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Evaluation of wastewater treatment technologies using TOPSIS

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ABSTRACT

The selection of appropriate wastewater treatment technology is now an important issue before any wastewater treatment plant is designed or implemented. Population growth, urbanization, industrialization, and numerous other factors are needed before such implementation and decision making, as all these factors are increasing the number of pollutants entering our waterways and into our environment, which needs to be treated prior to discharge. TOPSIS, a widely used compensatory multi-criteria decision-making technique, has been selected for ranking and evaluating different wastewater treatment alternatives and this paper will effectively identify the most appropriate process in terms of cost, maintenance, energy use, and more. Choosing the process is becoming more concerning for decision-makers and to overcome this difficulty, TOPSIS is proposed to deal with this vagueness in relation to decision-makers' judgments. The outcomes of this study will help the concerned parties in choosing the best option among these technologies and will provide an insight for relevant stakeholders such as engineers, town planners and other government personnel for making decisions. The most commonly used wastewater treatment technologies were evaluated and compared with the fuzzy PROMETHEE decision-making theory. Based on this research, the activated sludge process is recommended as the best option, followed by the nano-filtration method.

Keywords: Wastewater treatment technologies; TOPSIS; Multi-criteria; Decision-making

1. Introduction

Our environment is facing many challenges as a result of the discharge of wastewater from our industries daily; these are associated with rapid urbanization, an increase in population growth, industrialization and many more factors. With all the above-mentioned factors, wastewater discharge needs to be treated and alternatives for the treatment need to evaluated for the proper monitoring of the environment and protection of our natural water resources [1]. At present, the two major problems facing the world are environmental pollution and energy crises and these issues are interrelated. Large volumes of organic and inorganic chemicals and toxic heavy metals from our domestic, commercial and industrial activities through anthropogenic activities enter our natural water sources [2]. Therefore, it is necessary and

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has become of paramount importance to treat wastewater before discharging into freshwater bodies or directly into the environment. To alleviate this problem, the need has arisen to devise alternative wastewater treatment measures. It was concluded by [3] that there is no ideal system or technology applicable to all treatment conditions and another research showed that there are difficulties associated with identifying the best overall option as some factors are not applied to certain technologies or processes [4].

Choosing an appropriate wastewater treatment technology by engineers, law, or policymakers that will enable sustainable development has become a challenge and this raises the need for a decision support tool for wastewater treatment technology in both developed and developing countries around the world.

Therefore, it is necessary to research to evaluate all or some of the wastewater treatment technologies, to choose the best process among all the different options in both developed and developing countries. These include activated sludge (AS), trickling filtration, membrane filtration, nano-filtration (NF), membrane bioreactor (MBR), waste stabilization ponds (WSPs), and constructed wetlands (CWs). The factors or criteria to be considered for this study include: pore size of membrane, Water flux, and pressure, biochemical oxygen demand (BOD) removal efficiency, space requirement, investment cost, energy required, etc. which will be used to evaluate or analyze the abovementioned treatment technologies and the TOPSIS Method will be used. Additionally, this paper only offers a framework for the selection of the best alternative wastewater treatment technology.

Multi-criteria analysis mainly focuses on three types of decision problems; choice- to select the most appropriate or best alternative; ranking- to draw a complete order of the alternatives from the best to the worst, and sorting- to select the best alternative from the list.

TOPSIS is one of the most efficient and easiest methods in terms of conception and application compared to other multi-criteria decision-making (MCDM) methods. According to [5], TOPSIS has the following advantages over other decision-making processes: TOPSIS is simple, rational and offers good computational efficiency, which also easily fits into a spreadsheet; it applies sound logic that represents the rationale of human choice; a scalar value that account for both best and worst alternatives simultaneously; performance measure for all alternatives with respect to attributes that can visualized as a polyhedron, at least for any two dimensions; with another advantage of having the ability to measure the relative performance for each alternative in a simple mathematical form.

