



TECHNOLOGY ASSESSMENT FRAMEWORK FOR E-WASTE RECYCLING: A MULTI-CRITERIA EVALUATION APPROACH

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Abstract

Technology is crucial for India to achieve its long-term development goals. With technological advancements, determining which technology is most effective for recycling electronic waste (e-waste) is crucial to minimising environmental impact in the recycling sector. Researchers employ multicriteria decision-making to assess the environmental implications of these continually evolving technologies (Zhou et al., 2006). Banta (2009), defines technology assessment as a policy study that examines the short- and long-term repercussions of technology adoption. The paper uses a Multicriteria Decision Making (MCDM) tool, the fuzzy-Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), for assessing the recycling technologies for e-waste. Pyrometallurgy, hydrometallurgy and bio-metallurgy are the three major technologies being used for recycling critical, precious and strategic minerals from electronic waste (Alam et al., 2022). Potential technology which can be deployed in India are chosen based on technological, environmental, and economic (TEE) evaluation criteria which determine the technical efficiency, economic viability and environmental impact of considered technologies. The working paper presents a more precise, effective, and systematic decision-making matrix for decision makers (policy makers, start-ups and industry players) to conduct the assessment process and select environmentally sound and economically viable e-waste recycling technologies, considering the fact that the formal recycling sector is at nascent stage.

Keywords: *Circular Economy, e-waste recycling, Technology assessment framework, Multicriteria decision making, Fuzzy-TOPSIS, recycling technology, environmental impact, economic viability*

JEL Classification: *O33, Q53, and Q55.*

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Abbreviation

AHP	Analytical Hierarchy Process
ANP	Analytic Network Process
AQI	Air Quality Index
CO₂	Carbon Dioxide
EEE	Electrical and Electronic Equipment
EOL	End of Life
EPR	Extended Producer Responsibility
INR	Indian Rupees
IRR	Internal Rate of Return
LIBs	Lithium-Ion Batteries
MCDM	Multi Criteria Decision Making
MTA	Metric Tons Per Annum
NPV	Net Present Value
ROI	Return on Investment
TAF	Technology Assessment Framework
TEE	Technology, Economic, and Environment
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TRL	Technology Readiness Level
VIKOR	VišeKriterijumska Optimizacija I Kompromisno Rešenje

Technology Assessment Framework for E-Waste Recycling: A Multi-Criteria Evaluation Approach

Amit Kumar and Anjali Singh

1. Introduction

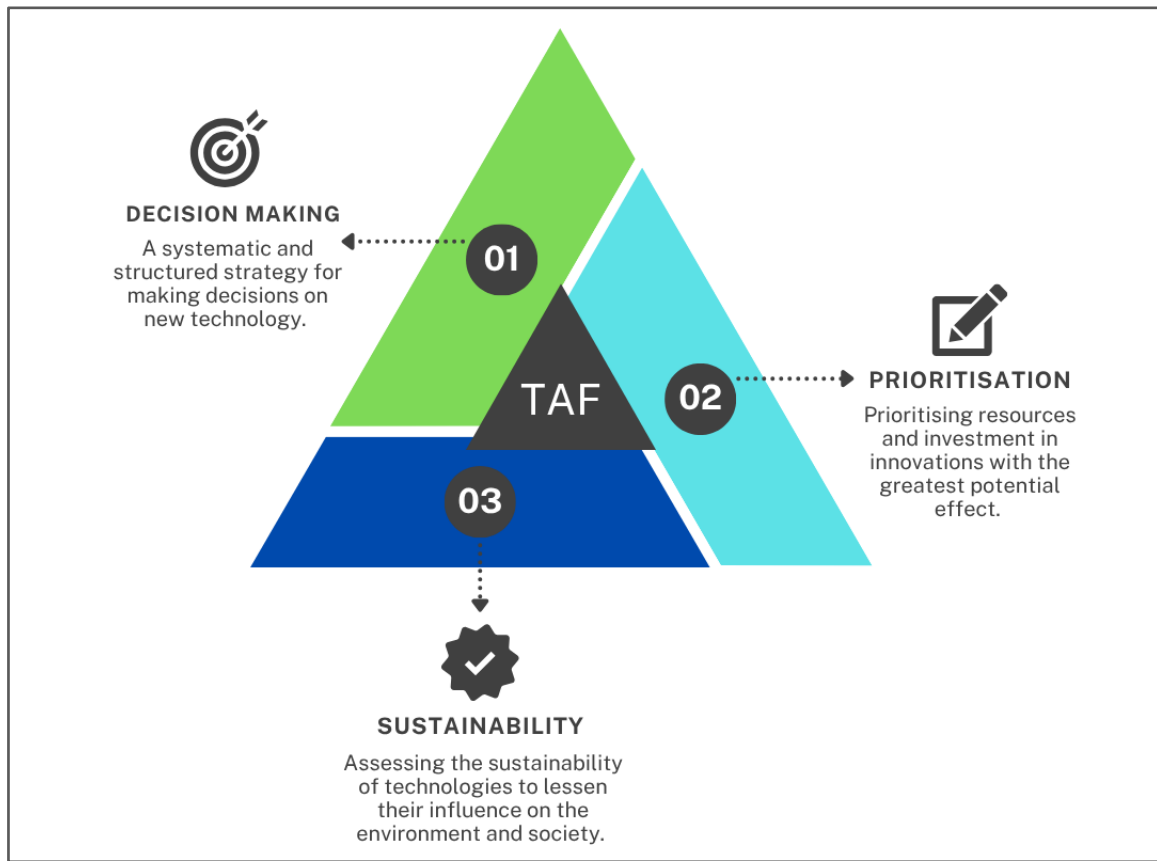
Technology assessment of e-waste recycling is crucial for India because the country is one of the world's largest and fastest-growing generators of electronic waste, yet a significant share is still processed through informal and environmentally hazardous methods. According to the Central Pollution Control Board, India generated over 1.6 million tonnes of e-waste in recent years, while policy implementation under the E-Waste (Management) Rules seeks to formalize collection and recycling through Extended Producer Responsibility (EPR). Without systematic technology assessment, India risks scaling its recycling systems that are inefficient, polluting, or economically unviable, leading to loss of valuable metals such as rare earths, and critical minerals, on which India has import-dependency. A structured assessment enables comparison of recovery efficiencies, environmental performance, energy intensity, cost structures, and social implications, especially integration of the informal sector, thereby ensuring that investments align with circular economy goals articulated by NITI Aayog. In essence, technology assessment provides the evidence base needed to protect public

health, recover strategic materials, strengthen regulatory compliance, and build a globally competitive recycling industry for India's clean and digital economy transition.

