

# CIRCUIT TO SOIL: TRANSFORMING E- WASTE INTO MICRONUTRIENT FERTILIZERS

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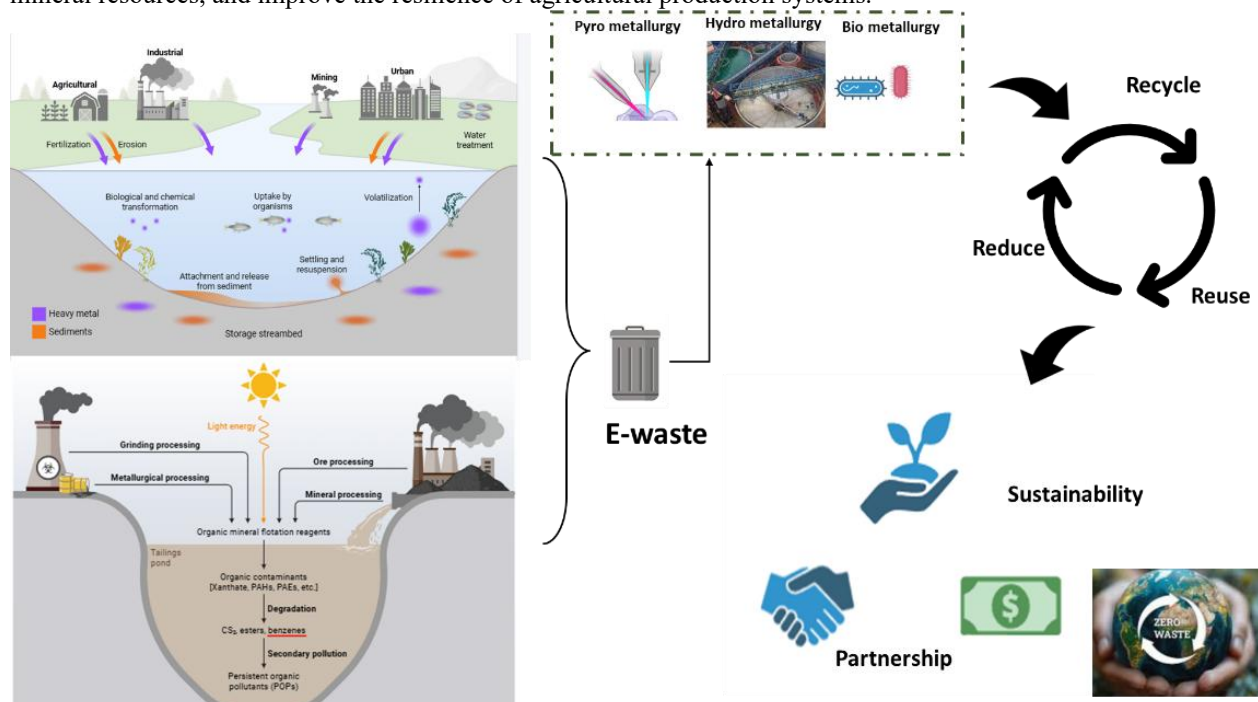
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## ABSTRACT:

The rapid growth of electronic consumption has led to a large amount of electronic waste (e-waste), which causes environmental issues and presents opportunities for resource recovery. Micronutrient deficiencies are becoming significant challenges in agricultural systems, impacting soil health and crop yields. E-waste contains high levels of heavy metals like zinc, copper, iron, and manganese, along with other valuable elements. These can serve as alternative sources of nutrients if we recover them through recycling processes that are friendly to the environment. Mechanical, hydrometallurgical, and bio-based extraction methods enhance the effective recovery of valuable metals without harming the environment. Using recovered micronutrients in agricultural nutrient management is a circular economy approach. It transforms waste into valuable resources. However, environmental safety, contamination control, and regulatory issues remain critical for successful implementation. Linking waste recycling to nutrient management offers a way to use resources sustainably, reduce dependence on primary mineral resources, and improve the resilience of agricultural production systems.



## Graphical abstract

**KEYWORDS:** Electronic waste recycling, Circular micronutrient agriculture, Resource recovery, Sustainable nutrient management, Circular economy

## INTRODUCTION:

Global electronic waste (e-waste) accumulation has raised significant concerns about climate change (Daszkiewicz, 2022; Ghimire & Ariya, 2020; Mahato *et al.* 2022). Each year, e-waste increases by 3-5%, composed of the Internet of Things, space debris, and emerging electronic goods (Bank *et al.* 2014; Daszkiewicz, 2022). The e-waste stream is growing rapidly on our planet due to the high consumption of electronic devices and

the lack of effective infrastructure. E-waste includes fibrous composite materials and plastics that pose serious environmental risks (Antip, 2024; Kumar *et al.* 2024; Widmer *et al.* 2005). Although e-waste processing is technically feasible, there is a lack of investment for establishing expensive large-scale recycling facilities (Forti *et al.* 2020; Migov, 2017). A circular economy based on reusing and recycling e-waste products could help lower the demand for raw materials and natural resources, create job opportunities, and prevent the overexploitation of these resources. The mining concept is gaining popularity for its potential to reduce environmental impact and recover waste (Antip, 2024; West *et al.* 2014; Xavier *et al.* 2021). According to the WHO's first report on e-waste, about 12.9 million women and 18 million children in the informal sector are exposed to the toxicity of electronic goods (Aayog, 2019). The lack of a sufficient e-waste collection system limits recycling effort. This issue can be addressed by raising public awareness and providing economic incentives (Cordell *et al.* 2009; Tesfaye *et al.* 2017). E-waste contains about 60% valuable materials (such as iron, copper, aluminium, gold, and other metals), while only 2.70% consists of pollutants. The metallic resources in e-waste can be recycled; otherwise, they will contribute to the depletion of natural resources (Mahesha *et al.* 2023). Micronutrients play an important role in ecological processes like photosynthesis, respiration, enzymatic activity, animal production, and biological nitrogen fixation (Bosecker, 1997; Fazilova *et al.* 2023; Fischer *et al.* 2016). The micronutrient content of soil reflects the health of the ecosystem and the stability of food supply, but at a super continental scale, the soil's micronutrient potential remains unknown (Shukla *et al.* 2015; Tao *et al.* 2021; Yudha *et al.* 2025). Hidden hunger is becoming a major issue in developing countries, where people rely on low-quality plant products for energy. Soil suffering from micronutrient deficiency creates significant challenges for sustainability (Bheemaiah Balyatanda *et al.* 2024; Naraharasetti *et al.* 2025). Soil microbial diversity is crucial for addressing hidden hunger. Factors like intensive farming, climate change, and soil pollution reduce microbial populations, worsening hidden hunger (Chary *et al.* 2025; Kumar *et al.* 2020). Nutrient deficiency begins with soils that lack nutrients, leading to crops that do not provide adequate nutrition for humans. Emerging technologies like circular economy strategies can utilize organic waste, such as substrate preparation, to enhance human nutrition (MacArthur, 2013; Xavier *et al.* 2021). Consuming nutrient-deficient crops due to poor soil fertility results in what is known as hidden hunger (Tran *et al.* 2018; Xavier *et al.* 2021).

The circular economy is becoming a transitional approach from a linear economy. It focuses on a broader strategy of extracting value from waste and achieving sustainability. This approach emphasizes the 3R (reduce, reuse, recycle) strategy, which promotes conservation and sustainability (Awasthi *et al.* 2018; Sadeghi *et al.* 2020). While some e-waste management practices from developed countries can be replicated in developing countries, there is still a shortage of investment and skilled labour (Ghimire & Ariya, 2020; Wang *et al.* 2020). Extracting precious metals from electronic items shows business potential in this area. E-waste contains valuable metals like gold, silver, copper, and many rare earth metals that can be reused (Awasthi *et al.* 2018; Cucchiella *et al.* 2015; Xavier *et al.* 2021). A new trend focuses on nutrient circularity in food and waste management, aiming to recover nutrients and minimize loss (Kumar *et al.* 2020). Agricultural production faces challenges like micronutrient deficiency, declining crop productivity, high fertilizer imports, and soil health degradation. Essential micronutrients such as zinc (Zn), iron (Fe), manganese (Mn), copper (Cu), and molybdenum (Mo) are critical for plant growth and food security, and many agricultural areas are increasingly deficient in these (Alloway, 2009; Broadley *et al.* 2012; Mikula *et al.* 2020). Converting e-waste into plant-based fertilizers is emerging as a solution in the circular economy; it reduces environmental pollution and meets crop nutrient needs (Azeem, 2025; Sadeghi *et al.* 2020). Most metals can be recovered from e-waste using eco-friendly methods like bioleaching, hydrometallurgy, and green solvent extraction (Ilankoon *et al.* 2018; Palaniandy *et al.* 2022). Once these nutrients are recovered, they can be reformulated into fertilizers, turning liabilities into a productive agricultural system (Bala & Nidhi, 2024; Forti *et al.* 2020; Kiddee *et al.* 2013). This integrated approach reduces environmental pollution, decreases reliance on imported chemical fertilizers, and promotes sustainability. Although there is growing research on e-waste management and micronutrient fertilization as separate topics, little work has been done to provide a unified framework for urban mining related to nutrient sustainability in urban agriculture. This introduces a new circuit-to-soil concept that views electronic waste as a secondary mineral resource, potentially addressing the global challenges of rising e-waste volumes and the depletion of soil micronutrients. The article consolidates existing knowledge about e-waste composition, new technologies in gold recovery, agronomic engineering solutions, environmental safety, and governance in the circular economy, creating a comprehensive roadmap to convert recovered electronic metals into plant-available micronutrient inputs. This review highlights how we can close the anthropogenic nutrient loop through a circular recycling system, reducing dependence on traditional mining, enhancing soil fertility, and maintaining climate-resilient and resource-efficient agricultural systems. It also identifies technological, economic, regulatory, and social barriers and suggests directions for future research necessary to implement circular micronutrient agriculture in support of sustainable development and climate-smart food production models.

#### **Need for recycling e-waste into micronutrient fertilizers**

Electronic waste (e-waste) is one of the fastest-growing waste streams in the world (Palaniandy *et al.* 2022; Yudha *et al.* 2025). While micronutrient deficiencies in soils are limiting crop productivity. Recycling e-waste into micronutrient fertilizers helps recover valuable elements such as zinc (Zn), iron (Fe), copper (Cu) and manganese (Mn) from discarded electronics and reuse them in agriculture (Fazilova *et al.* 2023). This reduces environmental

pollution, conserves natural mineral resources, and supports sustainable nutrient management. However, proper processing is essential to remove toxic metals and ensure fertilizer safety (Baldé *et al.* 2017; Forti *et al.* 2020).

### Classification and scale of e-waste streams

Today, worldwide production of E-waste is thought to be around 20 to 25 million tonnes per year and major producing countries are Europe, the United States and Australia (Blasi *et al.* 2023). Over the next ten years, China, Eastern Europe and Latin America will become major E-waste producers (Ghimire & Ariya, 2020). The European Waste Catalogue Classified E-waste into six main groups comprising temperature exchange equipment, screens and monitors, lamps, large equipment, small equipment and small IT and telecommunications equipment (Sarvothaman, 2024). The European countries alone generated more than 300,000 tonnes per year of end-of-life portable batteries in 2022, of which zinc-based components had been produced more European Portable Battery Association (de Oliveira Neto *et al.* 2023). Among them the most relevant sub-streams for fertilizer production are portable batteries (especially alkaline and zinc–carbon cells), printed circuit boards (PCBs) from computers and mobile phones, cathode ray tube (CRT) glass and a variety of metal-bearing sludges from informal e-waste processing sites (Shin *et al.* 2019; Yue *et al.* 2021). Classification of e-waste is shown in Figure 1.