TOPSIS as any other MCDM tool can be used in evaluating not only wastewater treatment technologies but in many other fields of study in selecting the best or worst alternative among many. This method has been used successfully in many fields such as supply chain management and logistics, engineering, manufacturing, human resource, water resources management and many more. TOPSIS will be a beneficial tool for decision-makers in government, non-governmental organizations, entrepreneurs, economic experts when making necessary decisions with regards to being the best alternative among different alternatives. Another advantage of using TOPSIS in evaluating wastewater treatment technologies is its ability in reducing the ambiguity of experts in different fields of study and uncertainty embedded by natural problems.

In this study, we propose the TOPSIS method, one of the most important MCDM techniques, to analyze the wastewater treatment technologies based on the criteria mentioned above.

2. Wastewater treatment methods

2.1. Activated sludge method

This system is called "activated" because it contains crowded particles of bacteria, protozoa, and fungi and produces what is called sludge. Settled at the bottom of the aeration tank, the sludge is produced as a result of the growth of these organisms [6]. Most effluent wastewaters from industries are treated using these systems as it removes most biodegradable contaminants in black, grey and brown water.

It is an excellent process mostly used for isolated facilities that was developed in the UK and is one of the most widely used wastewater treatment systems used around the world [7]. It consists of an aeration tank where the biological reactions take place, an aeration source which supplies oxygen and helps in proper mixing of suspended organic matter and microorganisms, a clarifier for easy settlement and separation of the solid waste from wastewater and a settling compartment where solid sludge is collected for disposal or return to the system [8].

The system offers low cost-effective technology, producing good quality effluent, low land requirement and is free from flies and odor nuisance when compared to other wastewater treatment technologies, which are more natural systems and appear to be more viable options than the AS system. Moreover, the AS system has the limitation of not being a flexible method, with more operational costs and sensitivity to certain industrial waste thus rendering it infeasible for these industries. Another disadvantage is the issue of sludge disposal, which is generally large in scale, in terms of the checks required and the amount of sludge to be returned, which requires skilled supervision and expertise in wastewater treatment.

2.2. Nano-filtration method

This is a recently developed pressure-driven liquid-phase membrane process with higher flux that substitutes reverse osmosis (RO) in many applications. The NF membrane falls in between ultrafiltration and RO [9]. With the development of NF technology, many pharmaceutical, textile and dairy industries use it in treating their effluents due to its lower energy consumption, its ability to recover metals from wastewater and its virus removal efficiency. In terms of organic matter and inorganic pollutants, NF is considered as the most promising technology for their removal from surface water. The sieving mechanism of the membrane is used to remove the organic matter, while the inorganic pollutants are removed by the action of the charge effect of the membranes and ions [10].

The drawbacks of this system are mostly associated with fouling, large amounts and concentrated sludge production, which affect the groundwater quality and performance affected by higher temperatures.

2.3. Membrane bioreactor method

MBR technology is becoming a more popular method of liquid–solid separation among water treatment technologies. This system is used in treating both domestic and industrial wastewater, as it is quite similar in operations with conventional AS process, with the only difference being the membrane module present in MBRs and aeration in the CAS process [11].

For MBRs to work effectively and to reduce the number of solids that find their ways into our membrane tanks, fine screens are attached prior to the membrane as a pre-treatment step. This process protects the membrane from solid particles and debris, decreasing the operational and maintenance costs of the system as well as ensuring higher sludge quality.

Most MBRs are cleaned weekly by chemicals; the process lasts between half an hour to an hour, and after every year or two, recovery cleaning is conducted when filtration is no longer durable. A deposit that is impossible to be expelled by the available methods of cleaning is called "irrecoverable fouling" [12].

Reduction in plant footprint, elimination of secondary and tertiary filtration, higher efficiencies, and lower sludge production are among the merits of MBR systems. In addition to all the above-mentioned advantages of membrane treatment technology, it is gaining more attention from numerous researchers in the field of water and wastewater engineering. Some of the limitations associated with these systems are high energy costs, membrane complexity, and fouling and the high operation and capital costs of the membranes [13,14].