Technology Assessment (TA) has increasingly emerged as a critical instrument in guiding the trajectory of technological advancement. As a broad and evolving concept, TA operates at multiple levels, including national, industrial, and corporate domains, each with distinct perspectives and objectives (Lo et al., 2007). This study seeks to elucidate the Technology Assessment Frameworks (TAFs) as discussed in existing literature (al-Sulbi et al., 2023; Choudhary & Shankar, 2012; Erdin & Akbaş, 2019; Nazim et al., 2022), and to potentially use them to assess e-waste recycling technologies.

A TAF serves as an important tool for informed decision-making. It helps in prioritising resource allocation for technology development while ensuring sustainable outcomes. TAF's systematic methodology analyses recycling technologies and their multifaceted implications to support organisations such as industry, policymakers and investors (Singh & N C, 2023).

Figure 1: Merits of Technology Assessment Framework.



Source: Author's construction

The *Electronic Waste Recycling Technology Assessment Framework* exemplifies a structured approach to assessing technologies employed in the recycling of various e-waste categories. This framework is designed to fulfil multiple objectives, notably enhancing environmental sustainability, ensuring economic feasibility, and promoting technological robustness. Research defines technology assessment as a policy-oriented study that aims to evaluate the short-term and long-term implications of a technology use-case, encompassing environmental, social, ethical, legal, and economic dimensions (Banta, 2009).

1.1 E-waste Recycling Technologies

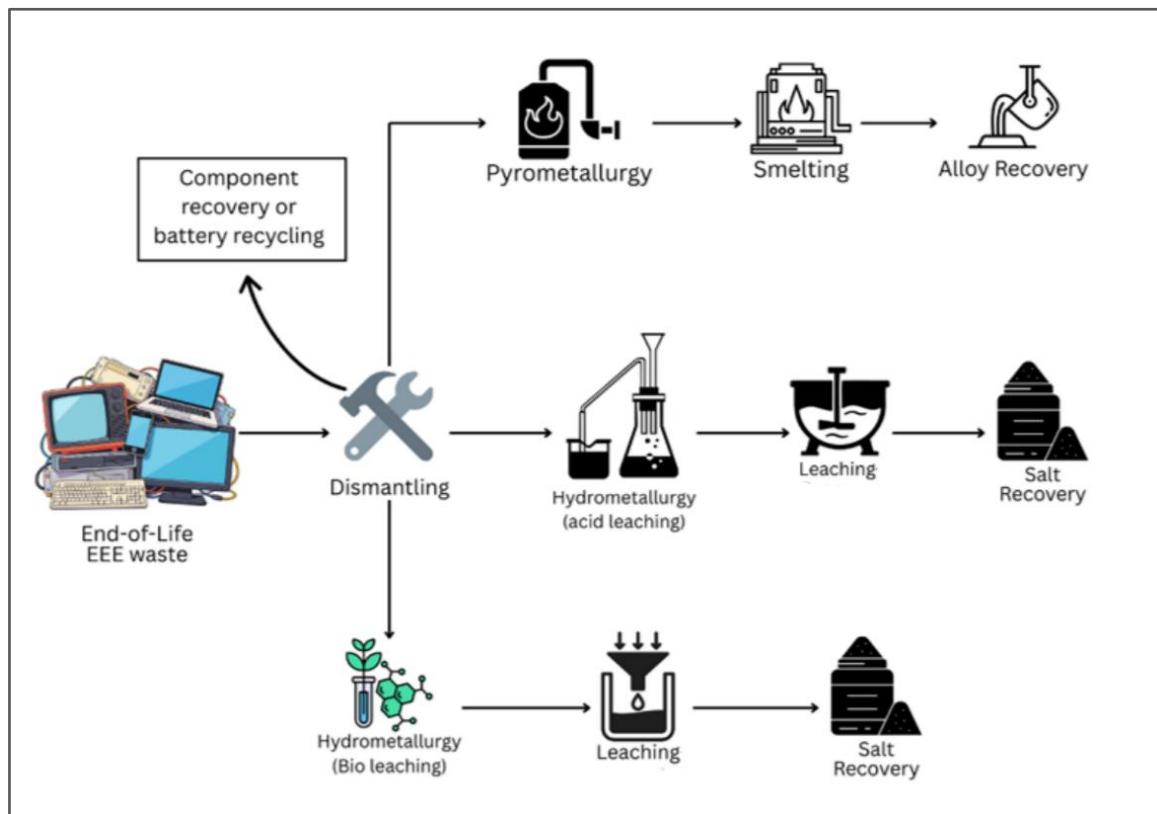
E-waste recycling is widely regarded as a crucial method for recovering precious metals while mitigating the environmental and health dangers associated with incorrect disposal. According to the attached paper, electronic trash includes considerable quantities of precious, base, and critical metals, which frequently surpass those found in natural ores, making it a valuable secondary resource. Recycling techniques are designed to safely recover these commodities while reducing harmful emissions, trash output, and energy consumption. The statement underlines that successful e-waste recycling not only promotes resource efficiency and circular economy goals, but it also decreases strain

on primary mining, reduces pollution, and helps to sustainable material management in an era of expanding global electronic use.

Minerals may be recovered from e-waste using a variety of recycling procedures, including hydrometallurgy (acid leaching), hydrometallurgy (bioleaching),

pyrometallurgy, and pyro-hydro. Figure 2 depicts a typical e-waste recycling process using the three technologies discussed in this research. Each of these technologies has particular benefits and disadvantages, and their acceptability is determined by the composition of e-waste, recycling efficiency, and its commercial scalability.

Figure 2: EEE waste recovery process through different technologies.



Source: Author's construction

Pyrometallurgy

Pyrometallurgical processing is one of the most established techniques for metal recovery from e-waste and end-of-life electronic components. It involves high-temperature operations such as smelting, roasting, and refining to separate valuable metals based on differences in melting points and chemical affinities. According to the literature, pyrometallurgy is particularly

effective for recovering precious metals like gold, silver, and copper from complex waste streams due to its robustness and ability to handle heterogeneous feedstock without extensive pre-treatment. Nevertheless, the process is highly energy-intensive and is associated with significant environmental concerns that include greenhouse gas emissions, slag generation, and the release of toxic gases if not properly controlled (Alam et al., 2022; Cui & Zhang, 2008;

Mairizal et al., 2023). These limitations, coupled with rising energy costs and stricter environmental regulations, have reduced the long-term sustainability of pyrometallurgical routes for e-waste recycling, especially in developing economies.