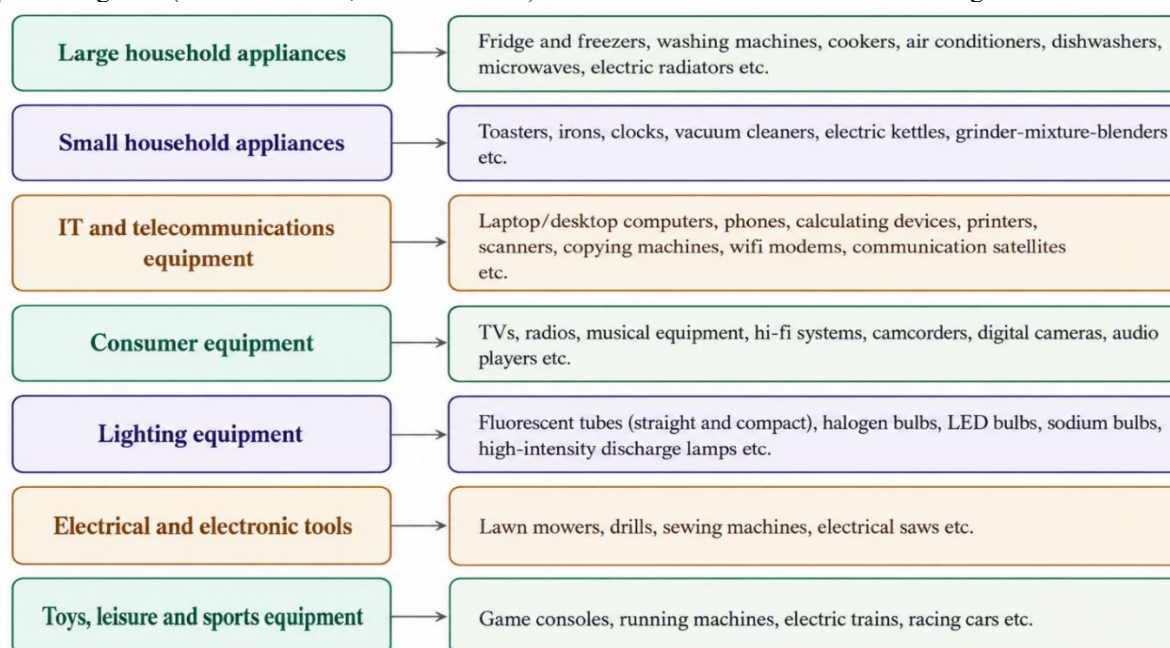


**Fig. 1** Classification of waste electrical and electronic equipment (WEEE)

### Agronomically important micronutrients present in e-waste

Micronutrient deficiencies are becoming a serious agricultural problem due to imbalanced fertilizer use, continuous rice–wheat cropping and alkaline soil conditions that reduce nutrient availability (Shukla *et al.* 2015; Sobianowska-Turek *et al.* 2016). Essential micronutrients such as Zinc (Zn), Iron (Fe), Manganese (Mn), Boron (B), Copper (Cu), and Molybdenum (Mo) play critical roles in enzyme activation, chlorophyll synthesis, photosynthesis, sugar transport, and nitrogen fixation (Brady *et al.* 2008). According to India's Soil Health Card Portal (2024–25), nearly 40–50% of soils are Zn deficient, while Fe deficiency affects 12–25%, B deficiency 18–33%, and Mn deficiency 5–15% of soils in several major agricultural states (Li *et al.* 2025). Zinc is the most important element for agriculture. Zinc act as a cofactor for over 300 enzymes in plant metabolism, which is essential for auxin synthesis, membrane integrity and carbon anhydrase activity (Pujar *et al.* 2020). When plant has Zn deficiency, its results in stunted growth, leaf chlorosis, reduced grain filling and depressed food nutritional quality (Ajeesh Krishna *et al.* 2023; Marschner, 2011). The World Health Organization estimates that zinc deficiency contributes to 800,000 child deaths annually through its effect on immune function and growth (Montoya *et al.* 2020). Zinc-enriched fertilizers, applied to soil or by foliar application, are a well-established and effective biofortification strategy and the agronomic and human nutrition literature are clear on the dose-response relationships for major crops (Alloway, 2009; Cakmak, 2008). Manganese is the second important micronutrient in electronic waste-derived fertilizer research. Plants need manganese for photosynthesis (it is part of the oxygen-evolving complex of Photosystem II), nitrogen assimilation and the activation of numerous enzymes including superoxide dismutase (Broadley *et al.* 2012; Tanong *et al.* 2017). Young leaves show interveinal chlorosis in manganese deficiency, which is common in sandy, high pH and waterlogged soils (Buzatu *et al.* 2013). One of the major advantages of this method is the simultaneous recovery of Zn and Mn from battery black mass into one bifunctional fertilizer solution as both deficiencies are often found in the same soil types and crops (Charef *et al.* 2017; Sadeghi *et al.* 2020). Spent alkaline batteries are used because it contains a black mass fraction a mixture of zinc oxide (ZnO), manganese dioxide (MnO<sub>2</sub>) and graphite that has approximately 60–70% of total battery mass after mechanical pre-treatment (Belardi *et al.* 2011). The chemical characterisation studies report on Zn

contents in the black mass in the range of 18–33% and Mn contents in the range of 28–42% which is further processed into Micro nutrient fertilizer. The rest is mainly potassium, carbon and trace impurities (Charef *et al.* 2017; Sadeghi *et al.* 2020). Significantly, modern alkaline batteries manufactured after the EU Directive on Batteries and Accumulators (2006/66/EC) contain very little cadmium and mercury, heavy metals that make the contaminant management challenge for fertilizer-grade products much easier (Puttonen *et al.* 2025; Shin *et al.* 2019). Another sub stream is PCBs that have complex e-waste substrate, but it also contains equivalent amount of micronutrient profile. They contain 20-30% copper by mass and tin, gold, silver, palladium and a variety of base metals, but also significant concentrations of lead from solder and brominated flame retardants from the epoxy substrate (Arshadi & Mousavi, 2015; Cucchiella *et al.* 2015). The heterogeneity of the PCB composition varies significantly between device generations and manufacturers complicating the standardised processing. However, the copper content of purified PCB leachates is directly relevant to the formulation of Cu-containing micronutrient fertilizers for deficient soils (Arshadi & Mousavi, 2015; Yudha *et al.* 2025). The circular pathway for converting e-waste into micronutrient fertilizers through recovery, purification, and agricultural reuse is illustrated in Figure 2.

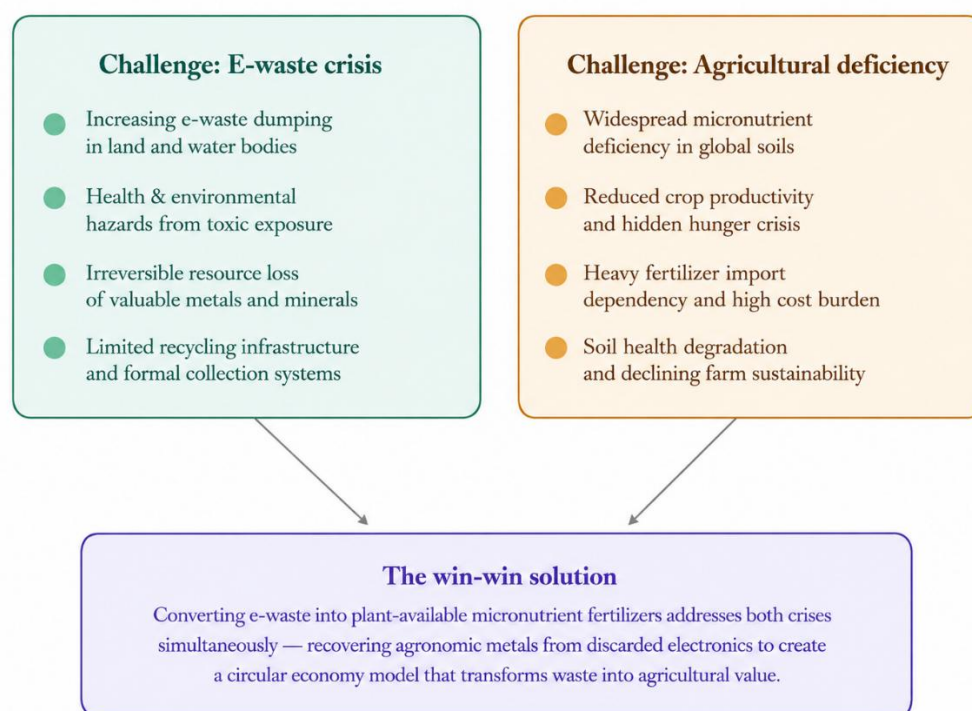


**Fig. 2** Recycling of e-waste into micronutrient fertilizers as a sustainable circular economy approach

## Technologies for nutrient recovery from e-waste

### Pre-processing and feedstock preparation

The conversion of raw e-waste to micronutrient fertilizer requires a series of unit operations from collection of logistics, pre-treatment, metallurgical processing, chemical conversion, quality assurance and agronomic validation in table 1.

**Table 1** Integrated process flow for recovery of micronutrient fertilizers from e-waste

| STEP 1 | E-waste collection & sorting     | Batteries, PCBs, WEEE sorted by category at authorized e-waste recycling facility                 | (Baldé & Kuehr, 2021)                                                 |
|--------|----------------------------------|---------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------|
| STEP 2 | Pre-treatment & dismantling      | Manual/mechanical disassembly; removal of casings, plastics, hazardous components (Hg, CFC)       | (Barragán-Mantilla <i>et al.</i> 2024; Binnemans & Jones, 2023)       |
| STEP 3 | Black mass feedstock preparation | Crushing, sieving, roasting (300–500°C) to obtain metal-rich powder (ZnO, MnO <sub>2</sub> , CuO) | (Sethurajan <i>et al.</i> 2019; Sobianowska-Turek <i>et al.</i> 2016) |

|         |                               |                                                                                                                                                             |                                                             |
|---------|-------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------|
| STEP 4  | Metal leaching                | Hydrometallurgy: H <sub>2</sub> SO <sub>4</sub> / NaOH / organic acid leaching /<br>Pyrometallurgy: 900–1200°C   Bioleaching: <i>Acidithiobacillus spp.</i> | (Fazilova <i>et al.</i> 2023;<br>Yudha <i>et al.</i> 2025)  |
| STEP 5  | Solid-liquid separation       | Filtration, centrifugation separation of leach solution from gangue residue                                                                                 |                                                             |
| STEP 6  | Purification & detoxification | Selective precipitation, ion exchange, solvent extraction removal of Cd, Pb, Hg, As, Cr                                                                     | (Palaniandy <i>et al.</i> 2022;<br>Shin <i>et al.</i> 2019) |
| STEP 7  | Fertilizer formulation        | Conversion to ZnSO <sub>4</sub> , MnSO <sub>4</sub> , FeSO <sub>4</sub> , CuSO <sub>4</sub> , chelated (EDTA/DTPA) or slow-release forms                    |                                                             |
| STEP 8  | Testing & compliance          | XRD, FTIR, SEM-EDX, AAS characterization; heavy metal limits verified (Cd ≤5, Pb ≤25, Hg ≤0.1 mg/kg)                                                        | (Jiang <i>et al.</i> 2024; Yudha <i>et al.</i> 2025)        |
| STEP 9  | Agronomic application         | Soil application (basal/top-dress), foliar spray, seed priming evaluated for crop growth, yield, and uptake                                                 | (Barragán-Mantilla <i>et al.</i> 2024)                      |
| STEP 10 | Validation & market release   | Multi-location trials, life cycle assessment, FCO registration, and commercial distribution                                                                 | (Cordell <i>et al.</i> 2009; Migov, 2017)                   |

