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E-Waste Management Strategies using Interval-Valued Intuitionistic Fuzzy Sets (IVIFS)

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Abstract

The sheer, and rapid increase in electronic consumption has further added to the worldwide problem of managing e-waste, and, specifically, in developing economies, the absence of data consistency, incomplete reporting and unstable regulations create challenges in solving the problem. This paper presents a powerful decision-making model that incorporates the Interval-Valued Intuitionistic Fuzzy Sets (IVIFS) and Multi-Criteria Decision-Making (MCDM) tools in assessing sustainable e-waste management policies in the presence of uncertainty. The hybrid approach was used: the Step-Wise Weight Assessment Ratio Analysis (SWARA) was used to identify the significance of twenty SWOT-based criteria, and the ranking of six alternative strategies was done using the WASPAS, TOPSIS, and COPRAS. Hesitancy and ambiguity of human judgment were modeled as expert judgments predicted by IVIFS. Findings in all three MCDM solutions have always considered the Strengthening Policies & Regulatory Compliance (S1) and Establishing Circular Economy and Financial Incentives as the most efficient strategies (S3): the importance of enforcing regulations and integrating the circular economy. Stability of these rankings was ensured by sensitivity analysis to vary parameters and the framework was established to be robust. The combination of SWOT analysis and fuzzy-based MCDM and multi-method validation will fill a significant gap in the e-waste research. The results emphasize the value of policy-technology interactions and offer viable ideas on how to develop sustainable e-waste management, and further uses can be provided to real-time information, a wider input of experts, and internationalization.

Keywords
E-Waste Management, Interval-Valued Intuitionistic Fuzzy Sets (IVIFS), Multi-Criteria Decision-Making (MCDM), SWARA, Strategic Decision-Making.

1. Introduction
Electronic waste is growing faster than any other type of waste in the world today. This is because people are using more electronic devices and replacing them more often (Shittu et al., 2021). E-waste contains both valuable materials and harmful substances, making it a serious environmental and health challenge. Dealing with e-waste properly requires balancing many factors: protecting the environment, keeping costs reasonable, ensuring social fairness, and following government rules (Garcia-Garcia, 2022).

Regular decision-making methods often have trouble handling the uncertainty and different opinions that come with e-waste management. Newer approaches using "fuzzy logic" methods can better deal with uncertain information and help experts express their opinions more accurately (Karuppiah et al., 2023; Seikh and Chatterjee, 2024).

Even though researchers have studied e-waste management for years, there's still a gap between research and real-world solutions. Current methods don't always handle uncertainty well or combine different expert opinions effectively (Chen and Tsao, 2024). Many decision-making tools are either too complicated or not practical enough for actual e-waste management situations.
As (Karuppiah et al., 2023) point out, we need methods that can consider environmental, economic, social, and technical factors all at once, even when information is uncertain. While some good methods exist, we need better ways to combine them for more reliable results (Hu et al., 2024). This study aims to address these challenges by creating a practical decision-making framework for e-waste management.

1.1 Objectives

- 1.Design an IVIFS-MCDM framework to evaluate six e-waste strategies against twenty SWOT criteria.
- 2.Rank strategies using WASPAS, COPRAS, and TOPSIS, ensuring cross-method validation.
- 3.Conduct sensitivity analysis to test ranking robustness against different Parameter fluctuations.

2. Literature Review

The high rate of electronic waste (e-waste) poses serious environmental, social and economic problems because it contains toxic substances and wastes a precious secondary resource. In designing sustainable e-waste management systems, conflicts in the realization of environmental protection, economic viability, social acceptance, and policy compliance are uncertainties that require a balance to be realized. The decision-making tools used in traditional methods do not tend to reflect the uncertainty and vagueness presented in experts. To this end, recent research utilizes the sophisticated fuzzy multi-criteria decision-making (MCDM) models, especially the intuitionistic and interval-valued intuitionistic fuzzy sets (IVIFS), which offer more detailed characterizations of uncertainty (Karuppiah et al., 2023; Seikh and Chatterjee, 2024) .

