

## Article

# Decision Analysis Approaches on the Collection Methods of Polyethylene Terephthalate Waste

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**Abstract:** The rising challenge of polyethylene terephthalate (PET) waste necessitates efficient collection methods to mitigate environmental impacts. The Analytic Hierarchy Process (AHP) is one of the Multi-Criteria Decision Analysis (MCDA) approaches utilized in this study. The Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS) was used to rank each alternative according to the objective weight that AHP had produced. Also, sensitivity analysis was performed to determine how robust the findings were when considering equal weights and entropy weights to maximize PET waste collection techniques. The alternative achieved the objective of obtaining the best collection method, Threshold Plastic Bottle Waste Collection ( $T_{pbw}$ ), out of all the three alternatives considered. Another MCDA approach, VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), was used to compare the results and validate the ranking result achieved by the TOPSIS method. The VIKOR technique's validation of the TOPSIS approach showed that the outcomes were highly consistent. Data for the study were gathered from the archives of waste management companies on possible practices of plastic waste collection, addressing costs, environmental impacts, social acceptance, feasibility, and efficiency. The findings provide a prioritized framework for enhancing PET waste collection strategies, contributing to sustainable waste management. Many criteria are considered when deciding the best collecting method for PET waste recycling, making it challenging. By using criteria importance, MCDA was applied in this study, and the objective weight of the criteria was determined using the AHP. The five criteria considered in this study are Initial investment cost, operational cost, transportation cost, environmental risk, employment potential, and the objective weights allocated to them. AHP results 0.4952, 0.1997, 0.1565, 0.0870, and 0.0616 are, respectively, determined.

**Keywords:** PET waste; AHP; TOPSIS; VIKOR; entropy weights; equal weights



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## 1. Introduction

The current state of the issue of plastic use and production is assessed annually because it is one of the most vital components of human activities as it consists of various features, such as strength, durability, mechanical properties, thermal properties, etc., without any doubt [1]. According to Alex Olanrewaju Adekanmbi, et al. (2024), the manufacturing, distribution, and extraction processes of plastic from virgin materials influence the environment greatly. Also, aside from the physical characteristics of plastics themselves, the use of plastics has health effects due to additives, pollutants, and degradation products [2].

Microplastic poses serious dangers to both humans and the environment. Plastic application has replaced most wooden, metal, and glass in the first stage of development [3]. Plastics became ubiquitous as they started finding a use in everyone's household and office. The study by [4] established the significance of households as an integral part of plastic pollution, lacking the information, attitude, and awareness necessary to separate plastic

waste before disposing of it, but the community nevertheless exhibited the behaviors associated with it because they understood that they were responsible for managing the waste in their respective households [4], as we are enjoying the convenience of plastics [5].

The most widely recycled plastic is polyethylene terephthalate (PET), used in many products, such as food packaging and beverage bottles [6]. Unlike the other thermoplastic polymers, polyethylene terephthalate is a widely used polyester class [7]. This substance is mainly used to make clothes and food containers, such as plastic water bottles [8]. PET is a solid material that does not absorb water; hence, it is suitable for food containers. The manufacture of PET and its consumption has resulted in unintended consequences for the environment and human health due to the large amount of PET disposal in natural ecosystems. With the growth of income level, the volume of waste becomes bigger, which is also in proportion to income [9]. Over the past few years, top scientists have researched how plastics and chemicals used in production might affect human health. The use of PET bottles has been a cause of insulin resistance [10], as affirmed by [11], which found that exposing PET to the sunlight temperature of (30°–60°) agitates the chemical substance contained in a PET bottled water, reduces the anogenital distance in male infants, and lowers levels of sex hormones, in addition to causing adverse effects on the immune system, particularly in young people [12]. The damage caused by littered plastics to ecological systems is more visible and disastrous. In a study by [13], plastic waste was found to have many different sizes and forms. Nevertheless, the breakdown of plastic into smaller pieces, known as microplastics (MPs), is the most significant and recent harm posed by plastic pollution.

The rapid increase in plastic production and consumption, particularly PET products, has led to a corresponding rise in plastic waste generation, posing significant environmental and health risks [14]. Plastic waste from PET can last for centuries, making it difficult for animals and plants in the environment to live. Suitable collection methods are vital for lowering the environmental impact of PET waste and encouraging recycling. In recent years, emphasis on sustainability and PET recycling has grown significantly relevant to companies and customers. Recycling PET bottles has drawn consumer attention. The percentage of PET single-use bottles keeps rising more and more as beverages in PET packaging materials are drunk on the go [15]. MCDA is the primary strategy used in this study, and there are other approaches to collecting plastic waste. MCDA is widely used to analyze and prioritize alternatives with multiple conflicting criteria. MCDA methods aim to equip decision-makers with knowledge and structure for complex problems, intangible factors, and better choices [16].

Different MCDA methodologies exist as tools for decision-makers in this process. A few commonly used approaches are AHP, a pair-wise comparison method that models complex problems as a hierarchy of criteria, sub-criteria, and alternatives, and allows for ranking decision priorities [17]. AHP is widely used in strategic planning, resource allocation, engineering and manufacturing, healthcare, business, supply chains, and project selection [17,18]. In TOPSIS, the ideal solution is closest to the positive ideal and farthest from the negative ideal. The decision matrix is normalized, and criteria weights are calculated. Then, the Euclidean distance is calculated for each alternative from the ideal and negative-ideal solutions [19]. For instance, the Euclidean distance between points  $(X_1, X_2)$  and  $(Y_1, Y_2)$  is calculated by finding the difference between  $X$  and  $Y$  coordinates given as  $(X_2 - X_1)$  and  $(Y_2 - Y_1)$ . Figure 1 presents a graphical representation of the TOPSIS method for calculating the Euclidean distance.

A wide range of problems, such as supplier selection, facility location, and portfolio management, have benefited from applying TOPSIS, designed explicitly for quantitative data analysis [20]. The Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) groups alternatives by comparing their preferences pairwise. Then, a preference function is assigned to each criterion, and positive and negative outranking flows are computed, resulting in the final ranking [21]. PROMETHEE is well suited explicitly to problems involving qualitative data. It is commonly used in environmental, transportation,

pollution control, and water management [21]. The use of MCDA in sustainable energy planning demonstrates its ability to incorporate both qualitative and quantitative criteria, and involve stakeholders in decision-making [22].