2.4. Trickling technology

This is a continuous process in which wastewater is distributed from a rotating influent distributer to a filter media containing microorganisms for easy digestion to take place. For this kind of wastewater treatment technology, synthetic materials, rocks, gravel sands and a wide range of plastics are used as packing materials. These packing materials are used to provide a high surface area to volume for the optimal functionality of the system. The two main processes that take place in a trickling filter for easy pollutant removal are absorption and adsorption of organic materials.

In the system, bacteria are allowed to grow on the filter media, which is comprised of either rocks or plastics. The wastewater to be treated is then distributed from the top of the filter through the rotating influent distributor or a stationary distribution mechanism [15]. Air is then supplied through the nozzles from beneath the filter for proper organic degradation. Organic matter is then adsorbed onto the film as the wastewater moves through the filter medium, which helps the organic matter and aerobic microorganisms to mix. The first stage of the process is called the sloughing process, which is then followed by the final stage where the liquid–solid separation takes place with some portion of the permeate taken back into the system to keep it active and moist [16].

2.5. Waste stabilization ponds

A very suitable technology used in treating wastewater in both developed and developing countries and the most common method of choice for municipal sewage treatment by many countries around the world due to its flexibility, especially in the tropics where the temperature is between 20°C–35°C [17]. The process involves natural treatment that takes place in a large, shallow basin carrying multiple bacteria, fungi, and algae, which is also referred to as "sewage lagoons" or "facultative lagoons" [18]. Moreover, it is possible to reuse the effluent water for irrigation as it contains nutrients such as nitrogen and phosphorus. This is one of the advantages of WSP that makes it feasible to be used as an integrated process [19,20].

Anaerobic pond, facultative pond (FP) and maturation pond (MP) are the three strings of a conventional WSP, which differ from each other geometrically in terms of the biochemical processes, hydraulic flows as well as in carbon, nutrient, and pathogen removal. The first stage in any WSP is designed to improve the settling activity of the system and to help in organic load removal. The second stage, which takes place in the FP, focuses on BOD, pathogens and nutrient reduction, where more time and more land is required. In the third stage, the purpose is the removal of pathogens from wastewater, which takes place in shallow basins called MPs [21].

2.6. Constructed wetlands

Artificially designed systems planned, designed and constructed for treating wastewater, CWs are natural wetlands comprised of vegetation, animal life, and water that assist in removing pollutants in wastewater. Pollutants removed by these systems include suspended solids, pathogens, heavy metals, nutrients, and other toxic and hazardous pollutants; this factor makes CWs an alternative for municipal and industrial wastewater treatment. However, for industrial effluents, pre-treatment is needed for the proper functioning of the biological elements in the effluent [3,4].

CWs are classified as either free water surface (FWS) systems or subsurface flow (SSF) systems depending on where the wastewater to be treated is supplied to the system. In the FWS system, the water is supplied from above and plants are rooted at the base of the water column called the sediment layer, while the SSF system water is supplied from beneath through a porous media comprising of gravels and aggregates [22].

As a result of the porous media used in CWs systems, they experience problems of clogging which impact the effectiveness of the system. Another disadvantage of the system is that it only treats domestic wastewater mainly consisting of oxygen-consuming organic pollutants. However, the system is easy to operate and maintain, operation and maintenance costs low and it provides an aesthetic view [22].

3. Methodology

3.1. TOPSIS

In the classical TOPSIS method, for any problem to be solved by a single decision-maker, we assume that the ratings and weights are well represented by numerical data.

For more than one decision-maker, complexity arises because the preferred solution must be agreed on by the interest groups who frequently have different goals. For this study, a single decision-maker algorithm of TOPSIS will be used, which is systematically described below;

Step 1: Construct the decision matrix and determine the weight of the criteria.

In this step, a decision matrix $X = X_{ij}$ and a weighing vector $W = [w_1, w_2, \ldots, w_n]$ are chosen. Where $X_{ij} \in \Re$, $W_j \in \Re$ and $w_1 + w_2 + ,...,w_n = 1$.

The criteria of the function can be either a benefit function (more criteria better result) or a cost function (less cost better results).