Hydrometallurgy (Acid Leaching)

Hydrometallurgical techniques have gained prominence as an alternative to pyrometallurgy due to their relatively lower energy requirements and higher selectivity in metal recovery. This approach relies on aqueous chemistry, where metals are leached using acidic, alkaline, or complexing solutions, followed by separation and purification through processes such as solvent extraction, precipitation, or electro-winning. The research highlights that hydrometallurgy enables higher recovery efficiencies for base and critical metals such as copper, nickel, cobalt, and lithium from electronic waste (Alam et al., 2022; Cui & Zhang, 2008). Moreover, hydrometallurgical processes operate at comparatively low temperatures, offering better control over emissions and waste streams. Despite these advantages, challenges remain, including the generation of secondary liquid waste, high reagent consumption, and the need for careful management of effluents to avoid environmental contamination.

Hydrometallurgy (Bioleaching)

Hydrometallurgy, particularly bioleaching, represents an emerging and environmentally benign approach for metal recovery from e-waste. This method employs microorganisms such as bacteria

and fungi to solubilise metals through biochemical reactions, often involving the production of organic acids or oxidative agents (Liu et al., 2020). The reviewed research indicates that biometallurgy offers significant advantages in terms of low energy consumption, reduced chemical usage, and minimal environmental impact compared to conventional methods. Bioleaching has shown promising results for the recovery of metals such as copper, nickel, cobalt, and zinc from low-grade electronic waste (Alam et al., 2022; Cui & Zhang, 2008). However, its large-scale industrial application is still limited by slower reaction kinetics, sensitivity to operational conditions, and the need for further optimisation to improve recovery rates and economic viability.

Strengthening e-waste recycling technology is crucial for driving a circular economy in India's fast-moving electronics sector. As the government strives to lessen its reliance on imported essential minerals, expanding energy-efficient and environmentally friendly recycling options may improve resource security while also supporting sustainability goals. Targeted governmental support for such technologies can help to hasten the renewable energy transition while also promoting long-term economic resilience.

1.2 Assessment of the Recycling Technologies

The technology evaluation is crucial for informed decision-making, as it provides a systematic method for analysing new technologies and their potential significance (Singh & N C, 2023). This research will assist

decision-makers, including start-up businesses and investors, regarding the technology adoption, investment making, and deployment of new technology.

In this study, the technology assessment is done for three major e-waste recycling technologies that are prominently used in India, that are, hydrometallurgy (acid leaching), pyrometallurgy, and hydrometallurgy (bioleaching) (Alam et al., 2022; Cui & Zhang, 2008) only on technical, environmental, and economic (TEE) parameters, due to a lack of data and literature on social and legal dimensions. A MCDM technique, the fuzzy TOPSIS, is used to rank e-waste recycling technology in India on TEE parameters. Fuzzy TOPSIS is widely regarded as a superior method for technology assessment because it effectively addresses the uncertainty, subjectivity, and complexity inherent in evaluating emerging or alternative technologies (al-Sulbi et al., 2023; Choudhary & Shankar, 2012; Erdin & Akbaş, 2019; Nazim et al., 2022). Technology assessment often relies on expert judgments expressed in linguistic terms such as “high,” “medium,” or “low,” which are difficult to represent using precise numerical values. By integrating fuzzy set theory with the traditional TOPSIS framework, Fuzzy TOPSIS allows these imprecise and vague

assessments to be systematically incorporated, resulting in more realistic and reliable evaluations. The ranking of the technologies is based on the relative closeness between an ideal and a non-ideal solution. This enables decision-makers to simultaneously consider trade-offs across technical, environmental, and economic criteria under uncertainty.

Literature demonstrates that Fuzzy TOPSIS is particularly effective in combining qualitative and quantitative criteria within a single decision framework, making it well-suited for sustainability-oriented and technology selection problems (Hwang & Yoon, 1981). Its extensive application in areas such as waste management, energy technologies, supplier selection, and environmental planning further validates its robustness and practical relevance (al-Sulbi et al., 2023; Choudhary & Shankar, 2012; Erdin & Akbaş, 2019; Nazim et al., 2022).

The assessment of e-waste recycling technologies is performed on TEE parameters and 30 sub-parameters, as listed in Table 1, to identify the optimal technology, which is common in most of the previous research (Choudhary & Shankar, 2012; Singh & N C, 2023). The main parameters are described later in this section.

Table 1: Parameters for Technology Assessment Framework

Main Parameter	Sub Parameter
P1: Technology	
P11	Throughput rate
P12	Energy efficiency
P13	Purity of recycled material
P14	Fraction of e-waste recycled
P15	Material recovery efficiency
P16	TRL
P17	Service life
P18	Reliability
P19	Ease of setup
P110	Average installation time
P111	Installation efforts
P112	Safety
P2: Environment	
P21	Impact on land
P22	CO ₂ emissions
P23	Water quality
P24	AQI near plant
P25	Waste management
P3: Economic	
P31	Land cost
P32	Plant and machinery cost
P33	Raw materials cost
P34	Labour cost
P35	Energy cost
P36	O&M cost
P37	Salvage value of the plant after 10 years
P38	ROI
P39	IRR
P310	NPV
P311	Employee training cost
P312	Cost of technology
P313	Employees insurance

P1. Technology

Technology is one of the important parameter that is assessed in most of the literature (Choudhary & Shankar, 2012; Singh & N C, 2023). It is further divided into 12 sub-parameters, as shown in Table 1. The

sub-parameters, such as TRL, efficiency, safety, ease of setup, etc., are the ones that one should consider before investing in a technology.

P2. Environment

In present context, environmental emissions and impacts are important parameter that needs to be considered for using any recycling technology. The environmental parameter is further divided into 5 sub-parameters as shown in Table 1. Note that this environment assessment is typically dependent on environmental parameters, we have not included policies and standards as a part of this assessment, recognising potential gaps in policy, standards, and monitoring frameworks for newer technologies, e.g. direct and bio leaching.

