

The Growing Challenge of Electronic Waste Management and Sustainable Solutions

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Abstract: The rapid advancement of technology and increasing demand for electronic products have led to a surge in electronic waste (e-waste) generation. Over the next five years, global e-waste production is expected to reach 44.4 million metric tons, with the electronics recycling market projected to grow to \$65.8 billion by 2026. However, e-waste management remains inadequate in many developing countries, where only 17.4% is properly collected and recycled. Poor waste treatment poses serious environmental and health risks while depleting valuable natural resources. E-waste contains numerous recoverable materials, including metals and rare earth elements, which can be repurposed for renewable energy technologies. Efficient recycling can reduce reliance on non-renewable resources and minimize environmental damage. However, many regions lack structured recycling programs, leading to hazardous informal practices such as open burning and acid leaching. Corporate social responsibility (CSR) initiatives have played a role in integrating informal recycling sectors into formal management systems. Additionally, proper e-waste management significantly reduces greenhouse gas emissions. The CO₂ reductions achieved through recycling can be monetized via carbon trading, creating economic incentives for sustainable waste management. This paper provides an overview of e-waste classification, recycling techniques, and the use of high-recycled value-added (HAV) materials in green energy technologies. Implementing effective recycling methods and structured waste management systems is crucial for environmental sustainability and the transition to a circular economy.

Keywords Sustainability: E-waste, Global market, Recycling, Metal recovery, Supercapacitor, Hydrometallurgy, Energy conversion, Green hydrogen, Energy storage.

1. INTRODUCTION

The electronics and telecommunications industry has seen rapid advancements over the past two decades, significantly impacting transportation, healthcare, security, and communications (Khetriwal et al., 2009).

Despite their importance, electronic devices often have short life cycles and are discarded rather than reused, contributing to a growing electronic waste (e-waste) crisis. Proper e-waste management is crucial for fostering a circular economy and ensuring sustainability. Since electronic devices consist of diverse materials, specialized recycling approaches are necessary to recover valuable resources. Global e-waste generation is expanding by approximately 2 million metric tons (Mt) annually, with projections indicating it could reach 74.7 Mt by 2030 due to economic growth and rapid technological advancements (Nithya et al., 2021; Kaliyavaradhan et al., 2022).

E-waste is one of the fastest-growing waste streams globally and poses significant environmental risks (Chung et al., 2011). Improper disposal methods, such as landfilling, manual sorting, and open burning, release hazardous substances, including lead, nickel, mercury, cobalt, cadmium, and brominated flame retardants, which can contaminate soil and water (Gurgul et al., 2018; Mohammadi et al., 2021). However, e-waste also contains valuable metals such as gold, silver, copper, and palladium, making it a promising secondary resource for material recovery at relatively low operating costs (Kumar et al., 2017a).

Another pressing issue is energy consumption, as fossil fuels remain the dominant energy source. In 2020, fossil fuels accounted for 79% of total US primary energy production (US EPA, 2017). If current consumption trends continue, petroleum and natural gas reserves could be exhausted within 35–70 years (US EPA, 2017). Additionally, fossil fuel combustion is a major contributor to greenhouse gas (GHG) emissions, accounting for over 70% of global carbon dioxide (CO₂) emissions (IRENA, 2018). To combat climate change, the Paris Agreement aims to limit global temperature increases to below 2°C, with an aspirational target of 1.5°C above pre-industrial levels.

Addressing e-waste through sustainable recycling and metal recovery can reduce reliance on finite resources, mitigate environmental damage, and support cleaner energy transitions.

To meet future energy demands, the share of renewable energy in the global energy supply must rise from 12% to 65% by 2050 (Abbasi et al., 2020; Gao et al., 2017). The Green Climate Fund, established in 2010, supports developing nations in reducing GHG emissions, with developed countries pledging \$100 billion annually from 2020 to 2025 to aid climate adaptation (COP 26, 2021). However, transitioning to renewable energy remains a challenge due to economic and technological barriers.

Recycling e-waste provides a potential solution by recovering metals like copper, gold, and silver, which are essential for energy conversion and storage applications. These materials act as effective catalysts in key reactions such as the oxygen evolution reaction (OER) (Jothi et al., 2018), hydrogen evolution reaction (HER) (Sengeni et al., 2020), methanol oxidation reaction (MOR) (Li & Kanan, 2012), and carbon dioxide reduction reaction (CRR) (Hazra et al., 2019). Water-splitting technologies utilizing OER and HER can generate green hydrogen (H₂), an eco-friendly fuel with high energy density (Karthik et al., 2022). Corporate Social Responsibility (CSR) plays a vital role in sustainable e-waste management by encouraging businesses to adopt efficient collection and recycling initiatives (Abbas et al., 2019; Al Halbusi et al., 2022). Social media further aids awareness and stakeholder engagement, promoting responsible disposal practices (Yu et al., 2022). Additionally, effective e-waste management contributes to international carbon market mechanisms under Article 6 of the Paris Agreement, facilitating ambitious mitigation goals in the waste sector (Deng et al., 2022).

