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

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## EXECUTIVE SUMMARY

India ranks among the largest and fastest-growing producers of electronic waste in the world, and the volumes keep climbing as digital consumption, urbanisation and rising incomes push households and businesses to replace devices more often. The Central Pollution Control Board has reported e-waste generation of more than 1.6 million tonnes in recent years. Despite this scale, a considerable portion of the material continues to flow in informal channels, where dismantling and metal extraction frequently rely on open burning, crude acid baths and manual handling. These practices expose workers and surrounding

communities to toxic emissions, contaminate soil and water, and destroy much of the economic value embedded in discarded equipment. The E-Waste Management Rules attempt to change this picture by moving collection and recycling into the formal economy through Extended Producer Responsibility (EPR), which makes manufacturers and importers accountable for the end-of-life handling of their products.

However, regulation alone, does not guarantee good outcomes. Once producers are obliged to arrange recycling, the decisive question becomes which processing technology should receive investment and

policy support. A poorly chosen process/technology can be inefficient, polluting, energy-consuming or economically unsustainable, and a country that scales such a system, locks in those weaknesses for years. The stakes are particularly high for India because electronic waste carries rare earth elements, precious metals and other critical minerals for which the country depends heavily on imports. Every tonne of these materials lost to landfill, informal burning or low-grade recovery represents a missed chance to strengthen domestic supply and reduce exposure to external shocks. A systematic comparison of recycling processes/technologies is therefore a matter of resource security as much as environmental protection.

A technology assessment framework (TAF) offers a systematic way to carry out that comparison. Such a framework examines how competing technologies perform across several dimensions at once, including how much material they recover, how they affect the environment, how much energy and money they require, and what they mean for people and institutions. Its practical value lies in informing choices: it helps industry, policymakers and investors decide where scarce funds and research effort should go, while keeping long-term sustainability in view (Singh & N C, 2023). Hence, technology assessment is not an academic exercise but a decision-support tool that links technical evidence to policy and investment.

This study accesses three e-waste recycling technologies most prominently used in India: hydrometallurgy based on acid leaching, pyrometallurgy, and hydrometallurgy based on bioleaching (Alam

et al., 2022; Cui & Zhang, 2008). Pyrometallurgy relies on high temperatures to smelt electronic scrap and concentrate metals into a recoverable form. It can handle mixed and complex feedstock, but it demands substantial energy and requires careful control of emissions. Acid-leaching hydrometallurgy dissolves metals from shredded and pre-treated scrap using chemical solutions, after which the metals are separated and purified. It can achieve selective recovery, yet it generates liquid effluents that must be managed responsibly. Bioleaching uses microorganisms to mobilise metals, offering a gentler chemical profile and lower energy needs, although its processing times tend to be longer and its readiness for large-scale operation is less established. Each option therefore carries a distinct mix of strengths and drawbacks, and none is best on every count.

To capture these trade-offs, the assessment evaluates the technologies against technical, environmental and economic (TEE) criteria. Technical criteria address how well a process recovers target metals and how reliably it can operate in long terms. Environmental criteria evaluate the technologies at emissions, effluents, waste generation and land use. Economic criteria consider capital and operating costs and the commercial viability of the recovered materials. The study restricts itself to these three dimensions because dependable data and published literature on social and policy & regulator aspects, such as employment effects, informal-sector integration and regulatory compliance, are still scarce for Indian scenarios. This assessment can be conducted on social, policy & regulatory and

resource available going forward subject to data availability to understand the impact of technologies on social aspect.

Thousands of workers earn their livelihoods from collecting, dismantling and trading discarded electronics, and any technology choice that ignores them risks pushing material away from formal channels. Although this study cannot model social outcomes directly, its findings remain relevant to that debate, since cleaner and more affordable formal processes make it easier to design partnerships, aggregation arrangements and training programmes that bring informal collectors into regulated supply chains instead of excluding them. Decision makers can also adjust the importance attached to each criterion to reflect local priorities, so the framework adapts to different contexts and stakeholder preferences.

Multicriteria decision-making (MCDM) technique has been adapted to assess the technologies considering their vast variety and difference in measurement methods. The paper employs fuzzy TOPSIS, the fuzzy version of the Technique for Order Preference by Similarity to Ideal Solution, to rank the three technologies. The method has gained wide acceptance for technology assessment because it copes well with the uncertainty, subjectivity and complexity that characterise the evaluation of new or alternative technologies (al-Sulbi et al., 2023; Choudhary & Shankar, 2012; Erdin & Akbaş, 2019; Nazim et al., 2022).

Assessments of this kind depend heavily on expert opinion, and experts usually describe performance in ranking such as high,

medium or low rather than in exact figures for some assessment matrices. Also, merging quantitative and qualitative rankings are a challenge here which require careful consideration. Forcing such statements into single crisp numbers can create a false sense of precision. Fuzzy set theory solves this problem by representing each linguistic judgement as a range of possible values with varying degrees of membership. When this treatment is combined with the TOPSIS ranking logic, vague and imprecise opinions can be processed in a consistent and transparent manner, producing evaluations that better reflect real-world conditions and are more dependable than those based on rigid numerical scoring.

The practical contribution of the working paper lies in the decision-making matrix that emerges from this process. It offers a more precise, effective and systematic process for those who must choose among recycling technologies, namely policymakers designing incentives and standards, start-ups selecting processes for new ventures, and established industry players planning expansion. Instead of relying on intuition, vendor claims or isolated technical studies, these users can apply a structured and repeatable procedure that weighs recovery performance, environmental burden and financial feasibility together. The matrices of this assessment can also be updated as new data arrive or as priorities change, which gives it lasting usefulness in a field where technology evolves quickly.

The timing of this effort matters because India's formal recycling sector is still at an early stage. Capacity is limited, many operators are still testing business models,

and investment decisions made now will shape the industry's trajectory for decades. Choosing technologies that are both environmentally sound and economically viable can help formal recyclers compete with informal operators on cost and quality, rather than depending on regulation alone. It can also help ensure that public and private money flows toward process capable of recovering high-value materials, including rare-earths and other critical minerals, instead of settling for crude recovery of only the easiest fractions.

The circular economy ambitions articulated by NITI Aayog depend on keeping valuable materials in productive use, and a credible technology assessment shows which recycling routes can deliver on that promise. It strengthens the case for compliance with EPR obligations by showing producers and recyclers which processes make sense in practice. It supports public health by steering the sector away from hazardous methods and it contributes to building a recycling industry that can compete internationally while supplying materials to the clean energy and digital technologies that India's economic transition will require.

In essence, technology assessment provides the evidence base that India needs to protect public health, recover strategic materials, enforce regulatory compliance and nurture a globally competitive recycling industry. By evaluating hydrometallurgy through acid leaching, pyrometallurgy and bioleaching on technical, environmental and economic grounds, and by using fuzzy TOPSIS to handle uncertainty and expert judgement, this working paper delivers a practical tool for informed decisions. While future work should extend the framework to social and policy & regulatory dimensions as data become available, the current analysis already gives policymakers, entrepreneurs and industry leaders a sound basis for choosing the technologies that will anchor India's emerging formal e-waste recycling sector. Such evidence-led choices keep investment aligned with long-term national priorities.