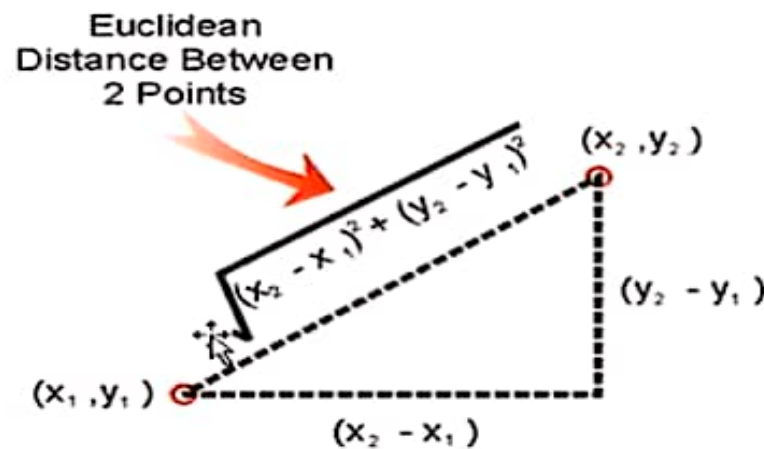


Figure 1. Euclidean distance for two points between two axes.

This paper aims to identify the best methods for collecting PET waste using Multi-Criteria Decision Analysis (MCDA) methods. This study aims to address this issue by examining different collection strategies from an efficiency and sustainability perspective while considering stakeholders' preferences.

## 2. Analytic Hierarchy Process (AHP)

The objective weights were determined using the AHP approach by adopting these six steps [23].

- a. The problem and goal are defined by prioritizing the criteria (Table 1). Constructing a pair-wise comparison matrix.

Table 1. Secondary data on plastic bottle waste collection methods from Mowaje Venture.

|                  | Criteria/Alternatives        | (T <sub>pbw</sub> )<br>(USD) | (P <sub>pbw</sub> )<br>(USD) | (E <sub>pbw</sub> )<br>(USD) |
|------------------|------------------------------|------------------------------|------------------------------|------------------------------|
| Cost criteria    | Initial investment cost (IC) | 9352                         | 37,407                       | 18,703                       |
|                  | Operational cost (OC)        | 25                           | 63                           | 38                           |
|                  | Transportation cost (TC)     | 11                           | 28                           | 17                           |
| Benefit criteria | Environmental risk (ER)      | 1                            | 5                            | 3                            |
|                  | Employment potential (EP)    | 1                            | 5                            | 3                            |

- b. Normalizing the constructed pair-wise comparison matrix (Table 2). Normalize the pair-wise comparison matrix by dividing each element by the sum of its column as given in Equation (1).

$$\tilde{a}_{ij} = \frac{a_{ij}}{\sum_{k=1}^n a_{kj}} \quad (1)$$

Table 2. Normalized pair-wise comparison matrix.

| Criteria | IC     | OC     | TC     | ER     | EP     | Criteria Weights | Weighted SUM Value | Ratio  |
|----------|--------|--------|--------|--------|--------|------------------|--------------------|--------|
| IC       | 0.5696 | 0.7803 | 0.6593 | 0.3000 | 0.1667 | 0.4952           | 3.46               | 6.9857 |
| OC       | 0.0633 | 0.0867 | 0.1319 | 0.3000 | 0.4167 | 0.1997           | 0.98               | 4.9082 |
| TC       | 0.1139 | 0.0867 | 0.1319 | 0.2000 | 0.2500 | 0.1565           | 0.81               | 5.2015 |
| ER       | 0.1899 | 0.0289 | 0.0330 | 0.1000 | 0.0833 | 0.0870           | 0.42               | 4.8194 |
| EP       | 0.0633 | 0.0173 | 0.0440 | 0.1000 | 0.0833 | 0.0616           | 0.30               | 4.8020 |

- c. Sum the values in each row to obtain a set of values called weighted sum, as shown in Table 2.
- d. Calculate the mean of the values from the preceding stage; this value is known as  $\lambda_{max}$ :

$$\lambda_{max} = \frac{6.9857 + 4.9082 + 5.2015 + 4.8194 + 4.8020}{5} = 5.343$$

- e. The consistency index (CI) is calculated as follows:

$$\begin{aligned} \text{Consistency Index (C.I.)} &= \frac{\lambda_{max} - n}{n - 1} \\ &= \frac{5.343 - 5}{5 - 1} = 0.085 \end{aligned} \quad (2)$$

where  $n$  is the number of compared elements (in this case  $n = 5$ )

- f. Now we can calculate the consistency ratio, given as:

$$\begin{aligned} \text{Consistency Ratio} &= \frac{\text{Consistency Index (C.I.)}}{\text{Ratio Index (RI)}} \\ &= \frac{0.085}{1.12} = 0.076 \end{aligned} \quad (3)$$

Table 3 contains a randomly generated comparison matrix's ratio index (RI), which is available and given as shown in Table 4. For  $n = 5$ ,  $RI = 1.12$ . It is possible to compute that using these CI and RI values. The authors presume that our judgment matrix is reasonably consistent because the proportion of inconsistency (CR) value of 0.076 is less than 0.10, allowing us to proceed with the AHP decision-making process

**Table 3.** Consistency indices for a randomly generated matrix.

| N  | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   |
|----|------|------|------|------|------|------|------|------|------|------|
| RI | 0.00 | 0.00 | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 |

**Table 4.** Relative ranking scale.

| The scale of Relative Importance | Definition             |
|----------------------------------|------------------------|
| 1                                | Equal importance       |
| 3                                | Moderate importance    |
| 5                                | Strong importance      |
| 7                                | Very strong importance |
| 9                                | Extreme importance     |
| 2,4,6,8                          | Intermediate values    |

### 3. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

Determining the best alternatives with the shortest distance from the positive ideal solution and farthest distance from the negative ideal solution with these nine (9) steps [24,25].

- a. Determining the objective, alternatives, and criteria.

The objective is to optimize the three (3) alternatives ( $T_{pbw}$ —Threshold Plastic Bottle Waste Collection;  $P_{pbw}$ —Project Plastic Bottle Waste Collection; and  $E_{pbw}$ —Eligible Plastic Bottle Waste Collection in a Region) based on the criteria (initial investment cost, operational cost, transportation cost environmental risk, and employment potentials).