### Mechanical pre-treatment

Physical pre-treatment steps refer to converting bulk e-waste into a process-ready feedstock, focusing on target mineral fractions while removing non-target materials. When it comes to used batteries, the process usually begins with collection, sorting, mechanically shredded or crushed, breaking open the battery casing and freeing up the internal components (Migov, 2017). Magnetic separation is then applied to recover ferrous materials (steel casings, springs) and air classification or sieving is used to separate the fine black mass fraction from the coarser brass and copper components (Petranikova *et al.* 2018; Tran *et al.* 2020). In this way, the black mass fraction required further homogenisation before leaching, as particle size is directly impacting leaching kinetics and metal recovery efficiency. Sadeghi *et al.*, (2020) reported that the extraction rates of Zn and Mn are significantly improved under both acidic and alkaline leaching conditions by reducing the particle size to below 100 µm, which is attributed to the increase in the reactive surface area available for mass transfer (Islam, 2019; Sadeghi *et al.* 2020). However, ultra-fine grinding also increases energy consumption during processing and can lead to contamination from wear metals originating from milling equipment (Fazilova *et al.* 2023). These are factors that need to be balanced during process design. PCBs and other complex e-waste are more complicated to pre-treat. Before shredding, thermal depollution steps are used to remove hazardous materials (batteries, capacitors with liquid electrolytes) (Petranikova *et al.* 2018; Yeşiltepe *et al.* 2019). The obtained metal-rich fraction is submitted to successive density and eddy-current separations to obtain copper-enriched and precious-metal-enriched fractions, which are used as inputs for hydrometallurgical recovery processes (Cucchiella *et al.* 2015). The prevailing industrial process to date has been the smelting of PCB fractions in copper smelters but this does not generate the metal solutions needed for direct fertilizer synthesis.

### Thermal pre-treatment

The mineralogical phase composition of Zn and Mn oxides of black mass after thermal pre-treatment prior to leaching shown to be strongly variable and directly related to leaching efficiency (Abdullah *et al.* 2024; Yue *et al.* 2021). Petranikova *et al.* (2018) studied the effect of heating black mass in air atmosphere at temperatures from 200°C to 700°C and found that calcination at 300–400°C transformed poorly crystalline Zn-Mn mixed oxides into more reactive phases, which increased the efficiency of H<sub>2</sub>SO<sub>4</sub> leaching of Zn by up to 30% compared to untreated material (Petranikova *et al.* 2018; Yudha *et al.* 2025). However, sintering and phase consolidation were observed at 600–700°C, which resulted in a decrease of leachability, indicating a range of optimal thermal treatment (Sadeghi *et al.* 2017). These results are relevant for process design moderate thermal pre-treatment can significantly improve hydrometallurgical recovery without the full energy cost of pyrometallurgical processing.

### Metal recovery technologies

#### Pyrometallurgical routes

Pyrometallurgical processing is the main industrial route for metal recovery from black mass of zinc-based alkaline batteries. These systems are operated at high temperatures (900–1200°C) in rotary kilns or electric arc furnaces where metal separation is carried out by volatilization of zinc, slagging of manganese along with iron and combustion of residual organics (Tran *et al.* 2020; Yudha *et al.* 2025). The pyrometallurgical recovery

pathway for zinc and manganese from spent alkaline and zinc-carbon battery black mass is shown in Figure 3. The key reaction is a carbothermic reduction where ZnO is reduced to metallic zinc vapour by carbon from graphite or added coke and then condensed and recovered as ZnO with recovery efficiencies of 90–98% (Fazilova *et al.* 2023; Yeşiltepe *et al.* 2019). Manganese is left in the slag as MnO or Mn<sub>3</sub>O<sub>4</sub> with 60–80% recovery and can be further processed to produce ferromanganese or refined further (Sobianowska-Turek *et al.* 2016).

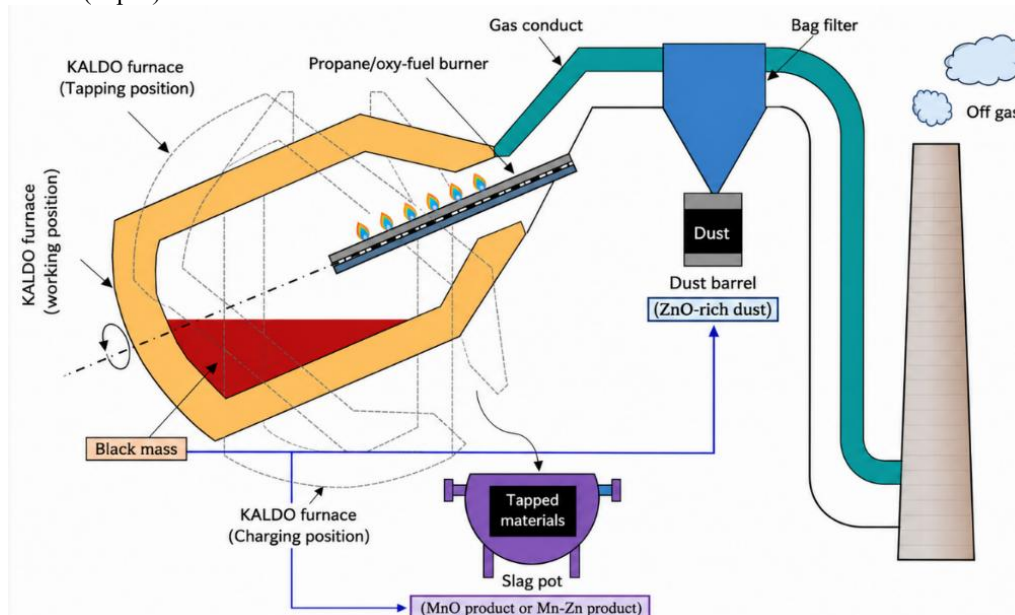
$$\text{ZnO} + \text{C} \rightarrow \text{Zn}(\text{vapor}) + \text{CO}$$


**Fig. 3** Recovery of Zn and Mn from the black mass of spent alkaline and zinc-carbon batteries in the kaldo furnace Pyrometallurgy does have these benefits, but also has significant disadvantages for fertilizer-oriented recovery. This process uses a lot of energy due to the high temperatures (>900°C) and emits SO<sub>2</sub>, NO<sub>2</sub> and metal fumes that require costly gas-cleaning systems (Tanong *et al.* 2017). For formulation of fertilizer from recovered metals, obtained as oxides or metallic phases, further acid dissolution is necessary and the graphite is burned away too, so there is no way to reclaim it separately (Tran *et al.* 2020). Furthermore, the centralised and capital-intensive nature of these systems makes them less appropriate for decentralised or low-cost recycling operations. The pyrometallurgical route for metal recovery and conversion into fertilizer precursors is illustrated in Figure 4.

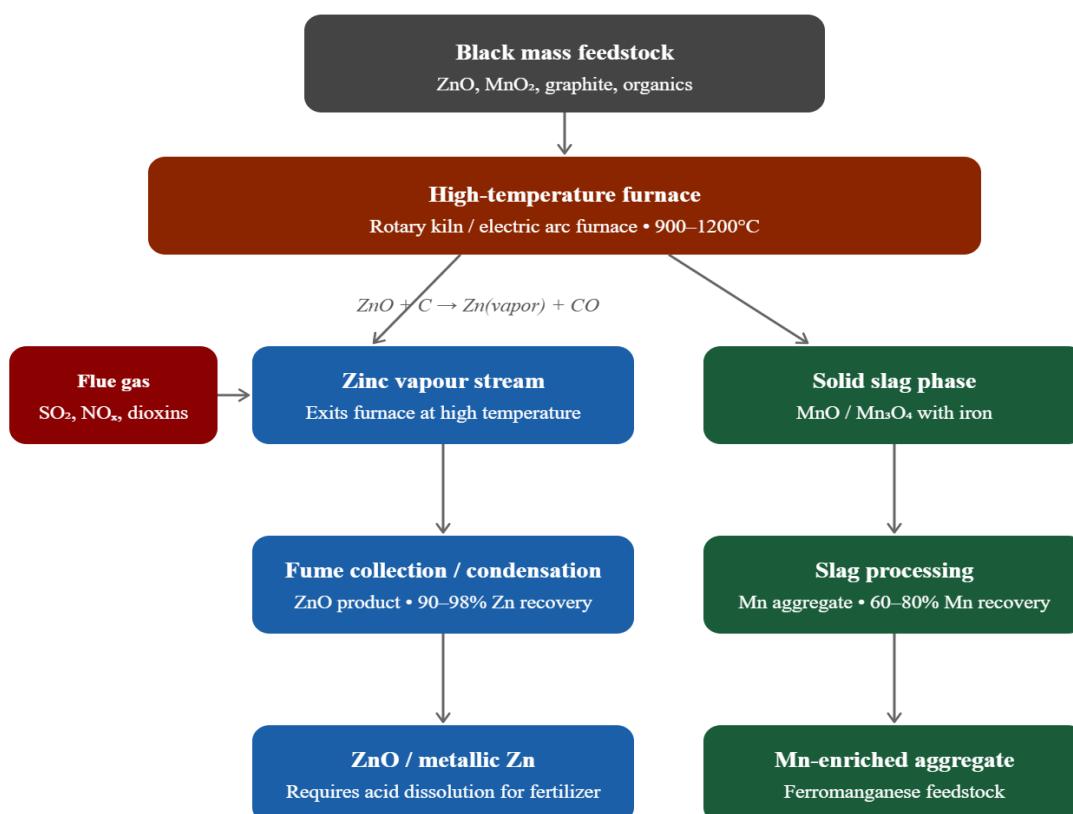


**Fig. 4** Metal recovery of Zn and Mn by pyrometallurgical routes

## Hydrometallurgical routes

Hydrometallurgical processing involves aqueous leaching of metals from battery black mass, with purification and recovery of soluble metal salts. Sulfuric acid ( $\text{H}_2\text{SO}_4$ ) is the most commonly used lixiviant because it can dissolve  $\text{ZnO}$  and  $\text{MnO}_2$  to form  $\text{ZnSO}_4$  and  $\text{MnSO}_4$  solutions that are directly suitable for micronutrient fertilizer production (Sadeghi *et al.* 2020). Under optimized conditions, Zn recovery can be 95% and Mn 80–90% (Fazilova *et al.* 2023; Tran *et al.* 2018). The process involves usually pre-treatment, acid or alkaline leaching, solid-liquid separation, purification and recovery by crystallization or precipitation (Li *et al.* 2023). The insoluble Mn (IV) is often reduced to soluble Mn (II) by leaching with glucose or  $\text{H}_2\text{O}_2$ . Zhang *et al.* (2023) developed a two-stage selective leaching method, achieving 98.2% Zn recovery by NaOH leaching and 91.2% Mn recovery by reductive  $\text{H}_2\text{SO}_4$  leaching (Sethurajan *et al.* 2019; Yue *et al.* 2021). Compared to pyrometallurgy, hydrometallurgy has lower operating temperatures, lower energy consumption, and produces water-soluble  $\text{ZnSO}_4$  and  $\text{MnSO}_4$  directly for fertilizer applications (Wang *et al.* 2020). However, the process produces acidic effluents and involves several purifications, which increase the chemical consumption and operational complexity. The hydrometallurgical recovery pathway involving leaching, purification, and metal recovery is shown in Figure 5.