Step 2: Calculate the normalized decision matrix.

In step 2, various attribute dimensions are transformed into non-dimensional attributes which allow for a comparison across all criteria. To make all scores to normalize form, each evaluation matrix X has to be transformed, because the majority of the criteria are usually measured in various units. The normalization of these values can be carried out using one of the several known standardized formulas. The most frequent method used for this calculation is the normalized value n_{ij} and is given by;

$$n_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{m} X_{ij}^2}} \quad (1)$$

$$n_{ij} = \frac{X_{ij}}{\max_i X_{ij}} X \quad (2)$$

$$n_{ij} = \begin{cases} \dfrac{x_{ij} - \min_i x_{ij}}{\max_i x_{ij} - \min_i x_{ij}} \\ \dfrac{\max_i x_{ij} - x_{ij}}{\max_i x_{ij} - \min_i x_{ij}} \end{cases} \quad (3)$$

if C_i is a benefit criterion and if C_i is a cost criterion.

For $i = 1,\ldots, m; j = 1,\ldots, n$.

Step 3: Calculate the weighted normalized decision matrix.

To find the weighted normalized value v_{ij}, it is calculated in the following way:

$$v_{ij} = w_j n_{ij} \quad (4)$$

For $i = 1,\ldots, m; j = 1,\ldots,n$.

where w_j is the weight of the j-th criterion, $\sum_{j=1}^{n} w_j = 1$.

Step 4: Determine of the positive ideal and negative ideal solutions.

In this step, the positive ideal alternative (extreme performance on each criterion) and the negative ideal alternative (reverse extreme performance on each criterion) are identified. The ideal positive solution maximizes the benefit criteria and minimizes the cost criteria, whereas the negative ideal solution maximizes the cost criteria and minimizes the benefit criteria.

The positive ideal solution A^+ has the form:

$$A^+ = \left(v_1^+, v_2^+, \ldots, v_n^+\right) = \left[\left[\max_i v_{ij} \middle| j \in I\right], \left[\min_i v_{ij} \middle| j \in J\right]\right] \quad (5)$$

While the negative ideal solution A^- has the form:

$$A^- = \left(v_1^-, v_2^-, \ldots, v_n^-\right) = \left[\left[\min_i v_{ij} \middle| j \in I\right], \left[\max_i v_{ij} \middle| j \in J\right]\right] \quad (6)$$

where I and J in the equation are associated with benefit criteria and cost criteria, respectively, $i = 1,\ldots,m; j = 1,\ldots,n$.

Step 5: Calculate the separation measures from the positive ideal solution and the negative ideal solution.

In the TOPSIS method, a number of distance metrics can be applied. Each alternative from the positive ideal solution is separated using the equation below;

$$d_i^+ = \left(\sum_{j=1}^{n} \left(v_{ij} - v_j^+\right)^p\right)^{1/p}, \quad i = 1,2,\ldots\ldots,m \quad (7)$$

And for the separation of each alternative from the negative ideal solution, the equation below is used;

$$d_i^- = \left(\sum_{j=1}^{n} \left(v_{ij} - v_j^-\right)^p\right)^{1/p}, \quad i = 1,2,\ldots\ldots,m \quad (8)$$

where $p \geq 1$. for $p = 2$ we have the most used traditional n-dimensional Euclidean metric.

$$d_i^+ = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^+\right)^2}, \quad i = 1,2,\ldots\ldots,m \quad (9)$$

$$d_i^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^-\right)^2}, \quad i = 1,2,\ldots\ldots,m \quad (10)$$

Step 6: Calculate the relative closeness to the positive ideal solution.

The relative closeness of the i-th alternative A_j with respect to A^+ is defined as;

$$R_i = \frac{d_i^-}{d_i^- + d_i^+} \quad (11)$$

where $0 \leq R_i \leq 1$, $i = 1,2,\ldots,m$.

Step 7: Rank the preference order or select the alternative closest to 1.

A set of alternatives now can be ranked by the descending order of the value of R_i.