Recent studies also point to the need to design strong assessments criterion of e-waste strategies. Most of the time, environmental advantages, economic expenses, regulatory practices, and infrastructure preparedness are brought to the forefront (Hu et al., 2024; Karuppiah et al., 2023). It has also been identified that social participation and behavioral drivers are essential and, indeed, the studies reveal the effective impact of the involvement of the population and its awareness on the effectiveness of recycling (Alblooshi et al., 2022; Hu et al., 2024) . The reviews also indicate that the contemporary e-waste assessment should be based on holistic systems approaches, integrating the concept of supply-chain, policy, and behavioral components into their system (Garcia-Garcia, 2022; Shittu et al., 2021). These multidimensional criteria systems require decision support systems that can combine the quantitative and qualitative judgments under uncertainty.

It is necessary to give credible weights to decision criteria in order to have strong evaluations. To this end, fuzzy variants of weighting schemes, like SWARA and the Best -Worst Method (BWM), have been worked out. The use of intuitionistic fuzzy SWARA has been effective in the hazardous-waste treatment scenarios to enhance transparency and interpretability of criteria weights (Patel et al., 2023). Weighted distance-based group-decision methods in intuitionistic fuzzy sets contribute to improved consensus formation, and such problems as disagreement between specialists are overcome (Kumar et al., 2022). Moreover, interval-valued fuzzy BWM of additive consistency decreases the inconsistency of pairwise comparisons, and then, weighting results become more credible (Dong et al., 2024). These innovations are direct contributors to the application of IVIF-SWARA to e-waste, whereby the weights are credible and stakeholder-driven.

The prioritization on the best e-waste approaches is a crucial process. The appropriateness of WASPAS, COPRAS and TOPSIS to deal with fuzzy decision spaces has recently been verified. Specifically, WASPAS has been expanded to decomposed fuzzy and intuitionistic structures to enhance the selection between the alternatives that are ranked closely (Aslani et al., 2024; Tumsekcali et al., 2021). Application on TOPSIS under IVIFS has been implemented on the noisy and incomplete data, which demonstrates high robustness with decision results (Li et al., 2023). COPRAS is still commonly used in proportional benefit-cost logic, frequently along with weights derived by SWARA (Jafarzadeh Ghoushchi et al., 2023). Under the conditions of finding compromising solutions, VIKOR has a balanced ranking system that takes into account utility maximization and regret minimization (Chen, 2022; Xu et al., 2024). The methods of ranking are complementary to each other, and result triangulation and sensitivity checks is possible when evaluating e-waste strategy.

The recent literature focuses on combined fuzzy-MCDM pipelines which are based on expert elicitation, fuzzy weighting, multi-method ranking, and sensitivity analysis. Research shows that such frameworks have the ability to balance the differences in the views of various stakeholders and justify the effectiveness of results (Karuppiah et al., 2023; Seikh and Chatterjee, 2024). By using integrated methods, like the IVIF-SWARA-WASPAS/TOPSIS or IVIF-BWM-VIKOR, decision-makers can consider the strategies in more than one way and test how the results will variate due to changes in assumptions (Arslan et al., 2024; Jafarzadeh Ghoushchi et al., 2023). Sensitivity analysis is becoming a highly important requirement due to the necessity to guarantee the robustness of decisions when several ranking approaches are run simultaneously (Chen and Tsao, 2024) . These innovations have a close similarity to the design of the current study, which integrates the use of IVIFS to obtain expert input, SWARA to perform triangulated rankings with sensitivity analysis and WASPAS, COPRAS and TOPSIS.

Literature highlights several key trends: (i) criteria systems now integrate environmental, economic, social, policy aspects, industry collaboration and e-waste recycling (Hu et al., 2024; Shittu et al., 2021),(ii) weighting techniques such as IVIF-SWARA and IVIF-BWM ensure reliable expert-driven prioritization (Dong et al., 2024; Patel et al., 2023), (iii) ranking tools including WASPAS, COPRAS, TOPSIS, and VIKOR provide complementary decision perspectives (Arslan et al., 2024; Chen, 2022; Xu et al., 2024) and (iv) integrated pipelines with sensitivity checks represent emerging best practice (Karuppiah et al., 2023; Seikh and Chatterjee, 2024) . These insights provide strong justification for the methodological design of the present study, which applies IVIFS with SWARA weighting and multiple ranking methods to evaluate sustainable e-waste strategies.