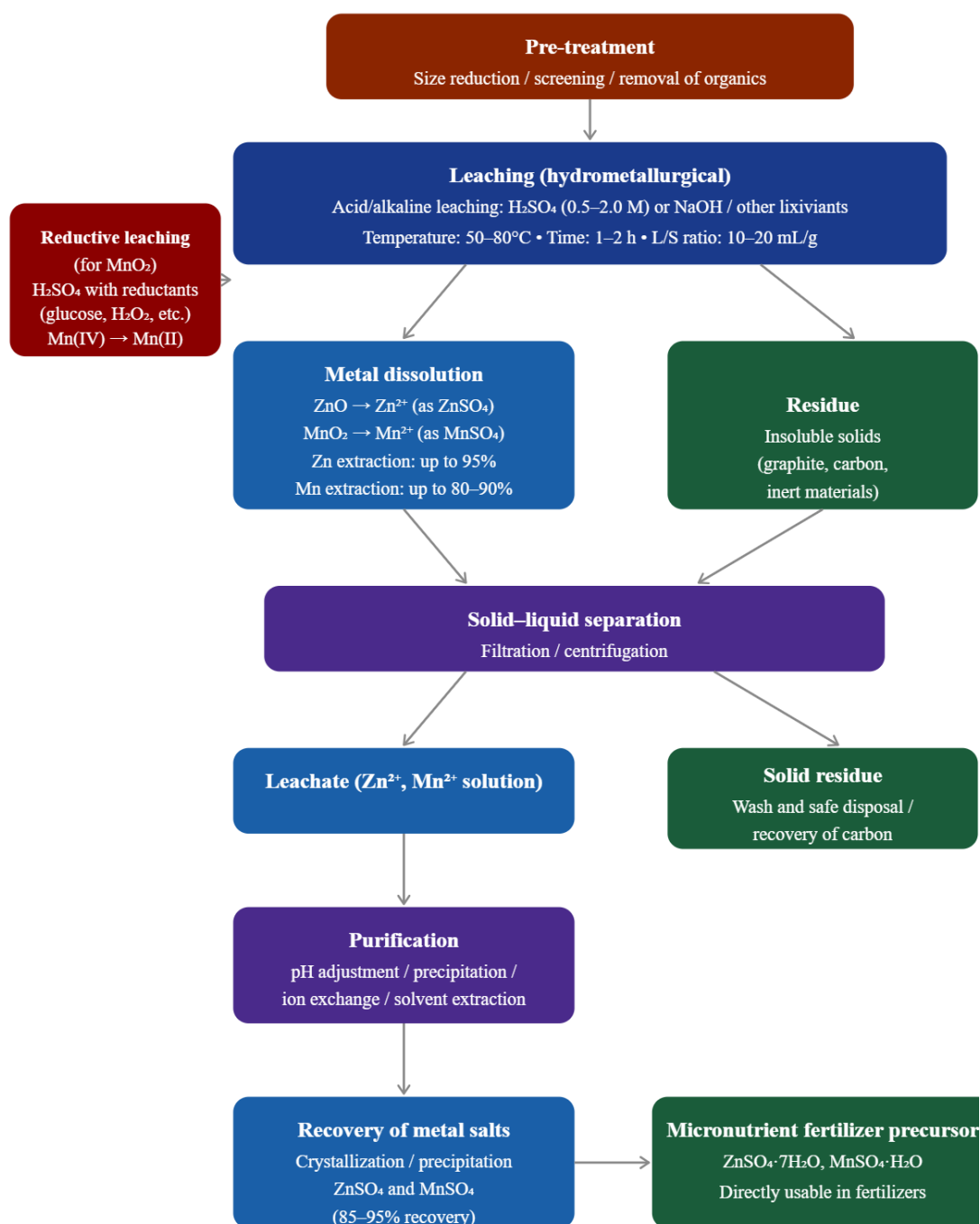
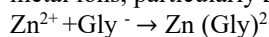


Fig. 5 Metal recovery through hydrometallurgical routes

## Green leaching systems

### Amino acid lixiviants: glycine

Glycine leaching is a promising green hydrometallurgical route for recovering metals from battery black mass and other streams of e-waste. Glycine ( $\text{NH}_2\text{CH}_2\text{COOH}$ ), the simplest amino acid, is biodegradable, has low toxicity, is relatively inexpensive and acts as a metal-complexing agent and a plant-available source of nitrogen and carbon (Barragán-Mantilla *et al.* 2024; Hu *et al.* 2021). Glycine under alkaline conditions in contrast to conventional mineral acids, decreasing the corrosivity and environmental burden (Li *et al.* 2023; Tanda *et al.* 2017). At alkaline pH ( $>9$ ) glycine is predominantly as glycinate ( $\text{Gly}^-$ ) and forms stable complexes with divalent metal ions, particularly  $\text{Zn}^{2+}$ :



The Zn-glycine complex is much more stable than the Mn-glycine complex, so that Zn can be selectively extracted, leaving most of the Mn in the residue (Tavallali & Karimi, 2017). Such selectivity is very important for fertilizer applications, which can allow Zn-enriched liquid fertilizer precursors with low Mn or separate recovery streams of Zn and Mn (Oraby & Eksteen, 2014). Efficient Zn extraction with limited Mn co-extraction was achieved by glycine leaching at pH 10–12, with glycine to Zn molar ratios of 6:1–10:1 (Barragán-Mantilla *et al.* 2024). The release of Zn-glycinate solutions was faster than that of Zn-citrate complexes in the initial stage but showed sustained release behaviour at later stages. Furthermore, glycine has demonstrated efficacy in the recovery of Cu from oxide minerals and PCB-derived materials, suggesting its wider applicability across diverse e-waste substrates (Li *et al.* 2023; Standardization, 2006; Tanda *et al.* 2017). Li *et al.* (2023) reported that glycine leaching becomes economically competitive with conventional  $\text{H}_2\text{SO}_4$  leaching when glycine recovery exceeds 70%, although large-scale industrial validation is still limited.

### Organic acid leaching systems

One of the most promising green routes for the recovery of micronutrients from the battery black mass is leaching with citric acid (organic acid based). Citric acid, a biodegradable tricarboxylic acid, is produced commercially by fermentation of *Aspergillus niger*, and dissolves well ZnO and  $\text{MnO}_2$  under mildly acidic conditions (pH 2–5) to form soluble Zn–citrate and Mn–citrate complexes (Barragán-Mantilla *et al.* 2024). Citrate is an EU approved complexing agent for micronutrient fertilizers (Ilankoon *et al.* 2018), so that the resulting Zn–Mn–citrate leachate can potentially be used directly as a fertilizer product without subsequent chemical conversion (Tavallali & Karimi, 2017). Barragán-Mantilla *et al.* (2024) showed that Zn–Mn–citrate solutions obtained from black mass showed a controlled and sustained pattern of nutrient release in sand column studies. Unlike Zinc sulphate solutions with rapid initial release followed by a decline in release rate and citrate complexes with more gradual and linear release of nutrients improved nutrients availability over longer periods of time while reducing leaching losses (Li *et al.* 2025; Pathak *et al.* 2021). This slow-release property is due to the moderate stability of Zn-citrate complexes which retards the release of free  $\text{Zn}^{2+}$  in soil systems (Charef *et al.* 2017; Pathak *et al.* 2021). Comparative studies by Sadeghi *et al.* (2020) concluded that citric acid offers the best balance between metal recovery efficiency, cost, environmental compatibility and direct fertilizer applicability.

### Bioleaching

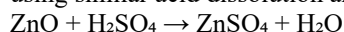
Bioleaching uses the metabolic activity of acidophilic or neutrophilic microorganisms to solubilize metals from solid matrices by producing organic or inorganic acids, oxidative enzymes or metal-complexing metabolites. *Acidithiobacillus thiooxidans* and *Acidithiobacillus ferrooxidans* have been studied extensively for the bioleaching of sulfidic minerals and more recently have been applied to e-waste processing (Arshadi & Mousavi, 2015; Bosecker, 1997). Fungal bioleaching with *Aspergillus niger* (a producer of citric, gluconic and oxalic acids as metabolites) and bacterial *Penicillium simplicissimum* can recover zinc and manganese from battery black mass (Yudha *et al.* 2025). Under optimised conditions (temperature, pH, carbon source) in batch experiments over 10–20 days, Zn extraction efficiencies of 50–85% and Mn efficiencies of 30–65% have been achieved (Arshadi & Mousavi, 2015). The important advantage of fungal bioleaching for the production of fertilizer is that the leachate produced is a mixture of Zn and Mn with the organic acid metabolites (citric, gluconic, oxalic) which act as chelating agents, essentially producing an e-waste derived chelated micronutrient solution directly, without the need to add the chelating agents separately (Bosecker, 1997; Sobianowska-Turek *et al.* 2016). Rasoulnia and Mousavi (2016) characterised Zn speciation in *Aspergillus niger* bio leachates of battery black mass and showed the prevalence of Zn-citrate, in agreement with the high citric acid production by this organism (Arshadi & Mousavi, 2015). The main limitations of this process are the relatively slow kinetics of bioleaching (days to weeks compared to hours for chemical leaching) and the sensitivity of microbial activity to feedstock toxicants, but the low energy, reagent, and equipment costs of bioleaching make it attractive for decentralised or low-resource processing contexts.

### Fertilizer formulation and conversion pathways

#### Sulphate and oxide forms

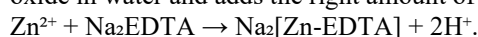
The most direct and commercially established way to convert recovered metals into fertilizer forms that plants can use is by producing water-soluble sulphate salts. Zinc sulphate monohydrate ( $\text{ZnSO}_4 \cdot \text{H}_2\text{O}$ , containing 35.5% Zn) and heptahydrate ( $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$ , containing 22.7% Zn) come from reacting ZnO or  $\text{Zn}(\text{OH})_2$ , which is precipitated from leach solutions, with sulfuric acid (Barragán-Mantilla *et al.* 2024; Yudha *et al.* 2025). Similarly, manganese sulphate monohydrate ( $\text{MnSO}_4 \cdot \text{H}_2\text{O}$ , containing 32% Mn) is obtained by reductive acid leaching of  $\text{MnO}_2$ -containing black mass, followed by evaporation and crystallization (Hu *et al.* 2021; Yue *et al.* 2021).