Relative closeness to the positive ideal solution for each alternative can decide the ranking. A positive ideal solution is a solution that consists of the best possible solution in terms of each criterion. It is the combination of the maximum value of the alternatives where the aim of the criteria is maximization, the minimum value of the alternatives where the aim of the criteria is minimization. A negative ideal solution consists of the worst possible solution in terms of each criterion. It is the combination of the maximum value of the alternatives where the aim of the criteria is minimization and the minimum value of the alternatives where the aim of the criteria is maximization. The best option is the positive ideal solution, but in real-world problems, no option consists of the best values in terms of each criterion. In such a case, the TOPSIS model provides a solution that the more preferred alternative is the one, which is closer to the positive ideal solution and also further from the negative ideal solution simultaneously in terms of the Euclidean distance. Since the relative closeness to the positive ideal solution is a rate

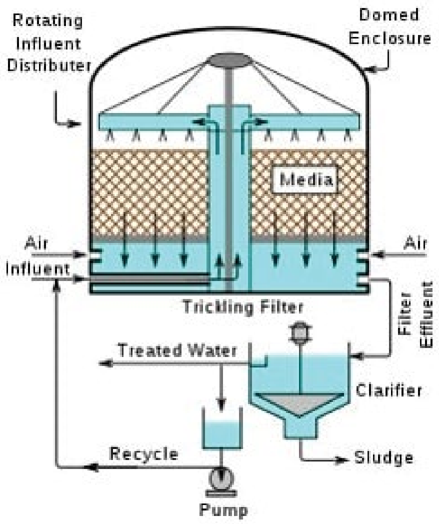

Fig. 1. Biological trickling filter diagram.

that shows the closeness to the positive ideal solution while considering the closeness to the negative ideal solution, it gives the net ranking results.

In the set of criteria used for ranking, some criteria are quantifiable (space requirement) in nature while others are qualitative. A cardinal scale of 0–5 (0 as the worst and 5 as the best) was used to transform qualitative criteria into quantitative criteria, as shown in Table 1 below.

In this study, the linguistic fuzzy scale has been used for obtaining the importance of the weights and seen in Table 2. However, the Yager index has been applied for de-fuzzification of this data of the weight of the criteria. Yager has determined the magnitude of a triangular fuzzy number $\tilde{F} = (N, a, b)$, which is equivalent to $\tilde{F} = (N - a, N, N + b)$, based on the center of the triangle with the function $YI = (3N - a + b)/3$. The importance weights of the sludge generation, energy consumption, efficiency, BOD removal has been selected as very high, for the aesthetics, space requirement; medium and for hydraulic retention time and typical water flow of the wastewater treatment method important.

After collecting many qualitative and quantitative data from different wastewater treatment technologies, the TOPSIS MCDM was firstly used to normalize the data collected, as presented in Table 3.

4. Results and discussion

The higher value of the relative closeness shows a better alternative. Table 4 shows the distance of the alternatives from the positive ideal solution and the negative ideal solution whereas Table 5 provides the ranking of wastewater treatment methods with the AS method being the best method and most preferred alternative (with a score of 0.474) to be used after considering all the criteria used for the study. It is good for developing countries where power is expensive, followed by NF treatment (with a score of 0.436), which is also good and can be used in developing countries where space is

Table 1
Data set used in the selection of the best wastewater treatment method

	Design method							
	Hydraulic retention time (Hour)	Aesthetics	Typical water flow (LMH)	Sludge generation (g/inhibitant d)	Energy consumption	Efficiency (%)	BOD removal (%)	Space requirement (m^2/inhabitant)
	Preference							
Min./Max.	Max.	Max.	Max.	Max.	Max.	Max.	Min.	Max.
Weight	0.75	0.50	0.75	0.92	0.92	0.92	0.92	0.50
Normalized weight	0.121	0.081	0.121	0.149	0.149	0.149	0.149	0.081
Act sludge	240	4	2	42.5	3	80	90	0.250
MBR	22	5	50	10.3	5	95	85	0.250
NF	30	5	120	2.0	5	98	90	0.250
CWs	168	5	0.6	20.0	3	80	90	0.375
Trickling	4	4	4.6	65.0	4	75	75	0.375
WSPs	26	5	0.6	20.0	3	80	80	1.125

Reference: [23–25].