- b. The decision matrix  $X$  is defined by Equation (4), with values given.

$$X = [X_{IJ}] = \begin{bmatrix} X_{11} & X_{12} & X_{1n} \\ X_{21} & X_{22} & X_{2n} \\ X_{m1} & X_{m2} & X_{mn} \end{bmatrix} \quad (4)$$

- c. The normalization of the decision matrix is conducted using Equation (5).

$$r_{ij} = \frac{X_{ij}}{\sqrt{\sum_{n=1}^m X_{ij}^2}} \quad (5)$$

- d. Calculate the values of the objective weight coefficients with Equation (6).

$$\sum_j^n w_j = 1 \quad (6)$$

- e. Determine the weighted decision-making matrix using Equation (7); this represents the multiplication of elements of a column of the normalized matrix with appropriate objective weight coefficients obtained from Equation (1).

$$V_{ij} = r_{ij} \cdot w_{ij} \quad (7)$$

- f. Identify the positive and negative ideal solution based on Equations (8) and (9).

$$V^+ = \{\max(v_{ij}), j \in J, \min(v_{ij}), j \in J, i = 1\} = \{V_1^+, V_2^+, \dots, V_n^+\} \quad (8)$$

$$V^- = \{\min(v_{ij}), j \in J, \max(v_{ij}), j \in J, i = 1\} = \{V_1^-, V_2^-, \dots, V_n^-\} \quad (9)$$

- g. Calculate the Euclidean separation distance of each competitive alternative from the positive and negative solution using Equations (10) and (11).

$$S_i^+ = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^+)^2} \quad (10)$$

$$S_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2} \quad (11)$$

- h. Calculate the distance between each location of the ideal solution.  $P_i$ . To determine how close a potential location is to the ideal solution for each competitive alternative using Equation (12).

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \quad (12)$$

- i. The alternatives are arranged in order based on the value of  $P_i$  found in Equation (12)

#### 4. VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR)

VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje) is a Serbian term that means Multi-criteria Optimization and Compromise Solution, which was applied practically in 1998 [26]. The following steps comprise the traditional VIKOR's compromise-ranking algorithm in Equations (13)–(17).

- a. Setting up the decision matrix according to Equation.

$$I = [I_{ij}] = \begin{bmatrix} I_{11} & I_{12} & I_{1n} \\ I_{21} & I_{22} & I_{2n} \\ I_{m1} & I_{m2} & I_{mn} \end{bmatrix} \quad (13)$$

- b. Normalization of the decision matrix is conducted using Equation (16).

$$f_{ij} = \frac{I_i^j}{\sqrt{\sum_{i=1}^m (I_i^j)^2}} \quad (14)$$

- c. Calculate utility measure  $S_i$  and regression measure  $R_i$  using Equations (15a), (15b) and (16a), (16b)

$$S_i = \sum_{i=1}^n w_i \left[ \frac{(f_{ij})_{\max} - (f_{ij})}{(f_{ij})_{\max} - (f_{ij})_{\min}} \right] \text{ Beneficial criteria} \quad (15a)$$

$$S_i = \sum_{i=1}^n w_i \left[ \frac{(f_{ij}) - (f_{ij})_{\min}}{(f_{ij})_{\max} - (f_{ij})_{\min}} \right] \text{ Non beneficial criteria} \quad (15b)$$

$$R_i = \text{maximum} \left\{ w_i \left[ \frac{(f_{ij})_{\max} - (f_{ij})}{(f_{ij})_{\max} - (f_{ij})_{\min}} \right] \right\} \text{ Beneficial} \quad (16a)$$

$$R_i = \text{maximum} \left\{ w_i \left[ \frac{(f_{ij}) - (f_{ij})_{\min}}{(f_{ij})_{\max} - (f_{ij})_{\min}} \right] \right\} \text{ Non beneficial} \quad (16b)$$

$$Q_i = v \left[ \frac{(S_i) - (S_i)_{\min}}{(S_i)_{\max} - (S_i)_{\min}} \right] + (1 - v) \left[ \frac{(R_i) - (R_i)_{\min}}{(R_i)_{\max} - (R_i)_{\min}} \right] \quad (17)$$

- d. Rank the alternatives by  $Q_i$ . The smaller the value of  $Q_i$ , the better the decision of the alternatives using Equation (17).

In this context,  $f_{ij}$  represents the decision matrix that has been normalized;  $S_i$  denotes the utility measure associated with each option, while  $R_i$  signifies the regression measure.  $w_i$  represents the objective weight assigned to each criterion, as determined through the Analytic Hierarchy Process (AHP). The value of  $v$  (the strategy that is compromised) is set to 0.5, and  $Q_i$  is the index that indicates the ranking of the options.

## 5. Results and Discussion

Table 1 presents the datasets collected from plastic waste stakeholders, suggesting the cost implications for plastic waste collection based on the selected alternatives of the study. Based on a three-point scale (1—Equal importance, 3—Moderate importance, 5—Strong importance), the two considered beneficial criteria are measured in relative relationships with alternatives. The pair-wise comparison matrix was created with the help of a scale of relative importance, as listed and defined in Table 4.

Table 2 also displays the components of the normalized decision matrix for the criteria: the coefficient of objective weight and the amount of information related to each criterion, respectively. The initial investment cost (USD) has the highest coefficient of the objective weight of 0.495, among other criteria, while the employment potential has the lowest coefficient of 0.062, as presented in Table 3. The implication is that the initial investment cost (USD) contributes more to the overall objective weight, while the employment potential has the least contribution.

After each criterion's objective weight coefficient was determined, each alternative's ranking was created using TOPSIS. The pair-wise comparison decision matrix based on the experts' judgement is presented in Table 5 as shown. The need to check the consistency level gives rise to conducting a consistency of the criteria illustrated in Table 6.

**Table 5.** Pair-wise comparison matrix.

| Criteria | IC  | OC  | TC  | ER | EP |
|----------|-----|-----|-----|----|----|
| IC       | 1   | 9   | 5   | 3  | 9  |
| OC       | 1/9 | 1   | 1   | 3  | 5  |
| TC       | 1/5 | 1   | 1   | 2  | 3  |
| ER       | 1/3 | 1/3 | 1/4 | 1  | 1  |
| EP       | 1/9 | 1/5 | 1/3 | 1  | 1  |

**Table 6.** Calculating the consistency.

|    | IC   | OC   | TC   | ER   | EP   |
|----|------|------|------|------|------|
| IC | 0.50 | 1.80 | 0.78 | 0.26 | 0.12 |
| OC | 0.06 | 0.20 | 0.16 | 0.26 | 0.31 |
| TC | 0.10 | 0.20 | 0.16 | 0.17 | 0.18 |
| ER | 0.17 | 0.07 | 0.04 | 0.09 | 0.06 |
| EP | 0.06 | 0.04 | 0.05 | 0.09 | 0.06 |

### 5.1. TOPSIS

Table 7 displays the outcome of normalizing Table 2 using TOPSIS. The weightage normalized decision matrix, also shown in Table 8, is then created by multiplying Table 7 by the objective weight coefficient of each criterion.