Research shows that  $\text{ZnSO}_4$  and  $\text{MnSO}_4$  recovered from e-waste can have nutrient levels comparable to those in commercially made products, with Zn at 13.3% and Mn at 12.7% in battery-derived preparations (Yue *et al.* 2021). These products also meet the nutrient guarantee thresholds set by FCO (Shukla *et al.* 2023). Iron sulphate ( $\text{FeSO}_4$ ), copper sulphate ( $\text{CuSO}_4$ ), and sodium molybdate ( $\text{Na}_2\text{MoO}_4$ ) are produced from their respective metal fractions using similar acid dissolution and crystallization processes (Hu *et al.* 2021).



### Chelation Chemistry and Fertilizer Speciation

Chelated fertilizers are a better option for alkaline and calcareous soils. In these soils, free metal ions quickly bind with hydroxides, carbonates and oxides, making them unavailable to plants (Shukla *et al.* 2015). Chelates are organic compounds that form bonds with metal cations using multiple electron-donating groups (Lewis bases) (Li *et al.* 2025). This process creates stable, water-soluble, electrically neutral or anionic complexes that resist precipitation and can be taken up by roots (Shin *et al.* 2019). The three main synthetic chelating agents in agriculture are EDTA (ethylenediaminetetraacetic acid, effective over pH 1.6 to 6.5), DTPA (diethylenetriaminepentaacetic acid, effective to pH 7.5) and EDDHA (ethylene diamine dihydroxyphenyl acetic acid, effective to pH 10). These compounds are listed in order of increasing stability constant and cost (Hu *et al.* 2021; Shin *et al.* 2019). To prepare chelated micronutrients from e-waste, one dissolves the metal sulphate or oxide in water and adds the right amount of chelating acid:



The strongest evidence for the agricultural benefits of chelated micronutrients from e-waste comes from (Adejumo *et al.* 2018). The synthesis pathway of chelated micronutrient fertilizer precursors derived from recovered metals is presented in Figure 6.

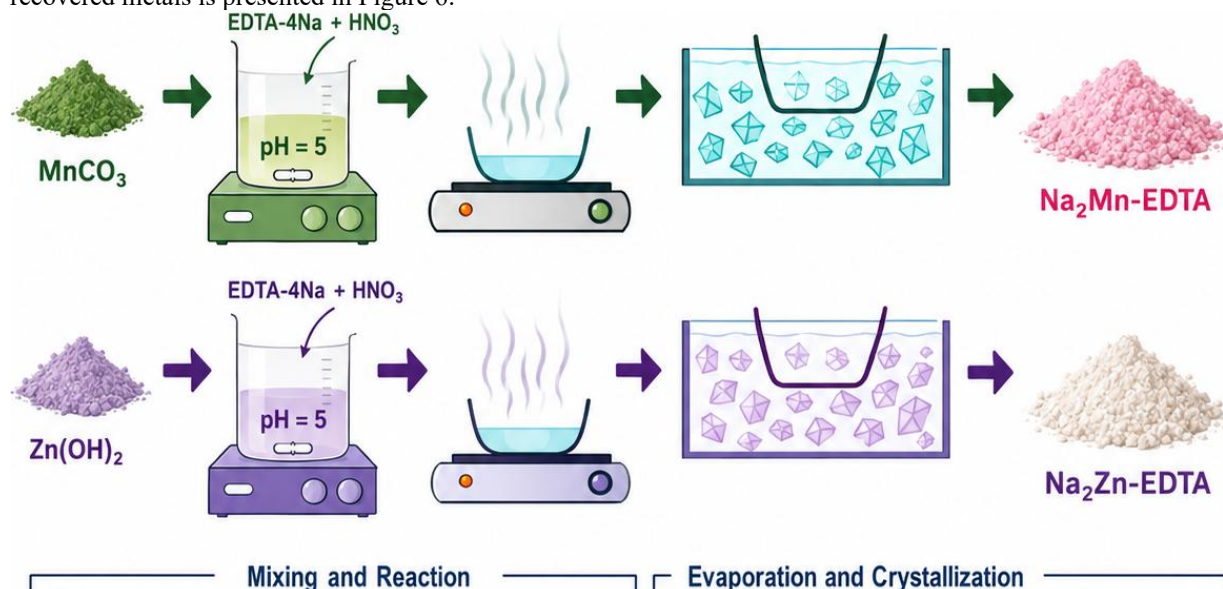


**Fig. 6** Synthesis of  $\text{Na}_2\text{Mn-EDTA}$  and  $\text{Na}_2\text{Zn-EDTA}$  chelate fertilizer precursors (modified from (Yudha *et al.* 2025))

### Nano and slow- release fertilizers

The development of nanotechnology and controlled-release systems have enabled the use of recovered e-waste metals in nano-fertilizers and slow-release fertilizer formulations (Garcia-Garcia (Garcia-Garcia *et al.* 2024; Mahesha *et al.* 2023). Nano-fertilizer is based on the principle of use of micronutrient particles which have been engineered to the nanoscale scale level and hence significantly increase the surface area, reactivity and interaction with the plant roots (Iqbal *et al.* 2019). Smaller particle size increases nutrient solubility and slows down nutrient release leading to increased uptake efficiency in the plant with reduced leaching losses. Other technologies to control the accessibility of nutrients are the use of encapsulation technologies such as polymer coatings, hydrogel structures, biochar carriers and nanocellulose composites, which are used in slow-release fertilizers (Azeem, 2025; Sales *et al.* 2024). These materials control the rate of diffusion of nutrients and coordinate the release of nutrients and physiological needs of plants. Controlled nutrient supply reduces the environmental contamination, reduces fertilizer losses and increases food production. The incorporation of e-waste-derived metals into nano-enabled and slow-release formulations therefore supports sustainable agriculture by integrating waste valorisation and smart nutrient management technologies (Biswas & Rai, 2024; Koley *et al.* 2025; Palaniandy *et al.* 2022). Major pathways for converting recovered e-waste metals into plant-available micronutrient fertilizers are summarized in Figure 7.

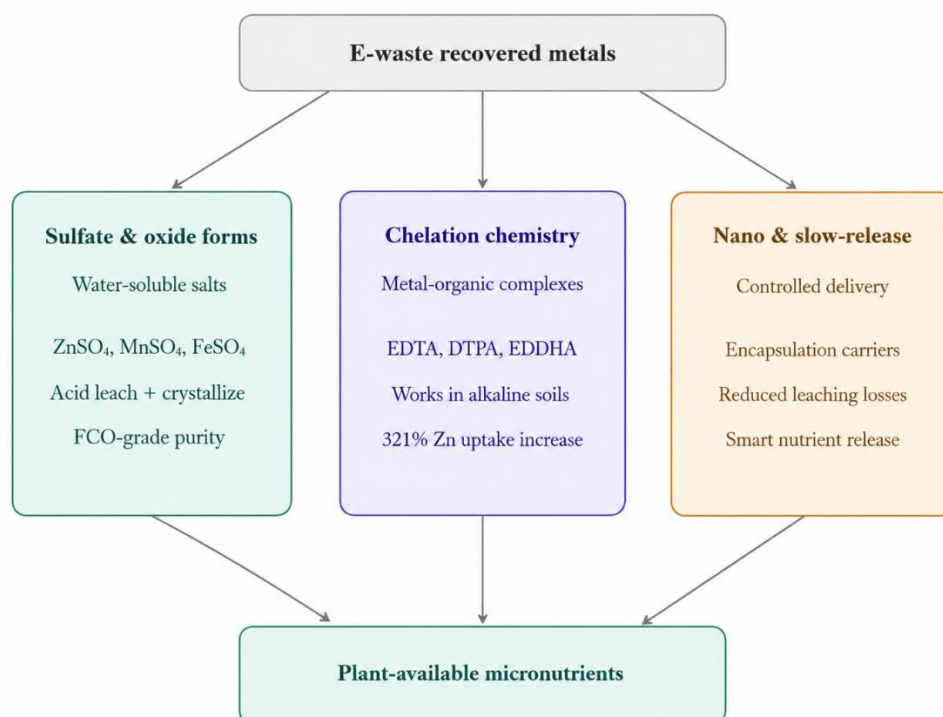


**Fig. 7** Major pathways for converting recovered e-waste metals into plant-available micronutrient fertilizers

#### Agronomic performance of e-waste-derived fertilizers

While research on e-waste-derived micronutrient fertilizers is increasing, it is still significantly less extensive than studies on conventional mineral fertilizers. Most published studies are used commercially available chelated fertilizers (Zn-EDTA, Zn-DTPA, Zn-citrate, Zn-gluconate) rather than those directly sourced from e-waste, as the latter are just beginning to be developed on a larger scale. Still, this existing literature offers solid mechanistic and empirical support for the fertilizer concept. The chelate chemistries from e-waste leaching (citrate, glycinate) closely resemble those of commercially tested products (Li *et al.* 2023; Oraby & Eksteen, 2014; Tavallali & Karimi, 2017). For zinc fertilizers, meta-analyses of field trials on wheat, rice, and maize consistently show that applying 0.5 to 5 kg Zn ha<sup>-1</sup> as ZnSO<sub>4</sub>, Zn-EDTA, or Zn-chelate significantly increases grain Zn concentration by 20 to 60% and improves grain yield by 5 to 25% in Zn-deficient soils (Hu *et al.* 2021). Chelated sources generally outperform inorganic salts in high-pH soils (Alloway, 2009; Cakmak, 2008). Almendros *et al.* (2019) showed in a field trial on calcareous soil (pH 7.9) that mixtures of Zn-DTPA-HEDTA-EDTA chelates applied at 3 kg Zn ha<sup>-1</sup> increased barley grain yield by 18% and grain Zn content by 32% compared to untreated controls while also reducing the amount of nitrogen needed for similar productivity (Almendros *et al.* 2019). The agricultural applications, fertilizer products, and key agronomic outcomes reported for spent battery-derived fertilizers are compared in Table 2. Montoya *et al.* (2020) found that the interaction of zinc and nitrogen on wheat biofortification was strongest when zinc was applied in a chelated form. Co-applying zinc and ammonium-based nitrogen fertilizers enhanced root Zn uptake through rhizosphere acidification. For manganese fertilizers, foliar application of MnSO<sub>4</sub> at 0.5 to 1.0 kg Mn ha<sup>-1</sup> is the standard practice for Mn-deficient crops, especially winter wheat and barley in northern Europe (Fazilova *et al.* 2023; Montoya *et al.* 2020). However, when applied to the soil, Mn quickly oxidizes from plant-available Mn<sup>2+</sup> to insoluble Mn<sup>3+</sup>/Mn<sup>4+</sup> oxides in well-aerated alkaline soils. This process significantly decreases its effectiveness (Broadley *et al.* 2012; Shukla *et al.* 2015).