P3. Economic

In India, economic investment and returns are key parameters considered for

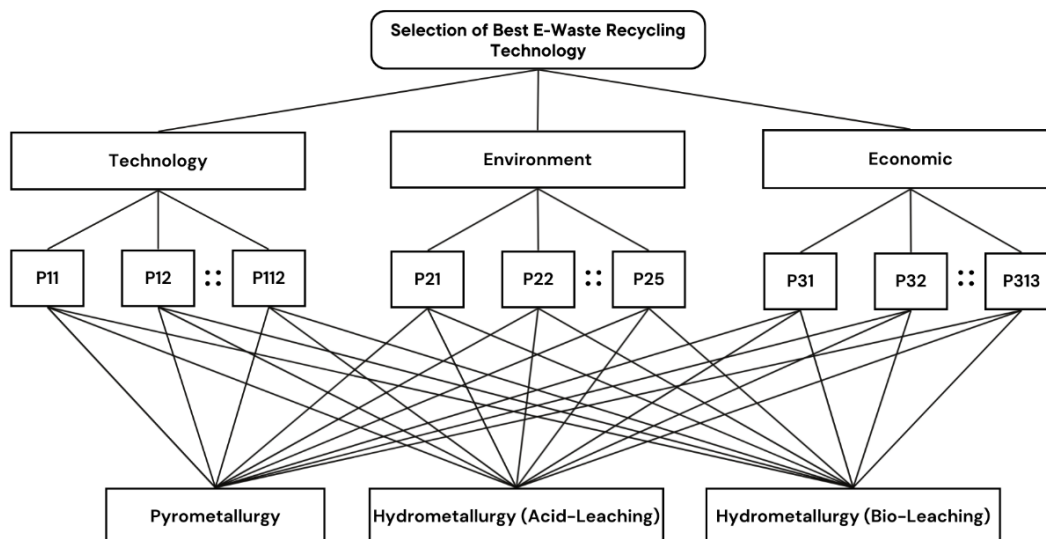
establishing an e-waste recycling plant of a certain technology. The economic parameter is further categorised in 13 sub-parameters, which are considered for evaluation as shown in Table 1.

The data collection was done for sub-parameters through an extensive literature review and was also vetted by experts working in the recycling sector.

Determination of the weight of the criteria

A fuzzy TOPSIS is a hierarchical structure, with sub-parameters in the middle, the parameters at the top, and technologies at the bottom. Figure 3 shows the structure of the assessment.

Figure 3: A hierarchical structure for the TOPSIS approach.



Source: Author's construction

Each parameter is weighted according to its relative importance, because not all parameters are equally important. The weight of the parameter is calculated using a

pairwise comparison method, which is an extension of the Analytical Hierarchy Process (AHP).

The weights of the fuzzy-TOPSIS technique are assigned on a scale of 1-5. 1 indicates very low relevance, but 2 shows somewhat less importance than the other. Table 2

shows that scales of 3, 4, and 5 indicate equally important, high significance, and extremely high importance, respectively.

Table 2: Fuzzy numbers used for expert ranking

Scale	Linguistic Term	Fuzzy Weights
5	Very High (VH)	7,9,9
4	High (H)	5,7,9
3	Average (A)	3,5,7
2	Low (L)	1,3,5
1	Very Low (VL)	1,1,3

A fuzzy decision matrix is generated for each parameter using the experts' ranks and translated into fuzzy weights. Tables 1A, 2A, and 3A of the annexure are constructed based on expert rankings obtained from industry experts, and the Fuzzy TOPSIS is used to determine the optimal approach for e-waste recycling in India.

The approach converts expert rankings into triangular fuzzy numbers and provides the relative importance of one parameter over another. The TOPSIS is applied to the fuzzified decision matrix for each parameter. The TOPSIS methodology is adopted from (Chen, 2000; Collan et al., 2015). The analysis provides rankings based on the closeness coefficient, as shown in equation 7 below (Chen, 2000; Collan et al., 2015).

The analysis starts by constructing an evaluation matrix $M = [M_{ij}]$, where M_{ij} denotes the valuation of the i^{th} alternative with respect to the j^{th} parameter. A calculated matrix for each parameter is shown in Tables 1A, 2A & 3A.

A normalised decision matrix $X = [X_{ij}]$ by using equation (1) is created for all parameters, as shown in Tables 4A, 5A, & 6A.

$$X_{ij} = \frac{M_{ij}}{\sqrt{\sum_{i=1}^n M_{ij}^2}}, j=1, \dots, m, i=1, \dots, n. \quad -(1)$$

Next, the estimated weighted normalised decision matrix $Y = [Y_{ij}]$ is obtained using equation (2) for all the parameters, as shown in Tables 7A, 8A, & 9A.

$$Y_{ij} = X_{ij} (\cdot) W_j, j=1, \dots, m, i = 1, \dots, n. \quad -(2)$$

The fuzzy positive (P^+) and negative ideal solutions (N^-) are identified using equations (3) & (4) as shown in Tables 10A, 11A, & 12A. The calculated P^+ and N^- for all the parameters are shown in Table 13A.

$$P^+ = \{Y^+_1, \dots, Y^+_m\} \\ = (\max_i Y_{ij} | j \in B), (\min_i Y_{ij} | j \in C), \quad -(3)$$

$$N^- = \{Y^-_1, \dots, Y^-_m\} \\ = (\min_i Y_{ij} | j \in B), (\max_i Y_{ij} | j \in C), \quad -(4)$$

Where C is the cost criterion, and B is the benefit criterion

$$d_i^+ = \sqrt{\sum_{j=1}^m (Y_{ij} - Y_j^+)^2}, i=1, 2, 3, \dots, n. \quad (5)$$

Lastly, equations (5) & (6) are used to calculate the positive ideal solution (d_i^+) and negative ideal solution (d_i^-). The calculated distances for all the parameters are shown in Table 3.

$$d_i^- = \sqrt{\sum_{j=1}^m (Y_{ij} - Y_j^-)^2}, i=1, 2, 3, \dots, n. \quad (6)$$

Table 3: Positive & Negative Ideal Distance for all matrices

	Technology		Economic		Environment	
Distance	d_i^+	d_i^-	d_i^+	d_i^-	d_i^+	d_i^-
Pyrometallurgy	13.45	12.46	31.21	3.44	9.55	6.30
Hydrometallurgy (Acid-Leaching)	8.77	18.57	12.75	24.17	8.64	8.26
Hydrometallurgy (Bio-Leaching)	12.70	13.15	6.84	28.53	4.52	11.60

Using the distance d_i^+ and d_i^- , relative closeness to the ideal solutions is calculated using equation (7). The Closeness Coefficient for all the parameters is given in Table 4.

$$CC_i = \frac{d_i^-}{(d_i^- + d_i^+)}, i=1, 2, 3, \dots, n. \quad (7)$$

Table 4: Closeness Coefficient for the Matrices

	Technology	Economic	Environment
Pyrometallurgy	0.48	0.10	0.40
Hydrometallurgy (Acid-Leaching)	0.68	0.65	0.49
Hydrometallurgy (Bio-Leaching)	0.51	0.81	0.72

The closer the CC_i is to one, the higher the ranking of the i^{th} technology.