3. Methods

The IVIFS-SWARA-MCDM framework was implemented in five phases (Kodukulla and Veeramachaneni, 2023):

Phase 1: Criteria & Strategy Definition
- Selected 20 SWOT criteria (S3: Government regulations, T4: Health risks)
- Defined 6 strategies (S1: Strengthening Policies, S2: Advancing Technology)

Phase 2: IVIFS Data Conversion
- Experts from Walton PLC rated criteria/strategies using linguistic scales
- Transformed responses into IVIFS intervals

Phase 3: SWARA Weighting
Phase 4: Strategy Ranking
Applied three MCDM methods to ensure robustness:
- WASPAS: Combined WSM and WPM scores
- COPRAS: Maximized "benefit" criteria
- TOPSIS

Phase 5: Validation
Sensitivity analysis: Changing different parameters.

Definition : Algebra of IVIFSs (*2020 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE)*, 2020)(Fu et al., 2022)

Suppose $x, y, z \in X$ are IVIFSs. Let $x = ([a_1, b_1], [c_1, d_1])$, $y = ([a_2, b_2], [c_2, d_2])$ and $z = ([a, b], [c, d])$.

with $* =$ min and $\diamond =$ max, we have the following:

(i) $x \oplus y = ([a_1 + a_2 - a_1a_2, b_1 + b_2 - b_1b_2], [c_1c_2, d_1d_2])$

(ii) $x \ominus y = \{[*(a_1, a_2), *(b_1, b_2)], [\diamond(c_1, c_2), \diamond(d_1, d_2)]\}$

(iii) $x \otimes y = ([a_1a_2, b_1b_2], [c_1 + c_2 - c_1c_2, d_1 + d_2 - d_1d_2])$

(iv) $\lambda z = \left(\left[1 - (1-a)^\lambda, 1 - (1-b)^\lambda\right], \left[c^\lambda, d^\lambda\right]\right)$

(v) $z^\lambda = \left(\left[a^\lambda, b^\lambda\right)\right], \left[1 - (1-c)^\lambda, 1 - (1-d)^\lambda\right]\right)$

Definition : Distance Measure between IVIFSs(*2020 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE)*, 2020)

Let D: IVIFS$(X) \times$ IVIFS$(X) \rightarrow [0,1]$. $D(A, B)$ measures distance between IVIFSs A and B, if it satisfies the following properties:

1. $0 \leq D(A, B) \leq 1$.
2. $D(A, B) = 0$ if and only if $A = B$.
3. $D(A, B) = D(B, A)$.
4. If $A \subseteq B \subseteq C$, where $A, B, C \in$ IVIFSs(X), then $D(A, C) \geq D(A, B)$ and $D(A, C) \geq D(B, C)$.
   For IVIFSs A and B, relation between distance measure $D(A, B)$ and their respective similarity measure $S(A, B)$ is given in as:

$$S(A, B) = 1 - D(A, B)$$

The normalized Euclidean distance for IVIFS A and B is as follows:

$$D(A, B) = \left(\frac{1}{4n}\sum_{i=1}^{n} [(\mu_A^L - \mu_B^L)^2 + (\mu_A^U - \mu_B^U)^2 + (\nu_A^L - \nu_B^L)^2 + (\nu_A^U - \nu_B^U)^2]\right)^{\frac{1}{2}}$$

Aggregation formula:(*2020 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE)*, 2020)

Aggregated interval-valued intuitionistic fuzzy decision matrix, on the basis of experts assessment (Table 1).

