criteria with respect to goal is presented in Table 4.

Table 4: Pairwise Comparison of Criteria with Respect to Goal

Goal	C1	C2	C3
C1	1	5	3
C2	1/5	1	1/3
C3	1/3	3	1

Pairwise comparisons of alternatives with respect to C1, C2 and C3 are summarised in Table 5, Table 6, and Table 7, respectively.

Table 5: Pairwise Comparison Matrix for the Weight of Alternatives with Respect to C1

C1	A1	A2	A3
A1	1	3	1
A2	1/3	1	1/3
A3	1	3	1

Table 6: Pairwise Comparison Matrix for the Weight of Alternatives with Respect to C2

C2	A1	A2	A3
A1	1	7	5
A2	1/7	1	1/3
A3	1/5	3	1

Table 7: Pairwise Comparison Matrix for the Weight of Alternatives Respect to C3

C3	A1	A2	A3
A1	1	½	1/3
A2	2	1	½
A3	3	2	1

One of the measures to check the accuracy of the evaluation is consistency ratio (*CR*). The *CR* can be calculated using Equation (5). The results of the *CR* for each pairwise comparison matrix is given in Table 8.

Table 8: The Consistency Ratio of Pairwise Comparison Matrix

Pairwise Comparison Matrix	CR
Alternatives with Respect to C1	0.000
Alternatives with Respect to C2	0.0834
Alternatives with Respect to C3	0.0096
Criteria with Respect to Goal	0.0477

The results provide evidence that all pairwise comparison matrices are consistent since the *CR* is less than 0.1. In other words, the evaluations made by decision makers is consistent.

Step 3: Construct the Relative Weights from Each Pairwise Comparison Matrix

Equation (1) is used to find the relative weights. Table 9 shows the relative weight for each alternative with respect to each criterion.

The row sum for alternatives A1, A2, and A3 with respect to C1 can be calculated as follows (refer Table 9):
Row sum (A1) = $1 + 3 + 1 = 5$
Row sum (A2) = $\frac{1}{3} + 1 + \frac{1}{3} = 1.6667$
Row sum (A3) = $1 + 3 + 1 = 5$

Then, the calculation of the weight for alternatives A1, A2, and A3 with respect to C1 is given as follows:
Weight (A1) = $\frac{5}{5+1.6667+5} = 0.4286$
Weight (A2) = $\frac{1.6667}{5+1.6667+5} = 0.1429$
Weight (A3) = $\frac{5}{5+1.6667+5} = 0.4286$
The rest of the calculations are shown in Table 9.

Table 9: Relative Weight of Alternatives with Respect to Criteria

	C1		C2		C3	
	Row Sum	Weight	Row Sum	Weight	Row Sum	Weight
A1	5.0000	0.4286	13.0000	0.6961	1.8333	0.1618
A2	1.6667	0.1429	1.4762	0.0790	3.5000	0.3088
A3	5.0000	0.4286	4.2000	0.2249	6.0000	0.5294
Total	11.6667	1.0000	18.6762	1.0000	11.3333	1.0000

Step 4: Ranking of the Alternatives

The composite weight is obtained by multiplying the normalized weights of alternatives and criteria weights. Table 10 shows the final composite weight of alternatives.

Table 10: Composite Weight of Alternatives

	C1	C2	C3		Criteria weight		Composite weight
A1	0.4286	0.6961	0.1618		0.6054		0.3784
A2	0.1429	0.0790	0.3088	*	0.1031	=	0.1847
A3	0.4286	0.2249	0.5294		0.2915		0.4370

* Denotes matrix multiplication

The application of the Analytic Hierarchy Process (AHP) in this study yielded a clear ranking of sustainable wastewater treatment (WWT) technologies, with Composting, A3 receiving the highest composite weight (0.4370), followed by Anaerobic Digestion, A1 (0.3784), and Phytoremediation, A2 (0.1847). This ranking suggests a marked preference for technologies that combine cost-effectiveness with operational simplicity and environmental impact mitigation.

Composting emerged as the most favourable option primarily due to its high performance across the economic (C1) and environmental (C3) criteria. This aligns with the practical advantages of composting, particularly in low-resource settings where capital investment and maintenance requirements must be minimized. Furthermore, composting produces usable by products such as soil amendments, enhancing its appeal in circular economy frameworks.

Anaerobic Digestion, ranking second, exhibited strong performance in the technological (C2) criterion, reflecting its efficiency in energy recovery and organic load reduction. However, its comparatively lower scores in cost-related and environmental aspects may have affected its overall standing. This result highlights the trade-off between technical performance and broader sustainability metrics in WWT technology selection.

Phytoremediation ranked lowest despite its recognized environmental benefits. This outcome may be attributed to its lower perceived technological maturity and longer treatment cycles, which can affect feasibility in urgent or high-load treatment scenarios. The low score in technological and economic aspects suggests that decision-makers valued immediacy, reliability, and cost control over long-term ecological gains. It is also possible that the decision-

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makers' familiarity with conventional technologies influenced their assessments, resulting in a bias against nature-based or less conventional solutions.

Overall, the ranking reflects a pragmatic decision orientation, favouring technologies that are affordable, accessible, and proven in application. While composting proves to be an optimal solution under the evaluated criteria, this result may not be universally generalizable. Future assessments should incorporate broader criteria—including social acceptance, maintenance burden, land use constraints, and regulatory alignment to ensure the selected technology meets the full spectrum of sustainability dimensions.

Conclusion

In complex decision-making scenarios, Multi-Criteria Decision-Making (MCDM) methods are typically employed to evaluate alternatives and simultaneously consider multiple criteria. This study demonstrated the application of the Analytic Hierarchy Process (AHP) to address a real-world decision-making problem involving the selection of the most sustainable wastewater treatment (WWT) technology—namely, Phytoremediation, Anaerobic Digestion, and Composting. The AHP technique was utilized to rank these technologies based on various decision-making criteria.

The approach enabled the evaluation of environmental considerations, technological factors, and economic costs in order to determine the optimal solution. AHP was integrated with a factor rating system to enhance its capability in handling the selection problem, particularly in the presence of ambiguous variables. Furthermore, the method allows for the simultaneous incorporation of both tangible and intangible factors in the evaluation process.

The model's results indicate that Composting is the most sustainable WWT technology among the alternatives considered. Future research should address several key issues, including the comprehensiveness of the technology list, the reliability of decision-makers, and the robustness and validity of the AHP methodology.

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