**Table 7.** Normalized decision matrix using TOPSIS.

| Weightage            | 0.495    | 0.200    | 0.156    | 0.087 | 0.062 |
|----------------------|----------|----------|----------|-------|-------|
| Alternative/Criteria | IC (USD) | OC (USD) | TC (USD) | ER    | EP    |
| (T <sub>pbw</sub> )  | 0.218    | 0.324    | 0.324    | 0.169 | 0.169 |
| (P <sub>pbwx</sub> ) | 0.873    | 0.811    | 0.811    | 0.845 | 0.845 |
| (E <sub>pbw</sub> )  | 0.436    | 0.487    | 0.487    | 0.507 | 0.507 |

**Table 8.** Weighted normalized decision matrix using TOPSIS.

| Weightage            | 0.495    | 0.200    | 0.156    | 0.087 | 0.062 |
|----------------------|----------|----------|----------|-------|-------|
|                      | IC (USD) | OC (USD) | TC (USD) | ER    | EP    |
| (T <sub>pbw</sub> )  | 0.108    | 0.065    | 0.051    | 0.015 | 0.010 |
| (P <sub>pbwx</sub> ) | 0.432    | 0.162    | 0.127    | 0.074 | 0.052 |
| (E <sub>pbw</sub> )  | 0.216    | 0.097    | 0.076    | 0.044 | 0.031 |

Table 9 displays the results of ranking each competing alternative by Euclidean distance from the positive.  $S_i^+$  and negative  $S_i^-$  solutions are based on the ideal best and ideal worst values. Figure 2 shows the alternatives and their ranking position via Euclidean distances.

**Table 9.** Euclidean distances and ranking.

| Alternatives         | $S_i^+$ | $S_i^-$ | $S_i^+ + S_i^-$ | $P_i$  | Rank Position |
|----------------------|---------|---------|-----------------|--------|---------------|
| (T <sub>pbw</sub> )  | 0.072   | 0.347   | 0.419           | 0.8280 | 1             |
| (P <sub>pbwx</sub> ) | 0.347   | 0.072   | 0.419           | 0.1720 | 3             |
| (E <sub>pbw</sub> )  | 0.121   | 0.234   | 0.355           | 0.6590 | 2             |

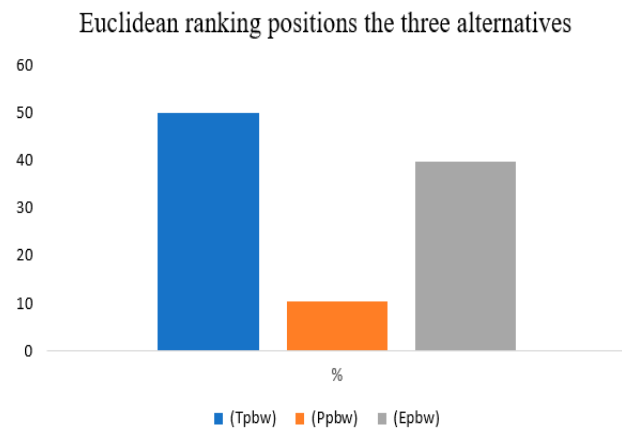


**Figure 2.** The Euclidean ranking positions the three alternatives.

### 5.2. VIKOR

The VIKOR method was used to normalize Table 2; the results are shown in Table 10. Table 9 is then multiplied by the coefficient of the criteria objective weights, determined by AHP, to produce the weightage normalized decision matrix shown in Table 11.

**Table 10.** Normalized decision matrix using VIKOR.

| Weightage            | 0.495    | 0.200    | 0.156    | 0.087 | 0.062 |
|----------------------|----------|----------|----------|-------|-------|
| Alternative/Criteria | IC (USD) | OC (USD) | TC (USD) | ER    | EP    |
| (T <sub>pbw</sub> )  | 0.218    | 0.324    | 0.324    | 0.169 | 0.169 |
| (P <sub>pbwx</sub> ) | 0.873    | 0.811    | 0.811    | 0.845 | 0.845 |
| (E <sub>pbw</sub> )  | 0.436    | 0.487    | 0.487    | 0.507 | 0.507 |

**Table 11.** Weighted normalized decision matrix using VIKOR.

| Weightage            | 0.495    | 0.200    | 0.156    | 0.087 | 0.062 |
|----------------------|----------|----------|----------|-------|-------|
|                      | IC (USD) | OC (USD) | TC (USD) | ER    | EP    |
| (T <sub>pbw</sub> )  | 0.108    | 0.065    | 0.051    | 0.015 | 0.010 |
| (P <sub>pbwx</sub> ) | 0.432    | 0.162    | 0.127    | 0.074 | 0.052 |
| (E <sub>pbw</sub> )  | 0.216    | 0.097    | 0.076    | 0.044 | 0.031 |

Subsequent computations from Table 11 are provided in Table 12, displaying the measure of utility  $S_i$ , the measure of regression  $R_i$ , and the final Ranking index  $Q_i$ .

**Table 12.** Values of measure of unity, measure of individual regression, and ranking index.

|                      | $S_i$  | $R_i$  | $Q_i$  | Rank Based on $Q_i$ |
|----------------------|--------|--------|--------|---------------------|
| (T <sub>pbw</sub> )  | 0.1486 | 0.0870 | 0.0000 | 1                   |
| (P <sub>pbwx</sub> ) | 0.8514 | 0.4952 | 1.0000 | 3                   |
| (E <sub>pbw</sub> )  | 0.3581 | 0.1651 | 0.2447 | 2                   |
| $S^*, R^*$           | 0.1486 | 0.0870 |        |                     |
| $S^-, R^-$           | 0.8514 | 0.4952 |        |                     |

Both methods have different normalization processes. The TOPSIS method employs vector normalization, whereas the VIKOR method uses linear normalization. The normalized value in linear normalization is independent of the criteria's unit. The normalized value in the TOPSIS method may vary depending on the evaluation unit used for a given

criterion. The ranking index with distances from the ideal and negative-ideal points is introduced by the TOPSIS method. In TOPSIS, these distances are summed without considering their relative significance [27].