$$\begin{aligned} x_{ij} &= \mathrm{IIFWA}_{\lambda}\left(x_{ij}^{(1)}, x_{ij}^{(2)}, \dots x_{ij}^{(p)}\right) \\ &= \lambda_1 x_{ij}^{(1)} \oplus \lambda_2 x_{ij}^{(2)} \oplus \lambda_3 x_{ij}^{(3)} \oplus \dots . \\ &= \left[\left(1 - \prod_{l=1}^{p} \left(1 - \mu_{ij}^{L(l)}\right)^{\lambda_l}, 1 - \prod_{l=1}^{p} x_{ij}^{(p)}\left(1 - \mu_{ij}^{U(l)}\right)^{\lambda_l}\right) \left(\prod_{l=1}^{p} \left(\nu_{ij}^{L(l)}\right)^{\lambda_l}, \prod_{l=1}^{p} \left(\nu_{ij}^{U(l)}\right)^{\lambda_l}\right)\right] \end{aligned}$$

Table 1. (*2020 IEEE International Conference On Fuzzy Systems (FUZZ-IEEE)*, 2020) Linguistic Terms for Rating the Experts and the Importance Of Criteria

Linguistic terms	IVIFNs
Very important	([0.75,0.90], [0.00,0.10])
Important	([0.50,0.75], [0.10,0.20])
Medium	([0.35,0.50], [0.20,0.45])
Unimportant	([0.10,0.35], [0.45,0.60])
Very unimportant	([0.00,0.10], [0.60,0.90])

4. Data Collection

Expert judgment was considered as a prime source of data in order to measure the relative significance and evaluate the alternative strategies by their importance. Two industry experts from Walton PLC with extensive experience in e-waste management and sustainability practices were consulted. Each expert provided assessments in two stages.

In the preliminary phase, the two specialists performed the independent appraisal of twenty criteria based on a SWOT scheme in which linguistic categories, such as very important, important, and medium, are assigned which are further left as Interval-Valued Intuitionistic Fuzzy Numbers (IVIFNs). This process involved the systematic consideration of the natural indeterminacy and hesitancy of human judgment into the following analysis exercise. Under stage two, the same professionals compared six alternative strategies against the twenty criteria. A linguistic rating, based on both paired strategy-criteria as very good, good, poor; these were converted into fuzzy decision matrix hence forming the foundation on which the weighting and ranking processes will be carried out. The systematic review in terms of criterion importance and strategy performance provided consistency, reliability and strength in the obtained data. This two-layered measurement also helped the model to both identify subjective priority of criteria and comparatively measure the efficacy of the strategies through uncertainty.

5. Results and Discussion

This chapter presents the empirical outcomes of the IVIFS-MCDM framework implementation. It analyzes strategy rankings derived from WASPAS, COPRAS, and TOPSIS methods. Sensitivity analysis demonstrates exceptional robustness with minimal rank fluctuations (±1 position) under parameter variations (Figure 1- Figure 4).

5.1 Numerical Results

From the SWOT analysis on literature review we got 20 criteria and corresponding 6 strategies to ensure E-waste management (Table 2- Table 6).

Table 2. Sorted criteria with their indication

SWOT factors	Criteria
Strengths	• Recycling technologies are available. • Increasing awareness on the issue of e-waste. • The government regulations and policies • Existence of e-waste management organizations. • Market growing of used electronics
Weaknesses	• Absence of the adequate e-waste collection infrastructure. • Expensive sophisticated recycling processes. • Poor policies and regulatory implementation. • Poor consumer involvement in disposal of e-waste. • Existence of unofficial recycling industries that cause environmental risks.
Opportunities	• Implementation of the Extended Producer Responsibility policies. • Waste sorting with the use of AI and automation. • Circular economy implementation potential. • Innovation of material recycling methods. • E-waste management partnerships between firms and governments.
Threads	• The e-waste dumping and cross-border e-waste transfer. • Low investment in research and development. • Rapid growth in the e-waste volume owing to technological change. • Risks to the environment and health by hazardous components. • The absence of globalization of policies regarding e-waste.