**Table 2 Comparison of Spent Battery-Derived Fertilizers: Agricultural Applications and Key Results**

| Source material                       | Fertilizer product                               | Crop  | Application method                                                    | Key result                                                                                                        | Reference               |
|---------------------------------------|--------------------------------------------------|-------|-----------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|-------------------------|
| Spent alkaline batteries (black mass) | Zn & Mn sulphate salts (selective acid leaching) | Wheat | Foliar spray (25 <sup>th</sup> & 35 <sup>th</sup> day post-emergence) | Foliar ME application outperformed soil application for yield; high Zn/Mn recovery efficiency via staged leaching | (Hu <i>et al.</i> 2021) |

| Source material                              |      | Fertilizer product                                                                             | Crop                | Application method                                    | Key result                                                                                                           | Reference                              |
|----------------------------------------------|------|------------------------------------------------------------------------------------------------|---------------------|-------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|----------------------------------------|
| Dry-cell batteries                           |      | MnSO <sub>4</sub> liquid (2.11% Mn)                                                            | Wheat               | Seed priming (0.05M) + foliar spray (0.75%)           | Yield ↑11.7%; plant height ↑43%; spikes ↑55%; improved drought tolerance                                             | (Varma <i>et al.</i> 2023)             |
| Spent batteries                              | LFP  | P-SRF (recovered HPO <sub>4</sub> <sup>2-</sup> /H <sub>2</sub> PO <sub>4</sub> <sup>-</sup> ) | Maize               | Soil pot application                                  | Growth comparable to KH <sub>2</sub> PO <sub>4</sub> control; controlled P release; Li recovery as by-product        | (Yue <i>et al.</i> 2021)               |
| LiFePO <sub>4</sub> cathode                  |      | LiFePO <sub>4</sub> nanoparticles (50 mg kg <sup>-1</sup> )                                    | Peanut              | Soil mixing pre-plant                                 | Yield ↑; allergenicity gene expression ↓99.78% at 10 mg kg <sup>-1</sup> ; improved seed quality                     | (Jiang <i>et al.</i> 2024)             |
| Spent Zn-C & alkaline batteries (black mass) |      | Zn-Mn sulphate / citrate / glycinate solutions                                                 | Citrus (pot)        | Hydrometallurgical leaching + soil/foliar application | Zn-Mn-CIT & GLY showed steady nutrient release; comparable growth to commercial ZnSO <sub>4</sub> ; no phytotoxicity | (Barragán-Mantilla <i>et al.</i> 2024) |
| Spent batteries                              | Zn-C | Na <sub>2</sub> Zn-EDTA + Na <sub>2</sub> Mn-EDTA (AB2: 2 g/L)                                 | Not specified (pot) | Soil application                                      | Plant height ↑42.8%; Zn uptake ↑321%; Mn uptake ↑98%; no toxic metals detected                                       | (Yudha <i>et al.</i> 2025)             |
| Spent (NMC cathode)                          | LIB  | AN: microelement fertilizer granules PMA N-                                                    | General crops       | Granular soil incorporation                           | pH correction; microelement (Li, Co, Mn, Ni) slow-release;                                                           | (Fazilova <i>et al.</i> 2023)          |

Note: LFP = LiFePO<sub>4</sub>; LIB = Lithium-Ion Battery; NMC = Nickel Manganese Cobalt; PMA = Polymetallic Ash; AN = Ammonium Nitrate; EDTA = Ethylenediaminetetraacetic Acid; P-SRF = Phosphorus Slow-Release Fertilizer; CIT = Citrate; GLY = Glycinate; BMLS = Black Mass Lignosulfonate; LCA = Life Cycle Assessment. Chelated sources like Mn-EDTA and Mn-DTPA perform much better when applied to high-pH soils, though they come at a significantly higher price than MnSO<sub>4</sub> (Barragán-Mantilla *et al.* 2024). The Zn-Mn-citrate complex formed from citric acid leaching of battery black mass presents a potential low-cost alternative to Mn-EDTA for soil application (Arshadi & Mousavi, 2015). The citrate chelation stabilizes Mn<sup>2+</sup> against oxidation during the critical period right after application when roots are absorbing it (Bosecker, 1997). For copper, the standard treatment for Cu deficiency involves applying CuSO<sub>4</sub> at 5 to 10 kg Cu ha<sup>-1</sup> (Tanda *et al.* 2017). The effects can last several years due to strong copper absorption to soil organic matter and oxides (Oraby & Eksteen, 2014). Agronomic assessments of e-waste-derived Cu from PCB leachates have not yet been published. A crucial part of assessing the agronomic effectiveness of e-waste-derived fertilizers is the potential presence of trace amounts of heavy metals especially Pb, Cd, and As that may be extracted during leaching, even from modern battery black mass that appears to lack these elements (Abdullah *et al.* 2024; Engwa *et al.* 2019; Klein, 2006). EPBA data suggest that alkaline batteries made after 2006 contain less than 5 ppm Hg and less than 10 ppm Cd (Ilankoon *et al.* 2018; Puttonen *et al.* 2025). However, the broader range of e-waste includes devices made before these regulations. Thus, any fertilizer product must be tested for contaminant metals and evaluated against the limits set by EU Regulation 2019/1009 (e.g., Cd < 1.5 mg kg<sup>-1</sup> of the fertilizer product, Pb < 120 mg kg<sup>-1</sup>) and equivalent national standards (Shukla *et al.* 2022; Xavier *et al.* 2021; Yuan). Purification steps, such as selective precipitation, ion exchange, or solvent extraction, may be necessary to meet contaminant level requirements before a battery black mass leachate can be registered as a fertilizer.

#### Environmental safety and toxicological considerations

Turning electronic waste into nutrients for plants presents a significant challenge. E-waste contains essential macro and micronutrients, but it also has harmful heavy metals, organic pollutants, and toxic compounds (Robinson, 2009). This section looks at major contamination risks, effective detoxification methods, and the regulations that oversee the safe use of recovered nutrients in agriculture.

#### Heavy metal contamination risks

Printed circuit boards (PCBs), cathode ray tubes (CRTs), and semiconductor packages have high levels of toxic metals that can be released during leaching, smelting, and hydrometallurgical recovery processes (Bolan *et al.* 2014). The main contaminants of concern include cadmium (Cd), lead (Pb), arsenic (As), mercury (Hg), hexavalent chromium (Cr<sup>6+</sup>), nickel (Ni), and antimony (Sb) (Ahmad *et al.* 2014). When these elements exist in fertilizer at levels above regulatory limits, they can harm soil microbes, plant health, food safety, and human health through ingestion (Nagajyoti *et al.* 2010). Cadmium is especially concerning because cereal crops and leafy vegetables easily absorb it. It accumulates in human kidneys, liver, and bones (Authority, 2012). Long-term exposure to Cd-contaminated food can lead to Itai-Itai disease, kidney dysfunction, and osteoporosis (Ghimire &

Ariya, 2020). Lead is less available to plants than Cd but poses serious neurological risks to children and can remain in soil for decades. Reports show e-waste leachates from informal smelting sites in Guiyu, China, and Agbogbloshie, Ghana, contain Cd levels above 50 mg/kg and Pb levels reaching 2,000 mg/kg in surface soils, significantly exceeding safe limits (Robinson, 2009). Mercury can become volatile at the high temperatures during pyrometallurgical processes, posing inhalation risks to workers and contributing to air pollution. Hexavalent chromium, which comes from etching and plating circuit boards, is a known carcinogen classified as Group 1 by the International Agency for Research on Cancer (Toda *et al.* 2020). Arsenic from gallium arsenide (GaAs) chips dissolves easily under acidic conditions and can disrupt phosphate uptake in plants, mimicking orthophosphate and entering root channels (Kiddee *et al.* 2013; Meharg & Hartley-Whitaker, 2002). The form of these metals, whether as free ions, oxide complexes, organic chelates, or co-precipitated phases, affects their bioavailability, movement, and ecological impact. Risk quotient (RQ) calculations, which compare environmental concentrations to predicted no-effect concentrations (PNECs), offer a quantitative way to assess safety (Awasthi *et al.* 2018). The permissible limits of major heavy metals under Indian, EU, US, and WHO/FAO standards are compared in Table 3.

**Table 3** Comparison of heavy metal limits under Indian, EU, US, and WHO/FAO standards

| Metal         | India FCO  | EU Reg. 2019/1009                           | US EPA (40 CFR 503) | WHO/FAO Guideline           |
|---------------|------------|---------------------------------------------|---------------------|-----------------------------|
| Cadmium (Cd)  | 5          | 1.5 (per kg P <sub>2</sub> O <sub>5</sub> ) | 85 / 39             | 0.04 mg/kg food (MRL)       |
| Lead (Pb)     | 100        | 120                                         | 840 / 300           | 0.025 mg/kg bw/week (PTWI)  |
| Arsenic (As)  | 10         | 40                                          | 41 / 41             | 0.3 mg/kg (inorganic As)    |
| Mercury (Hg)  | 0.2        | 1                                           | 57 / 17             | Minamata: near-zero targets |
| Chromium (Cr) | 50 (total) | 2 (Cr VI)                                   | Not specified       | IARC Group 1 (Cr VI)        |
| Nickel (Ni)   | 50         | 100                                         | 420 / 420           | 0.02 mg/L water (WHO)       |

Source: (Aayog, 2019; Abdullah *et al.* 2024; Authority, 2012; Engwa *et al.* 2019; Mikula *et al.* 2020)

#### Detoxification and Purification Strategies

Detoxification of nutrient-rich e-waste leachates requires multi-step purification processes to remove toxic heavy metals while preserving essential nutrients such as phosphorus, potassium, zinc, and copper for agricultural use (Shin *et al.* 2019). Three major purification approaches are selective precipitation, ion exchange, and adsorption which have been widely studied for producing safe nutrient streams (Gunatilake, 2015; Palaniandy *et al.* 2022). Selective precipitation removes contaminants based on differences in metal solubility under controlled pH conditions. A staged pH cascade enables sequential removal of Fe, Al, Cu, Pb, Cd, and As while retaining nutrients in solution, with reported removal efficiencies of 95–99% (Ilankoon *et al.* 2018; Jiang *et al.* 2024). Ion exchange employs selective cation and anion exchange resins to capture toxic metal ions based on charge and affinity. Chelating resins such as IDA-functionalized materials effectively remove Pb and Cd, while anion exchange resins selectively remove As and Cr, achieving removal efficiencies of >96–98% (Barragán-Mantilla *et al.* 2024; Sharma & Bhattacharya, 2017; Yudha *et al.* 2025). Adsorption methods use high-surface-area materials such as activated carbon, biochar, hydroxyapatite, and nanocomposites to remove heavy metals from dilute leachates. These systems are cost-effective and achieve 85–95% removal efficiencies, with magnetic composites improving post-treatment recovery (Ahmad *et al.* 2014; Mohan & Pittman Jr, 2006; Yankovych *et al.* 2021). Together, these detoxification strategies generate safe nutrient-rich streams suitable for agricultural applications by removing contaminants while preserving valuable nutrients. Multi-step purification strategies used to remove heavy metal contaminants from e-waste leachates are illustrated in Figure 8.