While the TOPSIS approach employs n-dimensional Euclidean distance, which might suggest a balance between overall and individual satisfaction, it does so in a different manner from VIKOR, which introduces weight. Both techniques produce listings. The option that scores the highest on VIKOR is the one that comes closest to the perfect answer. Although the option with the highest ranking by TOPSIS is the best according to the ranking index, this does not always imply that it is the best option overall. The VIKOR method ranks and suggests an acceptable solution with an improved rating [27].

However, it is interesting that the normalization processes of TOPSIS and VIKOR resulted in similar results, as presented in Tables 7 and 10.

The alternative  $T_{pbw}$  was considered the ideal alternative, having the highest ranking among the two MCDA methods used in the analysis. However, the alternative  $P_{pbw}$  was considered the worst alternative of the two analysis methods.

The graph provides a comparative analysis of three PBW (plastic bottle waste) collection alternatives ( $T_{pbw}$ ,  $P_{pbw}$ , and  $E_{pbw}$ ) using six different multi-criteria decision analysis (MCDA) approaches TOPSIS, VIKOR, Entropy Method with TOPSIS, Entropy Method with VIKOR, Equal Weights with TOPSIS, and Equal Weights with VIKOR. The performance results of each alternative against each method are presented in Table 13.

**Table 13.** Performance results.

|               | Topsis | Vikor | Entropy Method with Topsis | Entropy Method with Vikor | Equal Weights with Topsis | Equal Weights with Vikor |
|---------------|--------|-------|----------------------------|---------------------------|---------------------------|--------------------------|
| ( $T_{pbw}$ ) | 0.828  | 0.000 | 0.489                      | 1.000                     | 0.498                     | 1.002                    |
| ( $P_{pbw}$ ) | 0.172  | 1.000 | 0.511                      | 0.484                     | 0.502                     | 0.482                    |
| ( $E_{pbw}$ ) | 0.659  | 0.245 | 0.578                      | 0.276                     | 0.580                     | 0.278                    |

The TOPSIS method indicates that  $T_{pbw}$  has the highest performance value, approximately 0.8. This shows that  $T_{pbw}$  is the most preferred alternative under TOPSIS, which relies on the geometric distance from the ideal solution. On the other hand,  $P_{pbw}$  is the lowest performer with a performance value of 0.2, thus making it the least favorable alternative.  $E_{pbw}$  has a performance value of about 0.65, is moderately preferred, and can be chosen as an alternative to  $T_{pbw}$ .

The VIKOR method shows a different strength of preference.  $T_{pbw}$  has the lowest performance value of 0, thus, it is the least preferred alternative for the VIKOR approach, as it favors compromise solutions. However,  $P_{pbw}$  has the highest performance at 1 and is the best alternative under VIKOR.  $E_{pbw}$  has an estimated performance value of approximately 0.25, which is therefore not too high compared to the total source size and thus not too low, implying moderate suitability.

With the entropy method with TOPSIS, the performance values for all three alternatives are similar, varying between 0.48 and 0.58.  $E_{pbw}$  is slightly higher than the other alternatives, with a value of about 0.58, while  $T_{pbw}$  and  $P_{pbw}$  have almost similar performance values, slightly lower than  $E_{pbw}$ . This minute change implies that when criteria weights are balanced through entropy, the performance gap between alternatives decreases so that all alternatives become equally desirable.

The entropy method with VIKOR presented the performance value of  $T_{pbw}$ , the most preferred alternative, with a value of 1.  $P_{pbw}$  scores around 0.48, and  $E_{pbw}$  has the lowest value at about 0.28. This method recommends  $T_{pbw}$  as the best alternative, so the results of adjusting the weights according to entropy and employing VIKOR confirm the preference for  $T_{pbw}$ .

The equal weights with the TOPSIS method showed that the performance values of all the alternatives were similar at about 0.5, with  $E_{pbw}$  slightly higher at about 0.58. This implies that if all concerns are treated equally,  $E_{pbw}$  takes a slightly higher position. The

close performance indicators mean no significant difference between the alternatives when considering equal weights.

The performance values using equal weights with VIKOR indicated that  $T_{pbw}$  and  $P_{pbw}$  performance values are comparable at around 0.48, while  $E_{pbw}$  has the lowest value at approximately 0.28. This method shows a significant preference for  $T_{pbw}$  and  $P_{pbw}$ , instead of  $E_{pbw}$ , and it is in line with the Entropy Method with VIKOR results. It is apparent from the graph that the preference for alternatives is significantly influenced by the MCDA method used.  $T_{pbw}$  has consistently scored highly in all methods, especially in TOPSIS and entropy, with VIKOR showing that it is the best PET waste collection method.  $P_{pbw}$  has its strength mainly in VIKOR and demonstrates its use when group utility and compromise matter the most. However,  $E_{pbw}$  is the most consistent moderately performing method and is preferred in equal weight or entropy with TOPSIS methods.

## 6. Sensitivity Analysis

Sensitivity analysis is performed to determine the impact of altering the objective weights of criteria on evaluating alternatives. This is done by identifying the various alternative ranking changes that arise for each method if the weight of each sub-criteria value is altered [28,29]. The Sensitivity analysis matrices derived from decision-making methods for this study are presented in Figure 3. When the original ranking is altered by altering the objective weights of the criteria, the results are considered sensitive, otherwise, the results are referred to as robust. These modifications produce various scenarios that could change the ranking of alternatives [30].