This review examines e-waste market dynamics, generation trends, material composition, and recycling opportunities, emphasizing its role in sustainable energy conversion and storage applications.

2. GLOBAL E-WASTE MANAGEMENT MARKET

The global electronics recycling market is expected to reach \$65.8 billion by 2026, growing at a compound annual growth rate (CAGR) of 12.7%. Among its key segments, metal recovery is projected to expand at a CAGR of 13.3%, reaching approximately \$53.6 billion. In 2021, the market was valued at \$7.5 billion, with significant regional variations in growth.

China's e-waste recycling industry is forecasted to reach \$15.3 billion by 2026, growing at a CAGR of 16.3%. Canada and Japan are also expected to experience growth, with projected rates of 9% and 8.9%, respectively. Germany's market is anticipated to expand at a CAGR of 12.5%, contributing to Europe's total projected market value of \$6.1 billion. Europe is expected to lead the global waste recycling sector due to its widespread adoption of sustainable waste management technologies across industries such as security, automotive, healthcare, retail, IT, and telecommunications.

The USA, Canada, Japan, China, and Europe will collectively drive a 12% CAGR in the global consumer electronics recycling segment, which was valued at \$14.5 billion in 2020 and is expected to reach \$35.4 billion by 2026. China remains one of the fastest-growing countries in this sector. Meanwhile, the Asia-Pacific region is projected to reach \$5.8 billion by 2026, and Latin America is set to grow at a CAGR of 16.2% (Global Electronics Recycling Industry, 2022). These projections highlight the growing global emphasis on e-waste recycling and resource recovery.

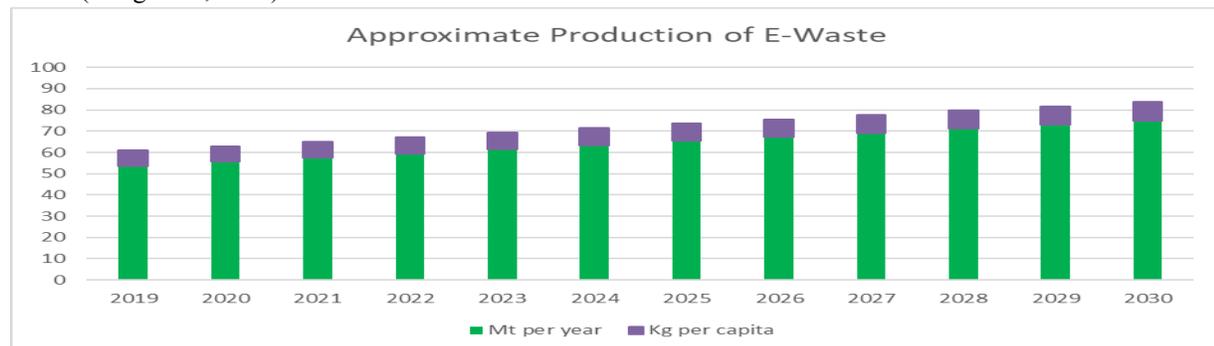


Fig. 1: Projection of e-waste generation (Forti et al., 2020)

3. GLOBAL E-WASTE GENERATION

Each year, approximately 40 million metric tons (Mt) of electronic waste are produced globally, making up around 5% of total solid waste (Kumar et al., 2017a, 2017b). The European Union alone generates about 9 million tons of e-waste from electronic devices such as phones, televisions, and computers. According to the

United Nations Environment Program (UNEP), waste from mobile phones is expected to increase 18 times, while computer-related e-waste is projected to grow fivefold, and television waste is expected to double by 2020. In 2019, global e-waste reached approximately 53.6 million tons, but only 17.4% of it was properly recycled (Forti et al., 2020).