2. Results and Discussion

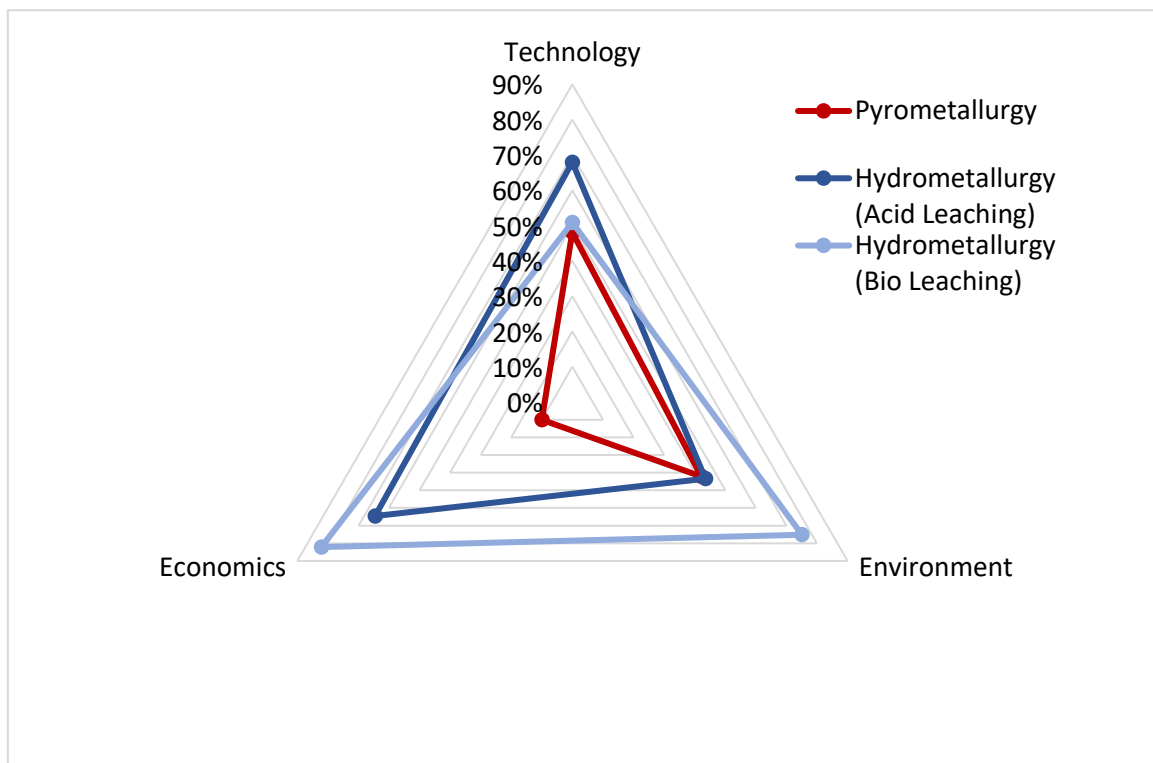
The technology assessment is performed for three technologies that are being used in

India for e-waste recycling (Figure 4). The framework was created based on three main parameters: technology, environment, and economics, which are considered for evaluation (Table 1). The normalised results are shown in Table 5.

Table 5: Fuzzy TOPSIS results for different technologies and parameters

Parameters Recycling Technology	Closeness coefficient Technical	Ranking	Closeness coefficient Environmental	Ranking	Closeness coefficient Economics	Ranking
Pyrometallurgy	0.48	3	0.40	3	0.10	3
Hydrometallurgy (Acid Leaching)	0.68	1	0.49	2	0.65	2
Hydrometallurgy (Bio Leaching)	0.51	2	0.72	1	0.81	1

Figure 4: Pictorial representation of recycling technology ranking on technology, environment and economic parameters.



The comparative assessment of recycling technologies highlights clear trade-offs across technical, environmental, and economic parameters. Pyrometallurgy ranks lowest across all three dimensions, with relatively modest technical performance (0.48), weaker environmental outcomes (0.40), and poor economic viability (0.10), placing it third in technical, environmental, and economic rankings, as shown in Table 5 and Figure 4. While pyrometallurgy is a

mature and widely used technology, its high energy intensity, emissions, and lower material recovery efficiency reduce its overall attractiveness.

In contrast, hydrometallurgy using acid leaching emerges as the technically strongest option, achieving the highest technical score (0.68) and ranking first on this parameter. It also performs reasonably well environmentally (0.49, ranked second)

and economically (0.65, ranked second), reflecting a balanced profile that combines higher recovery rates with moderate costs and environmental impacts, as shown in Table 18 and Figure 4. This makes acid leaching a practical and scalable option, particularly for industrial applications seeking reliability and efficiency.

Hydrometallurgy based on bio-leaching demonstrates the most sustainable and cost-effective profile overall. Although it ranks second in technical performance (0.51), it achieves the highest environmental score (0.72) and top economic score (0.81), ranking first in both categories, as shown in Table 18 and Figure 4. These results indicate that bio-leaching offers significant advantages in terms of reduced environmental footprint and improved economic feasibility, likely due to lower energy requirements and reduced chemical inputs.

3. Conclusion

Multi-criteria decision making is a prevailing tool widely used to solve technology adoption problems in most of the research applications containing multiple conflicting criteria (Choudhary & Shankar, 2012; Hwang & Yoon, 1981; Zhou et al., 2006). A wide range of multi-criteria decision-making (MCDM) techniques has been developed to support complex decision problems, including methods such as AHP, ANP, TOPSIS, and VIKOR (Choudhary & Shankar, 2012; Hwang & Yoon, 1981; Kaya & Kahraman, 2010; Nazim et al., 2022). Among these, fuzzy AHP, an integration of the analytic hierarchy process with fuzzy logic, has been found particularly useful in

situations where both qualitative and quantitative factors are assessed using imprecise or linguistic judgments. However, a key limitation of fuzzy AHP lies in its reliance on expert judgment, as linguistic inputs are inherently subjective and shaped by individual experience and perception. As a result, evaluations of parameters, sub-parameters, and alternatives may vary across experts, introducing bias into the decision-making process.