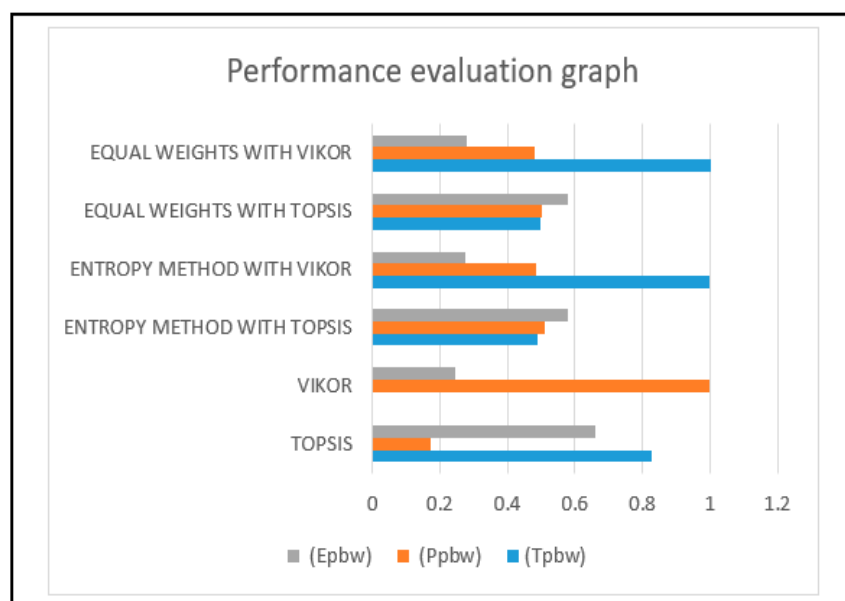


**Figure 3.** Sensitivity analysis of decision-making matrices.

Through the utilization of four (4) scenarios, sensitivity analysis was performed. Instead of using the original AHP approach, the objective weights were redistributed using the entropy method. The second possibility involved giving each criterion the same weight. Table 13 presents each of the four situations. This indicates that alterations in the criteria's objective weights can impact the ranking outcomes determined by the two techniques. Alternative  $T_{pbw}$  is confirmed to be the best choice in all four scenarios, and it was considered for the sensitivity analysis of the TOPSIS and VIKOR procedures since it was ranked first almost in the four scenarios presented.

The MCDA tools AHP, TOPSIS, and VIKOR have been effectively utilized to choose the most effective techniques for collecting plastic bottle waste. The weight of each criterion's objective costs associated with initial investment, operations, transportation, environmental

risk, and employment potential are determined using the AHP method. TOPSIS and VIKOR were used to rank and ultimately choose among the alternatives for the PET waste collection methods: Threshold Plastic Bottle Waste Collection, Project Plastic Bottle Waste Collection, and Eligible Plastic Bottle Waste Collection in a Region. The results were the same when the ranking results from TOPSIS were compared as a further investigation with the VIKOR method.  $T_{pbw}$  was ranked as the best alternative by TOPSIS and VIKOR methods.

According to the sensitivity analysis, changes in the objective weight of the criteria impact both TOPSIS and VIKOR, which were used to rank the alternatives. The selection of additional criteria to strengthen the process can be further explored in future research to examine the robustness of the outcomes. This can include the following: social impact, environmental impact, ease of sorting plastic waste [31], energy consumption, sustainability, processing cost [32], and other waste management factors.

## 7. Materials and Methods

Secondary data collected includes statistics and feedback from all stakeholders involved in the PBW business chain, such as manufacturers, distributors, retailers, policy-makers, and researchers. Issues concerning PET waste generation, collection methods, environmental problems, industry practices, and government rules were explored.

Information was also gathered on preferences for plastic bottle products and how plastic bottle waste can be recycled. Findings revealed that plastic bottle waste pollution poses health or environmental risks, with them naming certain risks associated with pollution. The data provided gave an insight into the level of plastic bottle waste pollution in the study. Specifically, for the purpose of this study, data were sourced from the archives of Mowaje Venture, a Public-Private Partnership (PPP) waste management company in Ibadan.

The information also covered the nature of the plastic products the post-consumers used the most, and the volume of disposable plastic bottle waste produced by their households each month. Experts revealed their approaches to handling plastic bottle waste, such as whether they segregate biodegradable and non-degradable waste, and whether they work with waste recyclers. This information helped to gain practical insights into waste disposal behaviors from the post-consumers regarding what usually occurs and what may need to change.

Experts gave their awareness to government or non-government campaigns about reducing the use of plastic bottles in their city or area and were asked to name any that they were aware of. This section analyzed levels of public post-consumers and the success of the current campaigns in advocating for waste reduction methods. Figure 4 illustrates the decision framework of AHP, while Table 14 clearly describes the assessment of the criteria under consideration.

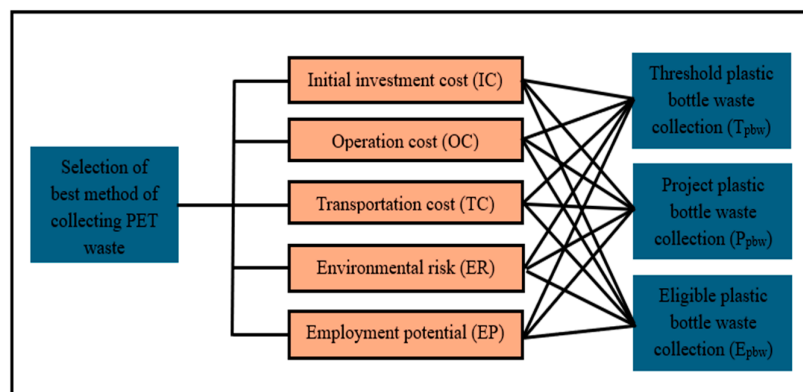
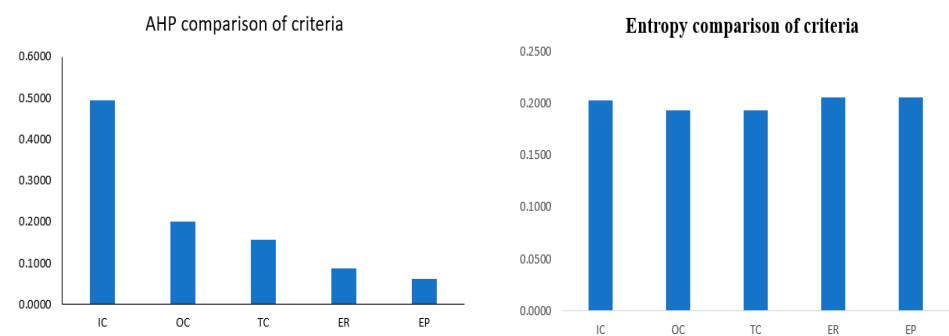


**Figure 4.** The hierarchal framework of PET waste collection for maximum recycling.

**Table 14.** Appraising criteria and accompanying the descriptions.

| Criteria                | Acronym | Description of Criteria                                                                                             |
|-------------------------|---------|---------------------------------------------------------------------------------------------------------------------|
| Initial investment cost | IC      | The initial investment cost is the necessary financial amount to begin a project, business, or investment.          |
| Operational cost        | OC      | The operational cost is the continuous expenses needed for the daily operation of a business or project.            |
| Transportation cost     |         | Transportation costs are the expenses of moving goods or people between locations.                                  |
| Environmental risk      | ER      | Environmental risk is the possibility of environmental harm from human actions or natural occurrences.              |
| Employment potential    | EP      | Employment potential signifies generating and maintaining job opportunities within a business, industry, or region. |

The secondary data also established how the post-consumers access information on plastic bottle waste pollution and what alternatives to plastic they use. Finally, the post-consumers identified the main reasons for the continued use of plastics and their opinions on the most effective ways to reduce plastic bottle waste pollution in the city. The methodology employed the utilization of various MCDA methods, including the Analytic Hierarchy Process (AHP), the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), entropy weights, and equal weights. The criteria weights were estimated using AHP, entropy weights, and equal weights methods, as shown in Figure 5.