Table 2
Linguistic fuzzy scale

Linguistic scale for evaluation	Triangular fuzzy scale	
Very high (VH)	(0.75, 1, 1)	Sludge generation, energy consumption, efficiency, BOD removal
Important (H)	(0.50, 0.75, 1)	Hydraulic retention time, typical water flow
Medium (M)	(0.25, 0.50, 0.75)	Aesthetics, space requirement
Low (L)	(0, 0.25, 0.50)	
Very low (VL)	(0, 0, 0.25)	

Table 3
Normalized weighted scores table for the alternatives for wastewater treatment methods

Methods	HRT	Aesthetics	Typical water flux	Sludge generation	Energy consumption	Efficiency	BOD Removal	Space
Unit	(hours)		LMH			(%)	(%)	Requirement
Act sludge	0.098	0.028	0.002	0.076	0.046	0.057	0.064	0.015
MBR	0.009	0.035	0.047	0.018	0.077	0.068	0.061	0.015
NF	0.012	0.035	0.112	0.004	0.077	0.070	0.064	0.015
CWs	0.069	0.035	0.001	0.036	0.046	0.057	0.064	0.023
Trickling	0.002	0.028	0.004	0.116	0.062	0.054	0.054	0.023
WSPs	0.011	0.035	0.001	0.036	0.046	0.057	0.057	0.069

Table 4
Distance of the alternatives from the positive ideal solution and the negative ideal solution

Methods	d_i^-	d_i^+	$d_i^- + d_i^+$
Act sludge	0.121	0.134	0.255
MBR	0.060	0.157	0.217
NF	0.117	0.152	0.269
CWs	0.075	0.152	0.227
Trickling	0.114	0.154	0.268
WSPs	0.064	0.166	0.231

Table 5
Relative closeness to the positive ideal solution for each alternative

Method	Score (R_i)	Ranking
ASP	0.474	1
NF	0.436	2
Trickling	0.427	3
CWs	0.331	4
WSPs	0.278	5
MBRs	0.277	6

very expensive and is normally used in cluster buildings such as hospitals, hotels, etc. AS requires more space than NF, has less energy consumption but requires a temperature greater than 20°C for biological reactions to take place for proper treatment. Moreover, the AS Method requires more supervision and experts for its operation. The least preferred method is MBR, which is because the method requires more energy, more land space, more supervision, higher installment costs, and removes less BOD compared to both the latter methods.

The weight of the importance has been selected according to the expert's opinion. Furthermore, the decision-maker could change the weights according to their priorities to obtain better ranking results for their needs. Other factors to be considered by experts can be the cost of land, topography, variations in seasons, etc.

5. Conclusions

In decision making, people of different disciplines find it difficult and maybe uncertain about their judgement when making decisions. Reliable ideas rather than random guesses are needed in decision making. In this study, wastewater treatment alternatives or methods are ranked using the TOPSIS MCDM tool. The TOPSIS decision-making tool has been proven to be an effective instrument that can be used for selecting the most preferred method among different wastewater treatment technologies. For this reason, this paper has presented a prototype framework using the TOPSIS algorithm as an effective tool for supporting machine selection decisions. The obtained results show that AS is the best method with the NF method being the second most preferred method for wastewater treatment, although it may not be feasible for developed nations where space is very costly and other countries with winter seasons almost all year round. Further understanding of the TOPSIS method and comparing it with other decision-making methods such as Fuzzy PROMETHEE and analytic hierarchy process (AHP) will be beneficial and will enable decision-makers and other governmental and non-governmental organizations to make necessary decisions and also to keep pace with other competitors in the modern economy, not only in the field of engineering but also in other fields of study.

For further researches, other decision-making tools such as AHP, ELECTRE, PROMETHEE, etc. can be applied and used to compare the results for better decision making. Furthermore, more criteria gives better results as it gives more room for more inputs to be incorporated.

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