This study uses a fuzzy TOPSIS approach where these biases are removed using a structured and transparent framework for ranking alternatives based on their relative closeness to an ideal solution to reduce the chances of errors in identifying the optimal e-waste recycling technology. Adopting a systematic and holistic decision-making framework is essential to identify optimal recycling technology that balances efficiency, sustainability, and stakeholder interests.

The results from the TAF, which was conducted on e-waste recycling technologies currently adopted in India, highlight that hydrometallurgy (acid leaching) outperformed pyrometallurgy, and hydrometallurgy (bioleaching) in terms of technology advancement and market availability.

On the other hand, Hydrometallurgy (bioleaching), which is an environmentally sound technology with a second rank in the TAF, provides a promising future in the Indian recycling ecosystem. This technology is a slow process, as the leaching is done using natural bacteria to extract metals from the waste.

The recent policy, national critical mineral mission (NCMM) contains a financial outlay of 1500 Cr rupees to promote recovery of critical minerals from e-waste, battery waste and other waste types (PIB, 2025). Partial financial support can be provided by this scheme to promote the recycling technology identified in this study.

Overall, the analysis suggests that while acid-based hydrometallurgy is currently the

most technically robust, bio-leaching represents a promising pathway for environmentally sustainable and economically viable recycling in the long term. As the volume of e-waste is increasing, a technology that is environmentally friendly and cost-effective, such as hydrometallurgy (bioleaching), can be considered a safer and more commercial option for larger-scale deployment.

Annexure

Table 1A: Fuzzified decision matrix (expert ranking) for sub-parameters under technology

Technological													
	Experts	Throughput Rate	Energy efficiency	Purity of Recycled Material	Fraction of E-waste recycled	Material Recovery Efficiency	TRL	Service Life	Reliability	Ease of Setup	Average Installation Time	Installation Efforts	Safety
Pyrometallurgy	E1	5,7,9	1,1,3	5,7,9	3,5,7	5,7,9	7,9,9	5,7,9	5,7,9	3,5,7	3,5,7	3,5,7	1,1,3
	E2	7,9,9	1,3,5	7,9,9	1,3,5	1,3,5	7,9,9	7,9,9	7,9,9	7,9,9	7,9,9	7,9,9	7,9,9
	E3	5,7,9	1,3,5	7,9,9	3,5,7	1,3,5	7,9,9	7,9,9	5,7,9	7,9,9	7,9,9	7,9,9	7,9,9
Hydrometallurgy (Acid-Leaching)	E1	3,5,7	5,7,9	7,9,9	5,7,9	7,9,9	5,7,9	3,5,7	5,7,9	5,7,9	5,7,9	5,7,9	1,3,5
	E2	5,7,9	3,5,7	7,9,9	5,7,9	5,7,9	7,9,9	5,7,9	7,9,9	3,5,7	5,7,9	7,9,9	7,9,9
	E3	7,9,9	3,5,7	7,9,9	5,7,9	5,7,9	7,9,9	5,7,9	7,9,9	3,5,7	3,5,7	5,7,9	7,9,9
Hydrometallurgy (Bio-Leaching)	E1	3,5,7	7,9,9	7,9,9	5,7,9	7,9,9	1,3,5	1,3,5	5,7,9	1,3,5	5,7,9	5,7,9	5,7,9
	E2	3,5,7	5,7,9	7,9,9	5,7,9	5,7,9	1,3,5	3,5,7	1,3,5	3,5,7	5,7,9	7,9,9	7,9,9
	E3	5,7,9	7,9,9	7,9,9	5,7,9	5,7,9	3,5,7	3,5,7	1,3,5	3,5,7	3,5,7	5,7,9	7,9,9

Table 2A: Fuzzified decision matrix (expert ranking) for sub-parameters under the environment

Environment						
	Experts	Impact on land	CO ₂ emissions	Water Quality	AQI near Plant	Waste management
Pyrometallurgy	E1	5,7,9	1,1,3	5,7,9	1,1,3	5,7,9
	E2	5,7,9	1,1,3	3,5,7	1,1,3	3,5,7
	E3	5,7,9	1,1,3	7,9,9	1,1,3	1,3,5
Hydrometallurgy (Acid-Leaching)	E1	1,1,3	3,5,7	3,5,7	3,5,7	5,7,9
	E2	1,3,5	5,7,9	1,1,3	3,5,7	3,5,7
	E3	1,1,3	1,3,5	1,3,5	5,7,9	1,3,5
Hydrometallurgy (Bio-Leaching)	E1	1,3,5	5,7,9	3,5,7	5,7,9	5,7,9
	E2	3,5,7	7,9,9	1,3,5	5,7,9	3,5,7
	E3	3,5,7	3,5,7	1,3,5	5,7,9	1,3,5

Table 3A: Fuzzified decision matrix (expert ranking) for sub-parameters under economics

Economical														
	Experts	Cost of land	Cost of Plant and Machinery	Cost of Raw Materials	Labour Cost	Energy Cost	O&M cost	Salvage Value of Plant	ROI	IRR	NPV	Employee training cost	Cost Technology	Employees insurance
Pyrometallurgy	E1	3,5,7	1,3,5	3,5,7	1,3,5	1,1,3	1,3,5	5,7,9	1,1,5	1,1,3	5,7,9	3,5,7	1,1,3	3,5,7
	E2	5,7,9	1,3,5	5,7,9	1,3,5	1,1,3	1,3,5	7,9,9	1,3,5	3,5,7	7,9,9	5,7,9	1,3,5	3,5,7
	E3	5,7,9	1,3,5	3,5,7	1,3,5	1,1,3	1,3,5	7,9,9	1,3,5	1,3,5	7,9,9	7,9,9	3,5,7	3,5,7
Hydrometallurgy (Acid-Leaching)	E1	3,5,7	5,7,9	3,5,7	3,5,7	5,7,9	3,5,7	3,5,7	3,5,7	5,7,9	3,5,7	3,5,7	5,7,9	3,5,7
	E2	5,7,9	3,5,7	5,7,9	5,7,9	1,3,5	5,7,9	5,7,9	7,9,9	7,9,9	5,7,9	5,7,9	3,5,7	3,5,7
	E3	5,7,9	3,5,7	3,5,7	3,5,7	3,5,7	5,7,9	3,5,7	7,9,9	7,9,9	7,9,9	7,9,9	3,5,7	3,5,7
Hydrometallurgy (Bio-Leaching)	E1	3,5,7	5,7,9	3,5,7	3,5,7	7,9,9	5,7,9	1,3,5	3,5,7	1,3,5	3,5,7	3,5,7	7,9,9	3,5,7
	E2	5,7,9	5,7,9	5,7,9	5,7,9	5,7,9	7,9,9	3,5,7	5,7,9	5,7,9	5,7,9	5,7,9	5,7,9	3,5,7
	E3	5,7,9	7,9,9	7,9,9	7,9,9	7,9,9	7,9,9	1,3,5	5,7,9	3,5,7	7,9,9	7,9,9	5,7,9	3,5,7