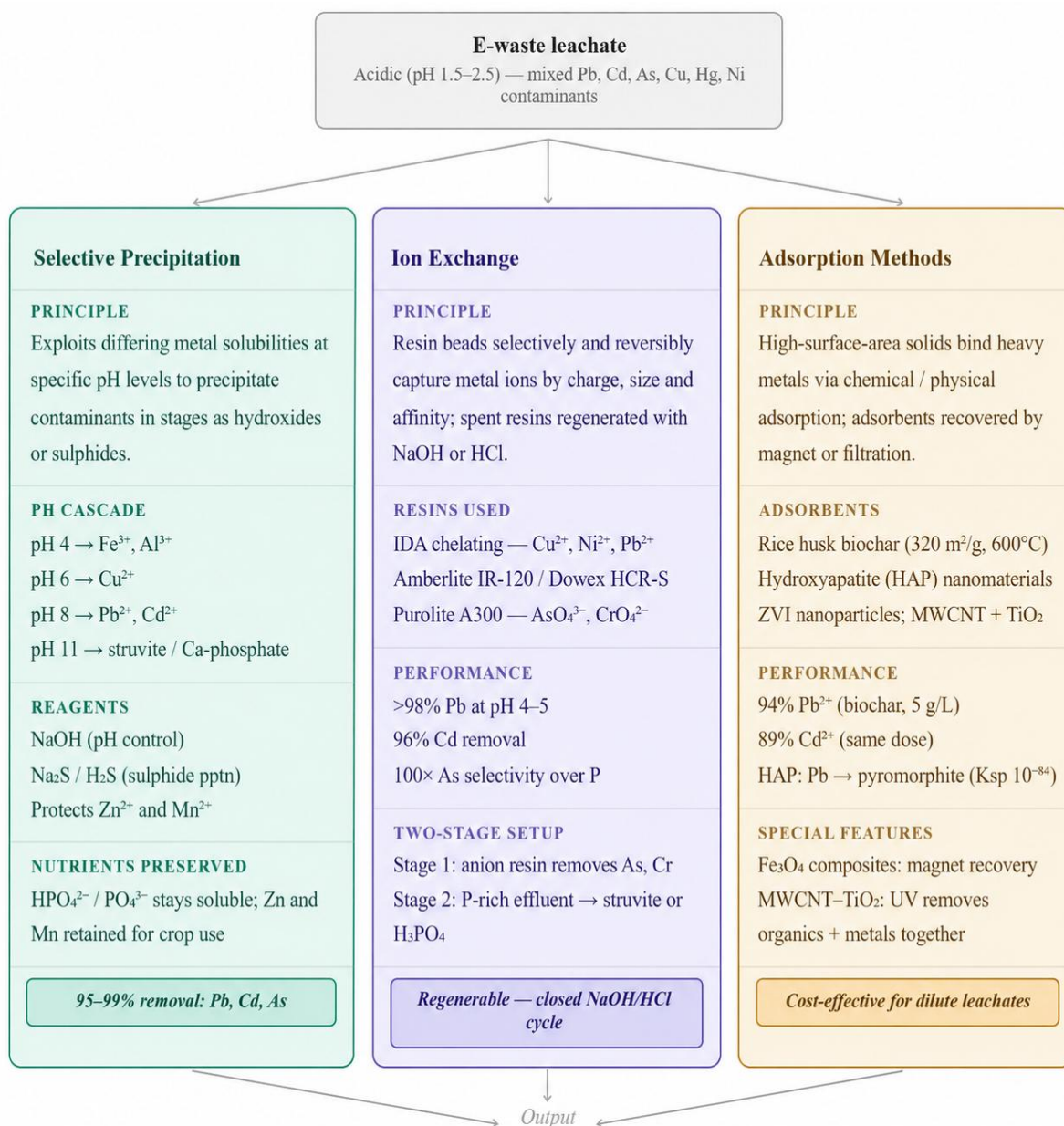


**Fig. 8** multi-step purification processes for removing heavy metal contaminants from e-waste leachates

## Regulatory standards and quality control

### Fertilizer control order standards

In India, the Fertilizer Control Order (FCO) of 1985, amended by the Fertilizer (Inorganic, Organic or Mixed) Control Order 1985 and a 2017 amendment, forms the main legislative framework for regulating quality, labelling, and allowable contaminant levels in fertilizers sold in the market (Shukla *et al.* 2022). The FCO sets maximum permissible levels for heavy metals in city compost, vermicompost, and organic fertilizers from waste. For cadmium, the permitted level is 5 mg/kg dry weight; for lead, 100 mg/kg; and for arsenic, 10 mg/kg. Chromium's limit is set at 50 mg/kg (Pathak *et al.* 2021; Shukla *et al.* 2023). The FCO requires mandatory certification from Regional Fertilizer Control Laboratories (RFCLs) before any commercial distribution (Mikula *et al.* 2020). For new fertilizer types from e-waste, the FCO review process requires submitting complete information, including toxicological data, crop effectiveness studies, and long-term soil effects assessments (Ghimire & Ariya, 2020). Compliance with the FCO is enforced through random market sampling, with penalties for non-compliance that include product seizures, cancelled registrations, and criminal charges under Section 3(2) of the Essential Commodities Act, 1955 (Commission, 2016; Nagajyoti *et al.* 2010)

### International safety frameworks

On the international stage, the European Union's Regulation (EU) 2019/1009 on EU fertilizing products sets limits for contaminants to obtain a CE mark, setting cadmium levels at 1.5 mg/kg P<sub>2</sub>O<sub>5</sub> for phosphate-based products. This is much stricter than the limits in India (Bala & Nidhi, 2024; Baldé *et al.* 2017; Forti *et al.* 2020; Toda *et al.* 2020). The regulation includes rules for organo-mineral fertilizers from industrial waste and requires meeting heavy metal limits for all materials used (Standardization, 2006). The US EPA places Cd limits at 85 mg/kg and Pb limits at 840 mg/kg in biosolids used on agricultural land, with stricter thresholds of 39 mg/kg and 300 mg/kg

for 'exceptional quality' products (Widmer *et al.* 2005). The Food and Agriculture Organization (FAO) and the Codex Alimentarius Commission provide guidance on acceptable heavy metal residue limits in food crops. These indirectly affect fertilizer standards through food safety requirements (Authority, 2012). The Stockholm Convention on Persistent Organic Pollutants (POPs) and the Minamata Convention on Mercury add restrictions on mercury-containing waste, requiring countries to reduce mercury use and release in manufacturing processes, including those linked to e-waste (Commission, 2016).

### **Life-cycle assessment (LCA)**

LCA provides a systematic framework to evaluate the environmental impacts and sustainability benefits of fertilizer production systems from raw material extraction to final application (ISO, 2006a; ISO, 2006b) (Hauschild *et al.* 2018; Nuss & Eckelman, 2014). In the context of e-waste-derived fertilizers, LCA helps quantify the trade-offs between the environmental advantages of diverting electronic waste from landfills and the impacts associated with chemical processing, energy consumption, and possible pollutant release during nutrient recovery (Hauschild *et al.* 2018; Tran *et al.* 2018). By applying ISO 14040/14044-compliant LCA frameworks, researchers can compare e-waste nutrient recovery systems with conventional mineral fertilizer production to assess their overall environmental sustainability (Blasi *et al.* 2023).

### **Carbon footprint**

Carbon footprint comparison indicates that conventional fertilizer production is highly energy-intensive and contributes significantly to greenhouse gas emissions. Processes such as Haber–Bosch ammonia synthesis, phosphate rock mining, and potash extraction require substantial fossil energy inputs and generate large amounts of CO<sub>2</sub> emissions (Cordell *et al.* 2009). In contrast, hydrometallurgical recovery of phosphorus, potassium, and micronutrients from e-waste leachates avoids energy-intensive mining and refining stages, resulting in substantially lower global warming potential (Sadeghi *et al.* 2020; Yudha *et al.* 2025). Studies have reported that e-waste-derived nutrient recovery systems can reduce carbon emissions by 40–70% compared with conventional phosphate fertilizer production, particularly when hydrometallurgical and bioleaching routes are employed (Yue *et al.* 2021). However, pyrometallurgical methods involving high-temperature smelting may increase energy demand and carbon emissions, emphasizing the need for careful process selection (Ilankoon *et al.* 2018).

### **Avoided mining impacts**

Avoiding mining is another important environmental benefit of nutrient recovery from e-waste. Conventional phosphate rock mining causes habitat destruction, land degradation, soil erosion, acid mine drainage, and depletion of non-renewable mineral resources (Cordell *et al.* 2009). Recovering nutrients from e-waste helps reduce dependence on virgin phosphate reserves while also lowering land transformation and resource depletion impacts (Tesfaye *et al.* 2017). Although e-waste contributes a relatively small share of global phosphorus demand, the combined recovery of phosphorus, potassium, zinc, and copper can significantly reduce pressure on natural mineral reserves and improve resource circularity (Xavier *et al.* 2021).

### **Challenges and constraints**

#### **Feedstock variability**

The varied composition of e-waste feedstocks is a major challenge for achieving consistent nutrient quality. Unlike mineral ores, which have stable geochemical compositions that change slowly over time, e-waste reflects the fast-changing nature of electronics design, material innovation, and consumer preferences (Commission, 2016; Robinson, 2009). The shift from tin-lead solders to RoHS-compliant silver-copper-tin alloys, the replacement of traditional FR4 glass-epoxy laminates with halogen-free materials, and the growing use of advanced semiconductor materials like gallium nitride (GaN) and silicon carbide (SiC) continually change the elemental makeup of incoming e-waste (Widmer *et al.* 2005). Compositional differences across device types are significant. Consumer PCBs from smartphones contain 150–400 g/ton of gold and 1–4% copper by weight, while industrial server boards have 250–600 g/t gold and 8–12% copper. CRT televisions have 1.5–3 kg of lead in the funnel glass, and LCD panels may contain mercury from fluorescent backlights or indium in ITO coatings (Wang *et al.* 2020; Yue *et al.* 2021). This variability affects nutrient recovery processes, leading to changes in leaching rates, precipitation conditions, and final product composition, which complicate compliance with fixed regulatory nutrient content standards (Tesfaye *et al.* 2017).

#### **Technological scalability**

Many promising nutrient recovery technologies, such as electrodeposition, nanomaterial-based adsorption, membrane bioreactors, and selective bioleaching, have mostly been tested at laboratory scales (100 g to 10 kg batch sizes) or small pilot operations (10–100 kg/day throughput) (Maia *et al.* 2022). Scaling these processes to commercially relevant volumes ( $\geq 50$  tonnes/day) presents issues like mass-transfer limitations, equipment fouling, reagent cost, and process control challenges that do not appear at the lab scale (Biswas & Rai, 2024; Migov, 2017).

#### **Infrastructure and logistics**

The geographic spread of e-waste, primarily generated in Indian cities like Delhi NCR, Mumbai, Bengaluru, and Chennai, contrasts with the largely rural area of fertilizer consumption (Jasinski, 2021; Kumar *et al.* 2024; Pinstrup-Andersen & Pandya-Lorch, 1998). This creates logistical challenges for the circuit-to-soil transition. Collection, sorting, and primary processing systems are mainly found in informal urban recycling sectors (Dharavi, Mumbai; Seelamadugu, Hyderabad) that often lack the environmental controls, worker safety measures, and quality management required for safe nutrient recovery (Aayog, 2019).

### Farmer acceptance and risk perception

Even technically superior and cost-competitive products struggle to gain acceptance due to farmer reluctance, lack of information, and distrust regarding new input sources. Surveys in Indian farming communities consistently show that 'source familiarity' and 'government endorsement' are the two strongest factors influencing fertilizer adoption, while 'price' ranks third. The origin of novel technology often negatively impacts willingness to adopt (Shukla *et al.* 2022; Shukla *et al.* 2023; Singh & Sapkota, 2025). Fertilizers from e-waste face an inherent perception challenge, as the stigma of toxic waste is difficult to separate from the recovered nutrient product in the eyes of consumers, even when safety is ensured through rigorous certification. The major scaling challenges associated with converting e-waste into fertilizer products are summarized in Figure 9.