**Figure 5.** Criteria weights of AHP, and entropy weights methods.

Three alternatives for PET waste collection methods are identified:  $T_{pbw}$ —Threshold Plastic Bottle Waste Collection;  $P_{pbw}$ —Project Plastic Bottle Waste Collection; and  $E_{pbw}$ —Eligible Plastic Bottle Waste Collection in a Region.

Threshold plastic waste collection is the quantity of plastic waste collected while project activities (such as MRF and/or recycling facilities, waste plastic for energy recovery through incineration or gasification, waste management agencies, etc.) are not taking place. The threshold waste collection for a capacity increase activity is determined based on the maximum collection potential of the waste collection system in the stipulated period before the start of the project activity.

Project plastic waste collection is the amount of plastic waste that is collected by the project activity. However, eligible plastic bottle waste collection is plastic waste available in the region that has not been recycled in the absence of project activity.

Criteria are categorized into two main groups: costs (initial investment cost, operational cost, transportation cost) and benefits (environmental risk, employment potential). These three (3) criteria were used in estimating the alternatives and were determined from the standardized Equations (18) and (19).

$$\text{Initial investment cost(USD)} = \frac{FC}{\left(1 - \frac{PC1}{100}\right)} \quad (18)$$

$$\text{Operation cost(USD)} = JC + PC2 \quad (19)$$

where  $FC$  is the final cost (USD),  $PC1$  is the percentage change in cost (%),  $JC$  is the job cost, and  $PC2$  is the process cost. The transportation cost,  $TC$ , depends on other costs in operation such as the estimated fuel consumption, the mileage for each shipment and multiplying it with the fuel cost, expenses on vehicle maintenance, and considering wages of the drivers involved in the transportation process with some other fees that may be added.

## 8. Conclusions

The best PET waste collection method has been chosen with the help of MCDA tools like AHP and TOPSIS. The AHP approach was used to calculate the objective weight of the consideration criteria, which included employment potential, environmental risk, operational costs (USD), transportation costs (USD), and initial investment costs (USD). TOPSIS was used to rank and decide the alternative (collection method). The initial investment demonstrates almost 50% weight, the operational cost demonstrates 20%, and the transportation cost demonstrates 16%. However, the environmental risk and the employment potential shared the lowest weights of approximately 8% and 6%, respectively, as defined by the objective weight technique considered.

To confirm this, the ranking findings from TOPSIS were compared with those from the VIKOR approach.  $T_{pbw}$  was ranked as the top alternative by the VIKOR technique as well. This study reveals the best alternatives to achieve the optimal collection method to enhance PET waste recycling further. According to the sensitivity analysis conducted, changes in the objective weight of the criteria impacted both TOPSIS and VIKOR, which were used to rank the alternatives. The study can be strengthened by adding more criteria and conducting research to incorporate other PET waste disposal techniques.

The assessment of PET waste collecting techniques demonstrates how MCDA tools may improve waste management decision-making. To develop more sustainable waste management solutions, this study emphasizes a balanced approach that takes into account social, environmental, and economic considerations. Several suggestions may be made to improve the efficacy of PET waste collecting techniques and decision-making procedures in light of these findings, among which are:

1. Encourage the usage of deposit-refund systems in regions that have facilities for recycling: policymakers in areas with established recycling systems ought to support and grow the PET waste collection to increase participation and recycling rates by providing financial incentives to consumers.
2. Engage stakeholders to improve the criteria used for making decisions: This study demonstrated how economic factors—specifically the cost of the initial investment—dominate over environmental factors. It is advised that decision-making involve stakeholders from other fields, such as economists, community leaders, and environmentalists, to rectify this imbalance.
3. Encourage long-term policy reforms to meet environmental and economic concerns: policies should encourage technological advancements in recycling to lower the operating costs of eco-friendly collecting techniques and increase their competitiveness with cost-driven alternatives.