Table 4A: Combined decision matrix for technological matrices

Combined Decision Matrix	Pyrometallurgy	Hydrometallurgy (Acid-Leaching)	Hydrometallurgy (Bio-Leaching)
Throughput Rate	5	3	3
	7.67	7	5.67
	9	9	9
Energy Efficiency	1	3	5
	2.33	5.67	8.33
	5	9	9
Purity of Recycled Material	5	7	7
	8.33	9	9
	9	9	9
Fraction of E-waste Recycled	1	5	5
	4.33	7	7
	7	9	9
Material Recovery Efficiency	1	5	5
	4.33	7.67	7.67
	9	9	9
TRL	7	5	1
	9	8.33	3.67
	9	9	7
Service Life	5	3	1
	8.33	6.33	4.33
	9	9	7
Reliability	5	5	1
	7.67	8.33	4.33
	9	9	9
Ease of Setup	3	3	1
	7.67	5.67	4.33
	9	9	7
Average Installation Time	3	3	3
	7.67	6.33	6.33
	9	9	9
Installation Efforts	3	5	5
	7.67	7.67	7.67
	9	9	9
Safety	1	1	5
	6.33	7	8.33
	9	9	9

Table 5A: Combined decision matrix for economic matrices

Combined Decision Matrix	Pyrometallurgy	Hydrometallurgy (Acid-Leaching)	Hydrometallurgy (Bio-Leaching)
Cost of Land	3	3	3
	6.33	6.33	6.33
	9	9	9
Cost of Plant and Machinery	1	3	5
	3	5.67	7.67
	5	9	9
Cost of Raw Materials	3	3	3
	5.67	5.67	5.67
	9	9	9
Labour Cost	1	3	3
	3	5.67	7
	5	9	9
Energy Cost	1	1	5
	1.67	5	8.33
	5	9	9
O&M cost	1	3	5
	3	6.33	8.33
	5	9	9
Salvage Value of Plant	5	3	1
	8.33	5.67	3.67
	9	9	7
ROI	1	3	3
	2.33	7.67	6.33
	5	9	9
IRR	1	5	1
	3	8.33	5
	7	9	9
NPV	5	3	1
	8.33	5	3
	9	7	7
Employee Training Cost	3	3	3
	7	7	7
	9	9	9
Cost of Sourcing Technology	1	3	5
	3	5.67	7.67
	7	9	9
Employees Insurance	3	3	3
	5	5	5
	7	7	7

Table 6A: Combined decision matrix for environment matrices

Combined decision matrix	Impact on land			CO ₂ emissions			Water Quality			AQI Near Plant			Waste management		
Pyrometallurgy	5	7	9	1	1	3	3	7	9	1	1	3	1	5	9
Hydrometallurgy (Acid-Leaching)	1	1.67	5	1	5	9	1	3	7	3	5.67	9	1	5	9
Hydrometallurgy (Bio-Leaching)	1	4.33	7	3	7	9	1	3.67	7	5	7	9	1	5	9

Table 7A: Normalised fuzzy decision matrix for technological matrices

Normalised fuzzy Decision Matrix	Pyrometallurgy	Hydrometallurgy (Acid-Leaching)	Hydrometallurgy (Bio-Leaching)
Throughput Rate	0.56	0.33	0.33
	0.85	0.78	0.63
	1	1	1
Energy Efficiency	0.11	0.33	0.56
	0.26	0.63	0.93
	0.56	1	1
Purity of Recycled Material	0.56	0.78	0.78
	0.93	1	1
	1	1	1
Fraction of E-waste Recycled	0.11	0.56	0.56
	0.48	0.78	0.78
	0.78	1	1
Material Recovery Efficiency	0.11	0.56	0.56
	0.48	0.85	0.85
	1	1	1
TRL	0.78	0.56	0.11
	1	0.93	0.41
	1	1	0.78
Service Life	0.56	0.33	0.11
	0.93	0.70	0.48
	1	1	0.78
Reliability	0.56	0.56	0.11
	0.85	0.93	0.48
	1	1	1
Ease of Setup	0.33	0.33	0.11
	0.85	0.63	0.48
	1	1	0.78
Average Installation Time	0.33	0.33	0.33
	0.39	0.47	0.47
	1	1	1
Installation Efforts	0.33	0.33	0.33
	0.39	0.39	0.39
	1	0.6	0.6
Safety	0.11	0.11	0.56
	0.70	0.78	0.93
	1	1	1

Table 8A: Normalised fuzzy decision matrix for economic matrices

Normalised fuzzy decision matrix	Pyrometallurgy	Hydrometallurgy (Acid-Leaching)	Hydrometallurgy (Bio-Leaching)
Cost of Land	0.33	0.33	0.33
	0.70	0.70	0.70
	1	1	1
Cost of Plant and Machinery	0.11	0.33	0.56
	0.33	0.63	0.85
	0.56	1	1
Cost of Raw Materials	0.33	0.33	0.33
	0.63	0.63	0.63
	1	1	1
Labour Cost	0.11	0.33	0.33
	0.33	0.63	0.78
	0.56	1	1
Energy Cost	0.11	0.11	0.56
	0.19	0.56	0.93
	0.56	1	1
O&M cost	0.11	0.33	0.56
	0.33	0.70	0.93
	0.56	1	1
Salvage Value of Plant	0.56	0.33	0.11
	0.93	0.63	0.41
	1	1	0.78
ROI	0.11	0.33	0.33
	0.26	0.85	0.70
	0.56	1	1
IRR	0.11	0.56	0.11
	0.33	0.93	0.56
	0.78	1	1
NPV	0.11	0.14	0.14
	0.12	0.2	0.33
	0.2	0.33	1
Employee Training Cost	0.33	0.33	0.33
	0.43	0.43	0.43
	1	1	1
Cost of Sourcing Technology	0.11	0.33	0.56
	0.33	0.63	0.85
	0.78	1	1
Employees Insurance	0.43	0.43	0.43
	0.71	0.71	0.71
	1	1	1