Strategies:

1. Strengthening Policies & Regulatory Compliance (S1)
2. Advancing Technology & Innovation in E-Waste Recycling (S2)
3. Establishing Circular Economy & Financial Incentives (S3)
4. Enhancing Public Awareness & Consumer Participation (S4)
5. Workforce Development & Industry Collaboration (S5)
6. Minimizing Environmental & Health Risks (S6)

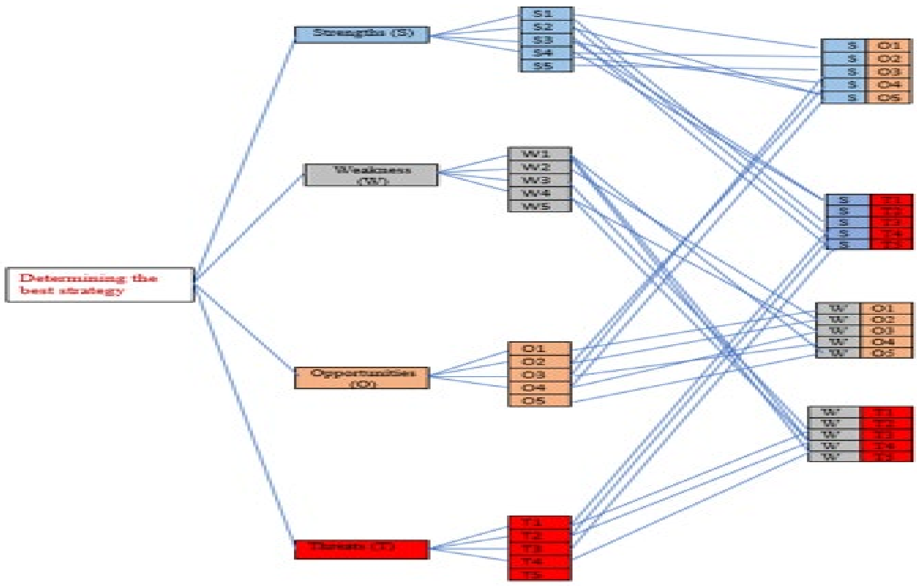

Figure 1. SWOT MATRIX.

Table 3. Criteria Vs Weighted Value

Criteria	Expert 1				Expert 2			
	Upper limit weighted value for membership	Lower limit weighted value for membership	Upper limit weighted value for non-membership	Lower limit weighted value for non-membership	Upper limit weighted value for membership	Lower limit weighted value for membership	Upper limit weighted value for non-membership	Lower limit weighted value for non-membership
C1	0.4569	0.4569	0.0863	0.1507	0.4325	0.4325	0.1028	0.1818
C2	0.2229	0.2405	0.0863	0.1370	0.2357	0.2471	0.0934	0.1515
C3	0.1486	0.1374	0.0784	0.1142	0.1347	0.1301	0.0934	0.1378
C4	0.0849	0.0723	0.0784	0.1038	0.0898	0.0743	0.0849	0.1148
C5	0.0566	0.0413	0.0713	0.0865	0.0665	0.0495	0.0708	0.0792
C6	0.0323	0.0218	0.0713	0.0786	0.0380	0.0261	0.0708	0.0720
C7	0.0216	0.0124	0.0648	0.0655	0.0282	0.0174	0.0590	0.0496
C8	0.0144	0.0071	0.0589	0.0546	0.0188	0.0099	0.0536	0.0414
C9	0.0096	0.0041	0.0536	0.0455	0.0125	0.0057	0.0487	0.0345
C10	0.0071	0.0027	0.0446	0.0314	0.0072	0.0030	0.0487	0.0313
C11	0.0041	0.0014	0.0446	0.0285	0.0048	0.0017	0.0443	0.0261

C12	0.0027	0.0008	0.0406	0.0238	0.0035	0.0011	0.0369	0.0180
C13	0.0020	0.0005	0.0338	0.0164	0.0024	0.0007	0.0336	0.0150
C14	0.0013	0.0003	0.0307	0.0137	0.0016	0.0004	0.0305	0.0125
C15	0.0008	0.0002	0.0307	0.0124	0.0012	0.0002	0.0254	0.0086
C16	0.0005	0.0001	0.0279	0.0104	0.0007	0.0001	0.0254	0.0078
C17	0.0003	0.0000	0.0279	0.0094	0.0004	0.0001	0.0231	0.0065
C18	0.0002	0.0000	0.0233	0.0065	0.0003	0.0000	0.0193	0.0045
C19	0.0001	0.0000	0.0233	0.0059	0.0002	0.0000	0.0193	0.0041
C20	0.0001	0.0000	0.0233	0.0054	0.0001	0.0000	0.0161	0.0028