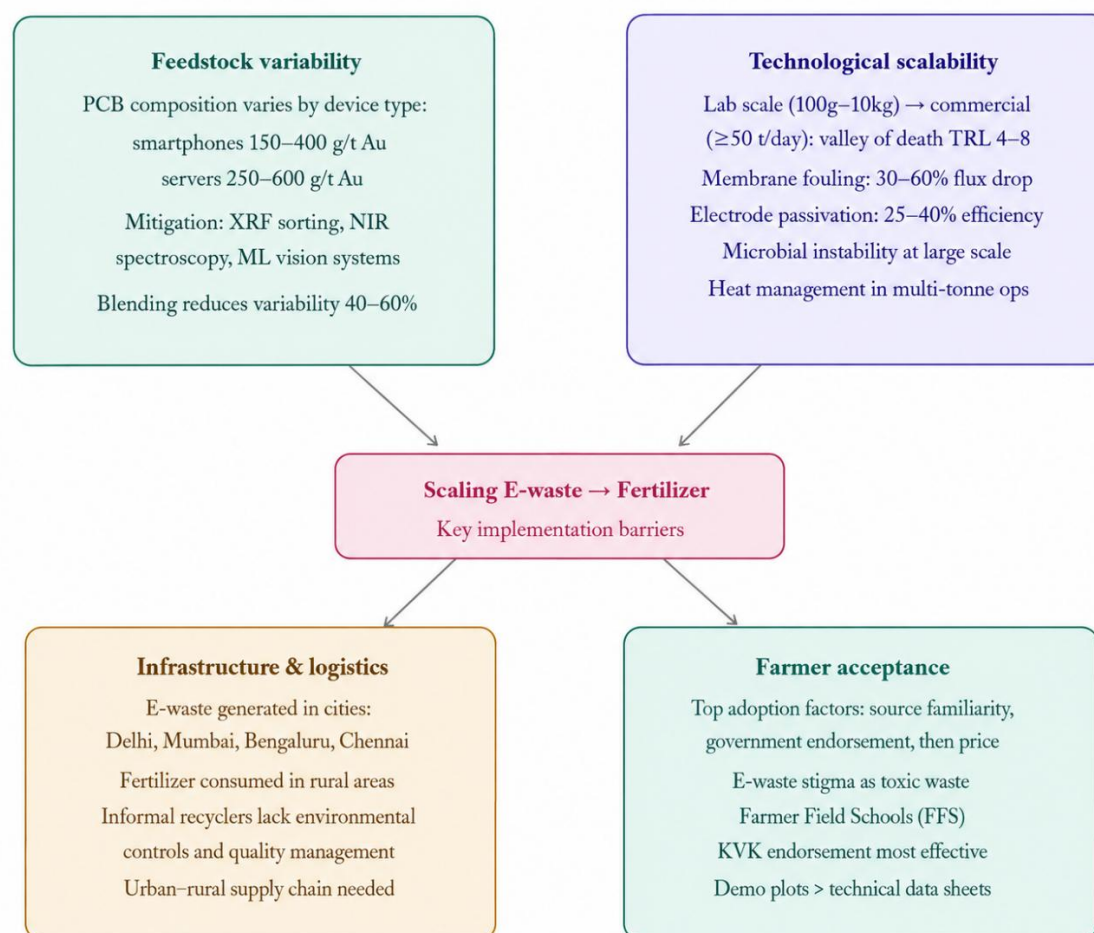


**Fig. 9** Scaling challenges in e-waste-to-fertilizer systems

### Future research frontiers

Emerging technologies such as artificial intelligence (AI), synthetic biology, precision agriculture, and smart urban infrastructure offer transformative opportunities to improve the feasibility, safety, and scalability of e-waste-to-fertilizer systems (Kumar *et al.* 2024; Yuan; Yue *et al.* 2021). These innovations move beyond conventional recovery processes by integrating digital intelligence, biological engineering, and circular nutrient management to support sustainable fertilizer production.

#### Ai-driven metal recovery

Artificial intelligence and machine learning can enhance e-waste nutrient recovery through real-time process optimization, predictive maintenance, and autonomous control systems. Computer vision and CNN-based algorithms can classify e-waste streams by material composition and contamination level, improving feedstock sorting and routing efficiency for optimized metal recovery (Abdullah *et al.* 2024; Avellan *et al.* 2021; Nagajyoti *et al.* 2010).

#### Synthetic biology for bioleaching

Synthetic biology enables the engineering of microorganisms with improved metal-mobilizing capacity, selective metal recovery, and resistance to harsh leaching conditions. Tools such as CRISPR-Cas9, metabolic engineering, and directed evolution can enhance siderophore production, acid tolerance, and heavy metal resistance, improving bioleaching efficiency in e-waste processing (Bosecker, 1997; Sethurajan *et al.* 2019).

#### Soil microbiome engineering

Soil microbiome engineering is emerging as an important strategy to ensure the safe use of e-waste-derived fertilizers in agricultural systems. By manipulating beneficial microbial communities through inoculants and

habitat engineering, nutrient availability, soil health, and resilience against trace metal stress can be improved while maintaining essential soil ecosystem functions (Gul *et al.* 2021; Mendes *et al.* 2011).

### Smart circular cities and nutrient tracking

Smart city technologies such as IoT sensors, RFID-enabled waste tracking, and blockchain-based traceability systems can support real-time monitoring of nutrient flows from urban waste streams to agricultural applications. These tools improve transparency, material tracking, and efficiency in developing closed-loop circular nutrient economies (Sobianowska-Turek *et al.* 2016; Tran *et al.* 2018; Xavier *et al.* 2021)

### Integration with climate-smart agriculture

Integrating e-waste-derived fertilizers with climate-smart agriculture (CSA) can improve crop productivity, enhance climate resilience, and reduce greenhouse gas emissions. Recovered micronutrients such as Zn, Mo, and Cu play important roles in drought tolerance, biological nitrogen fixation, and structural crop resilience, supporting sustainable agricultural adaptation to climate change (Food & Nations, 2010; Singh & Sapkota, 2025; Singh, 2009). Merging technologies supporting a transformative circular nutrient economy are illustrated in Figure 10.

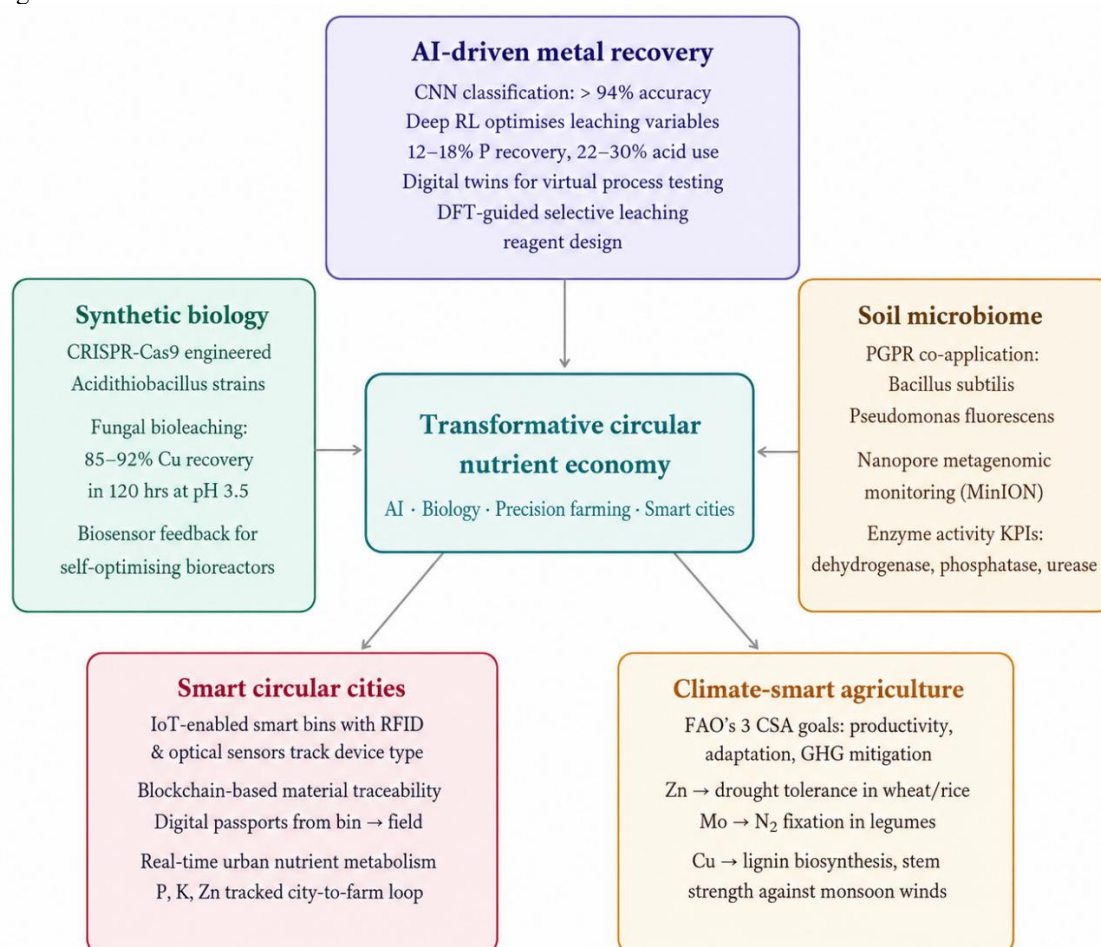


**Fig. 10** Transformative circular nutrient economy for sustainable agriculture

## CONCLUSION

The circuit-to-soil paradigm offers a scientifically grounded and ecologically compelling response to two concurrent global challenges the exponential accumulation of electronic waste and the pervasive depletion of micronutrients in agricultural soils. This review has established that spent batteries and printed circuit boards constitute a concentrated secondary mineral resource, from which zinc, manganese, copper, and iron can be efficiently recovered through hydrometallurgy, bioleaching, and green leaching systems, and subsequently reformulated into agronomically effective sulphate, chelated, and nano-enabled fertilizer products. Agronomic evidence confirms that these e-waste-derived inputs support crop growth and nutrient uptake comparable to conventional commercial fertilizers, while life cycle assessments affirm their considerably lower carbon and resource footprint relative to primary mineral production. However, translating laboratory promise into field-scale impact requires overcoming critical barriers feedstock heterogeneity, contaminant purification, technological scalability, regulatory harmonization between national and international frameworks, and farmer acceptance rooted in perception and trust. Emerging tools including AI-driven process optimization, engineered bioleaching microorganisms, and smart urban material tracking systems offer credible pathways to address these constraints. Ultimately, realizing the full potential of e-waste as a micronutrient resource demands coordinated investment

across science, policy, industry, and agricultural extension. The discarded electronics of today hold the nutrients that degraded soils urgently need closing this loop is both an environmental necessity and a food security opportunity that sustainable development can no longer afford to overlook.

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### Author contributions

Delux sachin V: Conceptualization, literature review, manuscript drafting; Vaiyapuri K: Literature review, writing – review and editing, Data compilation, visualization, and literature organization; M Raju, A Kamalakannan, M Kathiravan, and Gourav Sabharwal: Conceptual design, supervision, and final manuscript revision. All authors have read and approved the final version of the manuscript.

### Data Availability Statement

No new data were generated or analysed in this study. Data sharing is not applicable to this article.

### Competing Interests

The authors declare that they have no competing interests.

### Ethical Approval

Not applicable, as this article is a review based on published literature and did not involve human participants, animals, or clinical studies.

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