Table 9A: Normalised fuzzy decision matrix for environment matrices

Normalised fuzzy decision matrix	Impact on land			CO ₂ emissions			Water Quality			AQI Near Plant			Waste management		
Pyrometallurgy	0.56	0.78	1	0.11	0.11	0.33	0.33	0.78	1	0.11	0.11	0.33	0.11	0.56	1
Hydrometallurgy (Acid-Leaching)	0.11	0.19	0.56	0.11	0.56	1	0.11	0.33	0.78	0.33	0.63	1	0.11	0.56	1
Hydrometallurgy (Bio-Leaching)	0.11	0.48	0.78	0.33	0.78	1	0.11	0.41	0.78	0.56	0.78	1	0.11	0.56	1

Table 10A: Weighted normalised fuzzy decision matrix for technological matrices

Weighted normalised fuzzy decision matrix	Pyrometallurgy	Hydrometallurgy (Acid-Leaching)	Hydrometallurgy (Bio-Leaching)
Throughput Rate	2.78	1.67	1.67
	5.96	5.44	4.41
	9	9	9
Energy Efficiency	0.78	2.33	3.89
	2.33	5.67	8.33
	5	9	9
Purity of Recycled Material	3.89	5.44	5.44
	8.33	9	9
	9	9	9
Fraction of E-waste Recycled	0.78	3.89	3.89
	4.33	7	7
	7	9	9
Material Recovery Efficiency	0.78	3.89	3.89
	4.33	7.67	7.67
	9	9	9
TRL	3.89	2.78	0.56
	7	6.48	2.85
	9	9	7
Service Life	2.78	1.67	0.56
	6.48	4.93	3.37
	9	9	7
Reliability	2.78	2.78	0.56
	5.96	6.48	3.37
	9	9	9
Ease of Setup	1.67	1.67	0.56
	5.96	4.41	3.37
	9	9	7
Average Installation Time	1	1	1
	1.96	2.37	2.37
	7	7	7
Installation Efforts	1	1	1
	1.96	1.96	1.96
	7	4.2	4.2
Safety	0.78	0.78	3.89
	6.33	7	8.33
	9	9	9

Table 11A: Weighted normalised fuzzy decision matrix for economic matrices

Weighted normalised decision matrix	Pyrometallurgy	Hydrometallurgy (Acid-Leaching)	Hydrometallurgy (Bio-Leaching)
Cost of Land	1	1	1
	3.52	3.52	3.52
	7	7	7
Cost of Plant and Machinery	0.78	2.33	3.89
	3	5.67	7.67
	5	9	9
Cost of Raw Materials	1.67	1.67	1.67
	4.41	4.41	4.41
	9	9	9
Labour Cost	0.78	2.33	2.33
	3	5.67	7
	5	9	9
Energy Cost	0.78	0.78	3.89
	1.67	5	8.33
	5	9	9
O&M cost	0.56	1.67	2.78
	2.33	4.93	6.48
	5	9	9
Salvage Value of Plant	3.89	2.33	0.78
	8.33	5.67	3.67
	9	9	7
ROI	0.78	2.33	2.33
	2.33	7.67	6.33
	5	9	9
IRR	0.78	3.89	0.78
	3	8.33	5
	7	9	9
NPV	0.78	1	1
	1.08	1.8	3
	1.8	3	9
Employee Training Cost	1	1	1
	2.14	2.14	2.14
	7	7	7
Cost of Sourcing Technology	0.78	2.33	3.89
	3	5.67	7.67
	7	9	9
Employees Insurance	1.29	1.29	1.29
	3.57	3.57	3.57
	7	7	7

Table 12A: Weighted normalised fuzzy decision matrix for environment matrices

Weighted normalised decision matrix	Impact on land			CO ₂ emissions			Water Quality			AQI Near Plant			Waste management		
Pyrometallurgy	2.78	5.44	9	0.78	1	3	2.33	7	9	0.56	0.78	3	0.56	3.89	9
Hydrometallurgy (Acid-Leaching)	0.56	1.30	5	0.78	5	9	0.78	3	7	1.67	4.41	9	0.56	3.89	9
Hydrometallurgy (Bio-Leaching)	0.56	3.37	7	2.33	7	9	0.78	3.67	7	2.78	5.44	9	0.56	3.89	9

Table 13A: Fuzzy Positive and Negative Ideal Solution for all matrices

Technology			Economic			Environment		
	P ⁺	N ⁻		P ⁺	N ⁻		P ⁺	N ⁻
Throughput Rate	2.78	1.67	Cost of Land	1	1	Impact on land	2.78	0.56
	5.96	4.41		3.52	3.52		5.44	1.30
	9	9		7	7		9	5
Energy Efficiency	3.89	0.78	Cost of Plant and Machinery	3.89	0.78	CO ₂ emissions	2.33	0.78
	8.33	2.33		7.67	3		7	1
	9	5		9	5		9	3
Purity of Recycled Material	5.44	3.89	Cost of Raw Materials	1.67	1.67	Water Quality	2.33	0.78
	9	8.33		4.41	4.41		7	3
	9	9		9	9		9	7
Fraction of E-waste Recycled	3.89	0.78	Labour Cost	2.33	0.78	AQI Near Plant	2.78	0.56
	7	4.33		7	3		5.44	0.78
	9	7		9	5		9	3
Material Recovery Efficiency	3.89	0.78	Energy Cost	3.89	0.78	Waste management	0.56	0.56
	7.67	4.33		8.33	1.67		3.89	3.89
	9	9		9	5		9	9
TRL	3.89	0.56	O&M cost	2.78	0.56			
	7	2.85		6.48	2.33			
	9	7		9	5			
Service Life	2.78	0.56	Salvage Value of Plant	3.89	0.78			
	6.48	3.37		8.33	3.67			
	9	7		9	7			
Reliability	2.78	0.56	ROI	2.33	0.78			
	6.48	3.37		7.67	2.33			
	9	9		9	5			
Ease of Setup	1.67	0.56	IRR	3.89	0.78			
	5.96	3.37		8.33	3			
	9	7		9	7			
Average Installation Time	1	1	NPV	1	0.78			
	2.37	1.96		3	1.08			
	7	7		9	1.8			
Installation Efforts	1	1	Employee Training Cost	1	1			
	1.96	1.96		2.14	2.14			
	7	4.2		7	7			
Safety	3.89	0.78	Cost of Sourcing Technology	3.89	0.78			
	8.33	6.33		7.67	3			
	9	9		9	7			
			Employees Insurance	1.29	1.29			
				3.57	3.57			
				7	7			

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