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## References

1. Oladele, I.O.; Omotosho, T.F.; Adediran, A.A. Polymer-Based Composites: An Indispensable Material for Present and Future Applications. *Int. J. Polym. Sci.* **2020**, *2020*, 8834518. [\[CrossRef\]](#)
2. Adekanmbi, A.O.; Ani, E.C.; Abatan, A.; Izuka, U.; Ninduwezuor-Ehiobu, N.; Obaigbena, A. Assessing the environmental and health impacts of plastic production and recycling. *World J. Biol. Pharm. Heal. Sci.* **2024**, *17*, 232–241. [\[CrossRef\]](#)
3. Singh, N.; Hui, D.; Singh, R.; Ahuja, I.P.S.; Feo, L.; Fraternali, F. Recycling of plastic solid waste: A state of art review and future applications. *Compos. Part B Eng.* **2017**, *115*, 409–422. [\[CrossRef\]](#)
4. Nasir, N.; Malek, H.A.; Januri, S.S.; Malek, I.A.; Jamidin, J.N. Plastic waste knowledge of households towards a sustainable environment. *IOP Conf. Ser. Earth Environ. Sci.* **2023**, *1151*, 012010. [\[CrossRef\]](#)
5. Puluhulawa, F.; Puluhulawa, M.R. Plastic Waste: Environmental Legal Issues and Policy Law Enforcement for Environmental Sustainability. *E3S Web Conf.* **2021**, *259*, 03006. [\[CrossRef\]](#)
6. Benyathiar, P.; Kumar, P.; Carpenter, G.; Brace, J.; Mishra, D.K. Polyethylene Terephthalate (PET) Bottle-to-Bottle Recycling for the Beverage Industry: A Review. *Polymers* **2022**, *14*, 2366. [\[CrossRef\]](#)
7. Soong, Y.-H.V.; Sobkowicz, M.J.; Xie, D. Recent Advances in Biological Recycling of Polyethylene Terephthalate (PET) Plastic Wastes. *Bioengineering* **2022**, *9*, 98. [\[CrossRef\]](#)
8. Ajaj, R.; Abu Jadayil, W.; Anver, H.; Aqil, E. A Revision for the Different Reuses of Polyethylene Terephthalate (PET) Water Bottles. *Sustainability* **2022**, *14*, 4583. [\[CrossRef\]](#)
9. Al-Thani, N.A.; Al-Ansari, T.; Haouari, M. Integrated TOPSIS-COV approach for selecting a sustainable PET waste management technology: A case study in Qatar. *Heliyon* **2022**, *8*, e10274. [\[CrossRef\]](#)
10. Pjanic, M. The role of polycarbonate monomer bisphenol-A in insulin resistance. *PeerJ* **2017**, *2017*, e3809. [\[CrossRef\]](#)
11. Molonia, M.S.; Muscarà, C.; Speciale, A.; Salamone, F.L.; Toscano, G.; Saija, A.; Cimino, F. The p-Phthalates Terephthalic Acid and Dimethyl Terephthalate Used in the Manufacture of PET Induce In Vitro Adipocytes Dysfunction by Altering Adipogenesis and Thermogenesis Mechanisms. *Molecules* **2022**, *27*, 7645. [\[CrossRef\]](#) [\[PubMed\]](#)
12. Rustagi, N.; Pradhan, S.; Singh, R. Public health impact of plastics: An overview. *Indian J. Occup. Environ. Med.* **2011**, *15*, 100–103. [\[CrossRef\]](#) [\[PubMed\]](#)
13. D'Angelo, S.; Meccariello, R. Microplastics: A Threat for Male Fertility. *Int. J. Environ. Res. Public Health* **2021**, *18*, 2392. [\[CrossRef\]](#)
14. Oyewale, J.A.; Tartibu, L.K.; Okokpujie, I.P. A Review and Bibliometric Analysis of Sorting and Recycling of Plastic Wastes. *Int. J. Des. Nat. Ecodynamics* **2023**, *18*, 63–74. [\[CrossRef\]](#)
15. Xu, Y.; Ward, P.S. Environmental attitudes and consumer preference for environmentally-friendly beverage packaging : The role of information provision and identity labeling in influencing consumer behavior. *Front. Agric. Sci. Eng.* **2023**, *10*, 95–108.
16. Hansen, P.; Devlin, N. *Multi-Criteria Decision Analysis (MCDA) in Healthcare Decision-Making and Multi-Criteria Decision Analysis*; Oxford University Press: Oxford, UK, 2024; pp. 1–26.
17. Chaube, S.A. An Overview of Multi-Criteria Decision Analysis and the Applications of AHP and TOPSIS Methods. *Int. J. Math. Eng. Manag. Sci.* **2024**, *9*, 581–615. [\[CrossRef\]](#)
18. Mondragon, A.E.C.; Mastrocinque, E.; Tsai, J.-F.; Hogg, P.J. An AHP and Fuzzy AHP Multifactor Decision Making Approach for Technology and Supplier Selection in the High-Functionality Textile Industry. *IEEE Trans. Eng. Manag.* **2019**, *68*, 1112–1125. [\[CrossRef\]](#)
19. Chakraborty, S. TOPSIS and Modified TOPSIS: A comparative analysis. *Decis. Anal. J.* **2021**, *2*, 100021. [\[CrossRef\]](#)
20. Menon, R.R.; Ravi, V. Using AHP-TOPSIS methodologies in the selection of sustainable suppliers in an electronics supply chain. *Clean. Mater.* **2022**, *5*, 100130. [\[CrossRef\]](#)
21. Journal, I.; Taherdoost, H.; Madanchian, M.; Taherdoost, H. Using PROMETHEE Method for Multi-Criteria Decision Making: Applications and Procedures. *Iris J. Econ. Bus. Manag.* **2023**, *1*, 1–7. [\[CrossRef\]](#)
22. Ezbakhe, F.; Pérez-Foguet, A. Decision analysis for sustainable development: The case of renewable energy planning under uncertainty. *Eur. J. Oper. Res.* **2021**, *291*, 601–613. [\[CrossRef\]](#)
23. Mu, E.; Making, P.D. *Understanding the Analytic Hierarchy Process*; Springer: Cham, Switzerland, 2015. [\[CrossRef\]](#)
24. Okokpujie, I.; Okonkwo, U.; Bolu, C.; Ohunakin, O.; Agboola, M.; Atayero, A. Implementation of multi-criteria decision method for selection of suitable material for development of horizontal wind turbine blade for sustainable energy generation. *Heliyon* **2020**, *6*, e03142. [\[CrossRef\]](#)
25. Agboola, O.O.; Akinnuli, B.O.; Kareem, B.; Akintunde, M.A. Decision on the selection of the best height-diameter ratio for the optimal design of 13,000 m<sup>3</sup> oil storage tank. *Cogent Eng.* **2020**, *7*, 1770913. [\[CrossRef\]](#)
26. Chang, C.-L. A modified VIKOR method for multiple criteria analysis. *Environ. Monit. Assess.* **2009**, *168*, 339–344. [\[CrossRef\]](#) [\[PubMed\]](#)

27. Sari, F. Comparison of topsis and vikor multi criteria decision analysis techniques. *Konya J. Eng. Sci.* **2018**, *6*, 825–831. [[CrossRef](#)]
28. Więckowski, J.; Sałabun, W. Sensitivity analysis approaches in multi-criteria decision analysis: A systematic review. *Appl. Soft Comput.* **2023**, *148*, 110915. [[CrossRef](#)]
29. Maliene, V.; Dixon-Gough, R.; Malys, N. Dispersion of relative importance values contributes to the ranking uncertainty: Sensitivity analysis of Multiple Criteria Decision-Making methods. *Appl. Soft Comput.* **2018**, *67*, 286–298. [[CrossRef](#)]
30. Jiří, M. The robustness of TOPSIS results using sensitivity analysis based on weight tuning. *IFMBE Proc.* **2018**, *68*, 83–86. [[CrossRef](#)]
31. Balwada, J.; Samaiya, S.; Mishra, R.P. Packaging Plastic Waste Management for a Circular Economy and Identifying a better Waste Collection System using Analytical Hierarchy Process (AHP). *Procedia CIRP* **2021**, *98*, 270–275. [[CrossRef](#)]
32. Sindhwani, K.; Gupta, P.; Kumar, A.; Srivastava, R. *Evaluation of Plastic Waste Management Methods Using Multi Criteria Decision Making Tool—AHP*; IOS Press: Amsterdam, The Netherlands, 2022. [[CrossRef](#)]

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