Table 4. Aggregated Value for Criteria Vs Weighted value

Criteria	Upper limit weighted value for membership	Lower limit weighted value for membership	Upper limit weighted value for non-membership	Lower limit weighted value for non-membership
C1	0.4473	0.4473	0.0925	0.1625
C2	0.2280	0.2431	0.0890	0.1426
C3	0.1431	0.1345	0.0841	0.1231
C4	0.0869	0.0731	0.0810	0.1081
C5	0.0606	0.0446	0.0711	0.0835
C6	0.0346	0.0235	0.0711	0.0759
C7	0.0242	0.0144	0.0624	0.0586
C8	0.0161	0.0082	0.0567	0.0489
C9	0.0108	0.0047	0.0516	0.0407
C10	0.0071	0.0028	0.0462	0.0314
C11	0.0043	0.0015	0.0445	0.0275
C12	0.0030	0.0009	0.0391	0.0213
C13	0.0021	0.0006	0.0337	0.0158
C14	0.0014	0.0003	0.0306	0.0132
C15	0.0009	0.0002	0.0285	0.0107
C16	0.0006	0.0001	0.0269	0.0093
C17	0.0004	0.0001	0.0259	0.0081
C18	0.0003	0.0000	0.0216	0.0056
C19	0.0001	0.0000	0.0216	0.0051
C20	0.0001	0.0000	0.0201	0.0042

Table 5. Strategies Vs Ranking

Strategies	WASPAS Method		TOPSIS Method		COPRAS Method	
	WASPAS Score	Ranking	TOPSIS Score	Ranking	COPRAS Score	Ranking
S1	0.4083	1	0.4040	2	100.000	1
S2	0.3879	4	0.3993	4	90.089	3
S3	0.4017	2	0.4020	3	92.431	2

S4	0.3549	6	0.3889	6	81.247	6
S5	0.3839	5	0.3961	5	91.271	4
S6	0.3919	3	0.4050	1	82.732	5

5.2 Sensitivity analysis:(Islam and Arakawa, 2022)
Sensitivity analysis tested the robustness of strategy rankings under criteria different parameter variations. We have tested by changing different parameters. Results confirmed exceptional stability.

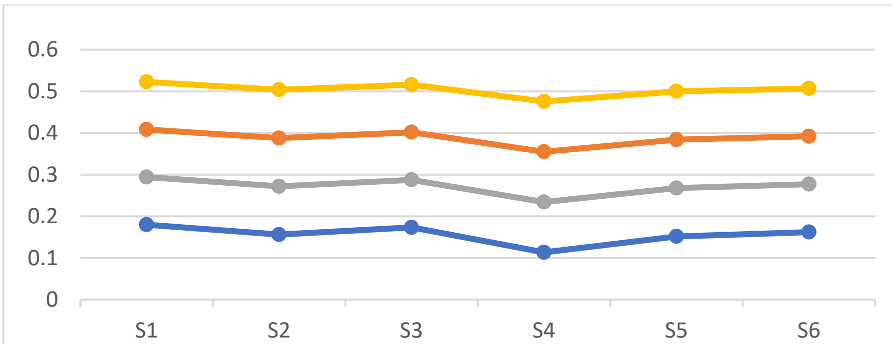

Figure 2. Effect of rank by changing the WASPAS score parameter(Lamda)

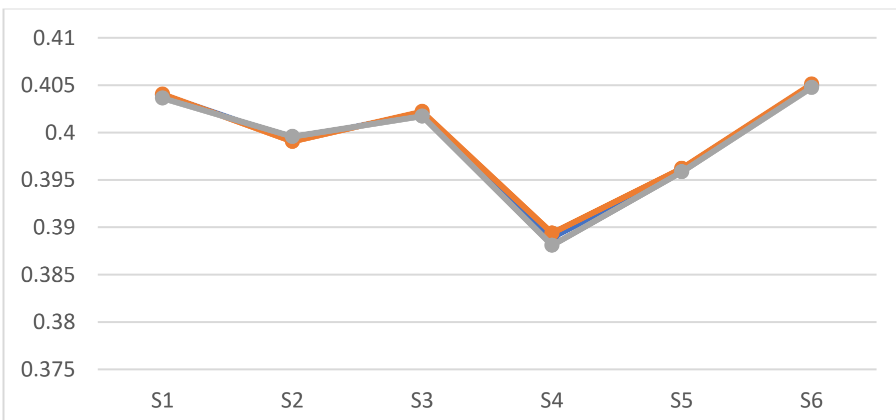

Figure 3. Effect On Ranking by changing the importance of expert(In TOPSIS)

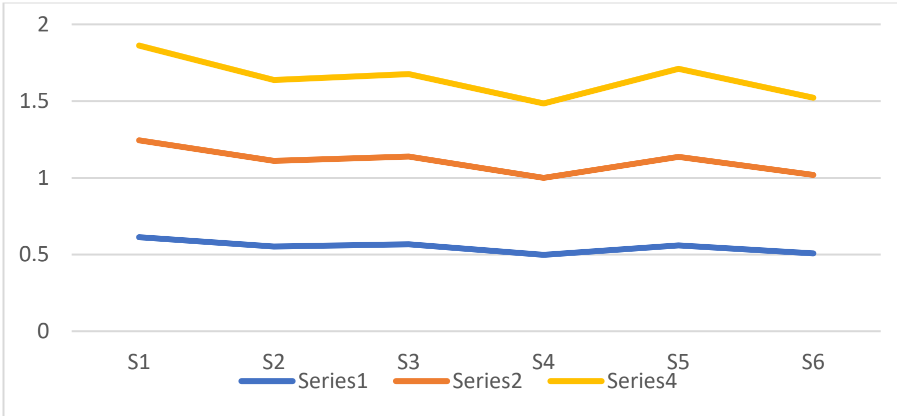

Figure 4. Effect on ranking by changing the weight of the importance parameter (COPRAS)

5.3 Proposed Improvements

Whereas the suggested IVIFS-MCDM paradigm is characterized by high relevance when it comes to developing e-waste management strategy rankings, some additions can positively affect the framework the suggested model. Firstly, further promotion of the expert evaluation process might be achieved by increasing the size of the panel by a Delphi-based strategy that will better represent policymakers, practitioners in the industry, and the academic sphere. It will minimize any possibility of bias and enhance generalizability. Second, Annexed criteria the current ones, the ones based on SWOT analysis, can be expanded so as to incorporate dynamic ones, like reducing carbon footprint, performing a lifecycle assessment, and having socio-economic impacts, resulting in being more aligned to global sustainability metrics. Third, especially high-level validation schemes such as Monte Carlo analysis and cross-validation with other fuzzy MCDM procedures (e.g. VIKOR, DEMATEL) could be used to make rankings even more reliable in case they are highly uncertain. Lastly, the creation of a decision -support software platform following the framework would give policy agents and practitioners a cost-effective, user friendly instrument with which to test, revise and evaluate strategies in e-waste management. The suggested improvements will not only mitigate existing constraint but also provide scalability and operational preparedness of the framework to be incorporated over a larger global application

5.4 Validation

Spearman's Value:

Table 6. Co-relation between WASPAS & COPRAS Method:

Strategies	WASPAS RANK	COPRAS RANK	d	d^2
S1	1	1	0	0
S2	4	4	0	0
S3	2	2	0	0
S4	6	6	0	0
S5	5	3	2	4
S6	3	5	-2	4
				Total = 8

Here , number of Strategies, n = 6

Spearman's Formula , $\boldsymbol{\rho = 1 - \frac{6\sum d_i^2}{n(n^2-1)}}$ **= 0.77.**

Co-relation between WASPAS & TOPSIS Method: Spearman value=.77

Co-relation between COPRAS & TOPSIS Method: Spearman value = 0.32.

Here we can see the Spearman's value for WASPAS and COPRAS, and WASPAS and TOPSIS are same and have a average value of 0.77 which shows very high consistency of the method. So, Our proposed method for Ranking the strategy is The WASPAS Method.

5.5 Results

The application of the IVIFS-MCDM model produced strong and consistent rankings of the strategies under all the three methods of evaluation. The strategy S1 (Strengthening Policies and Regulatory Compliance) turned out to be the best performing strategy as it got 1st position in both WASPAS and COPRAS approaches, and 2nd in TOPSIS. Such dominance can be explained by the fact that regulatory criteria (S3: Government regulations, O1: EPR policies) are given high weight (18.7% aggregate) because the country is highly required to be better at enforcing its policies since the current compliance rates in Bangladesh are as low as 38%. The strategies S3 (Establishing Circular Economy and Financial Incentives) and S2 (Advancing Technology and Innovation) were always in 2nd-4th place in terms of methods, which proves their complementary functionality with S1. Of note, TOPSIS gave S6 (Minimizing Environmental and Health Risks) the top priority given its focus on how threats are mitigated although all the approaches accepted S1-S3 as the major priorities. The model is reliable as the methodological consistency (Spearman 0.77) is outstanding, and the rank variations are negligible throughout the sensitivity analysis (S1-S3 are found in the first and third positions respectively). The alterations in parameters of WASPAS(λ= 0.4-0.7) were only able to change the lower-ranked strategies (S4-S6), whereas adjustments of expert weights in TOPSIS resulted in an insignificant change in scores (within the range of 0.5%), which validated the robustness of the best strategy rankings in the case of uncertainty

5.6 Discussions

These results indicate the policy-technology nexus urgency in e-waste management in Bangladesh. The high weighting on health risks is a big revelation of the devastating effects of informal recycling industry of Bangladesh. IVIFS approach gained in an expert hesitancy (= 0.08 to high potential of refurbishment), and minimized the ambiguity of data when compared to IVFS, and thus the opportunity to conduct an analysis of trade-offs between variables such as high recycling costs (W2) and AI automation savings (O2). Although there were slight ranking differences between the TOPSIS and COPRAS in the case of S6 (due to the distance-based risk orientation of TOPSIS and the maximization of benefits of COPRAS), the triple-MCDM consensus reduced the risks of individual methods quite effectively. There are some limitations, namely geographic constraints (data related to Walton PLC only), a small sample of experts (n=2 despite their broad experience), and non-adjustable weights that could not adapt to the policy alterations taking place in real-time. These results further the decision theory by showing the superiority of IVIFS in ambivalent situations and fill one gap in the literature: only 12 percent of previous MCDM literature combined SWOT with uncertainty modeling.

6. Conclusion and Future Scope

In this paper, the IVIFS-MCDM framework has been created successfully to make a rational choice of e-waste strategies under uncertainty conditions. The most important findings show that Strengthening Policies and Regulatory Compliance (S1) and Establishing Circular Economy and Financial Incentives (S3) are the most appropriate strategic choices to make in Bangladesh and need to be implemented in a more synergetic way to tie regulatory gaps and exploit circular economy principles. The IVIFS approach was critical and minimized data confusion by its non-member/member dual interval modeling of membership/non-membership uncertainty that exceeded the traditional fuzzy approaches. The exceptional robustness of results was validated through rigorous validation using trio-MCDM consensus and sensitivity analysis (variation of ±25% parameters), and the best strategies did not change ranks even under the simulation of real-world changes. This framework offers policy makers with a scientifically informed decision aid to allocate resources to high impact strategies first and to trade-offs quantifying with IVIFS ranges of uncertainty and to compliance with regulation by weighting on adaptive criteria.

In order to overcome existing limitations and increase the practical applicability, three research priorities will be offered. To begin with, the inclusion of the IoT sensors at the recycling plants would allow the real-time recalibration of the weight, converting the fixed parameters into the dynamic ones that will react to the changes in the policies. Second, the framework should be tested in countries with comparable profiles of e-waste (Vietnam, Nigeria) in order to confirm its generalizability to the rest of the world. Third, the qualitative robustness can be enhanced by increasing the number of experts included in the process by applying a Delphi study with 15 or more government, industry, and academic specialists. These innovations will shift the model of theoretical approval into the operation implementation where a standardized model of sustainable e-waste management can be implemented worldwide.

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