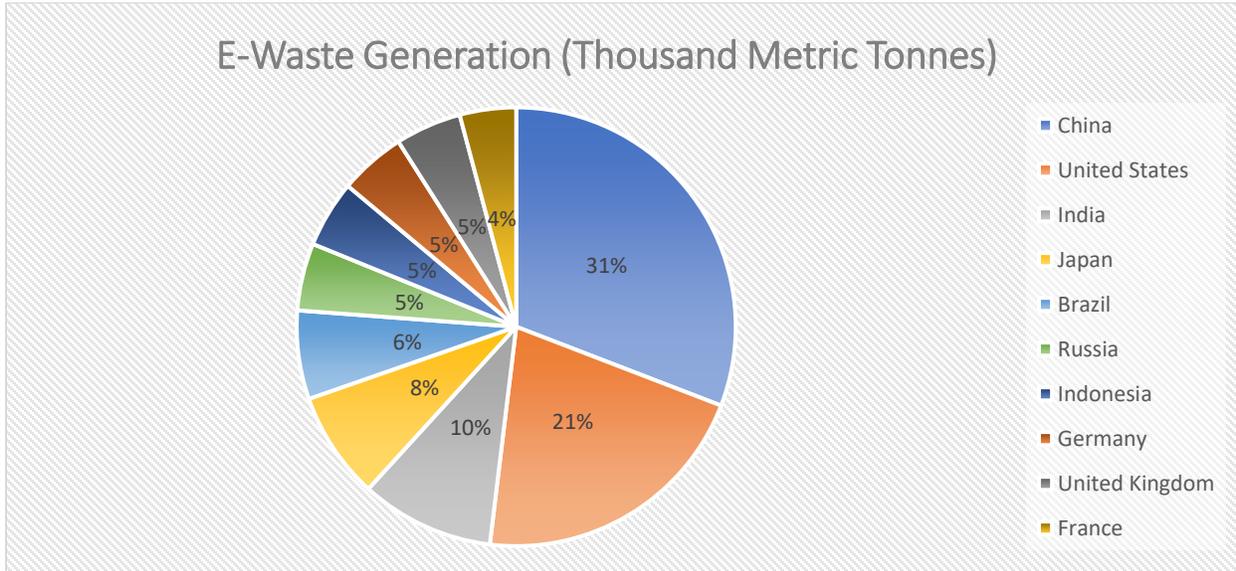


Fig.2: Leading nations in terms of global electronic trash production in 2019

3.1 Categories of Electronic Waste

E-waste encompasses all outdated or non-functional electronic devices. The Waste Electrical and Electronic Equipment (WEEE) Directives 2012/19/EU and 2002/96/EC classify e-waste into ten categories, including:

- Information technology and telecommunications equipment
- Large and small household appliances
- Consumer electronics
- Non-industrial electrical and electronic tools
- Lighting equipment
- Toys and leisure equipment
- Medical devices (excluding infected ones)
- Monitoring and control instruments
- Automated dispensers

The composition of e-waste varies, with approximately 42% consisting of home appliances, 34% communication devices, 14% electronic equipment, and 10% accessories (Forti et al., 2020).

3.2 Composition of Electronic Waste

The composition of e-waste depends on factors such as the manufacturer, model, type of device, production year, and overall lifespan. Information technology and communication systems contain a higher proportion of valuable metals compared to household appliances (Chancerel et al., 2009). A single mobile phone consists of over 40 different elements, including precious metals like gold (Au), silver (Ag), and palladium (Pd), along with base metals such as tin (Sn) and copper (Cu) (Liu et al., 2009).

Printed circuit boards (PCBs) found in electronic devices contain valuable recoverable materials like gold and copper but also hazardous substances such as lead. Due to the rapid advancements in technology and high consumer demand, electronic devices have a shorter lifespan, resulting in large quantities of e-

waste. Efficient recycling techniques that extract both metallic and non-metallic fractions in an environmentally responsible manner are essential for sustainable resource management. Additionally, factors such as recycling infrastructure, economic conditions, and waste segregation policies play a crucial role in shaping effective e-waste management strategies (Gautam et al., 2022).

4. ELECTRONIC WASTE MANAGEMENT SYSTEM

An efficient e-waste management system consists of three key stages: collection, pretreatment, and recovery (Islam & Huda, 2018). Recycling can be done through formal or informal methods, with informal recycling involving hazardous techniques like open burning and acid leaching to extract metals such as copper, aluminum, gold, and lead. These processes release toxic substances, including cyanide, nitric acid (HNO₃), hydrochloric acid (HCl), and sulfuric acid (H₂SO₄), posing serious environmental and health risks. A structured and regulated approach is essential to ensure safe recycling practices.

4.1 Proposed System for E-Waste Collection

Developing a proper e-waste collection system is crucial for sustainable waste management. A mobile-based application can streamline collection efforts by connecting users with designated drop-off points and recycling facilities. This system would categorize e-waste based on device type and disposal method.

The first category includes smart electronic devices such as laptops, mobile phones, and tablets, along with locations where users can sell or recycle them. The second category focuses on household appliances, distinguishing between large and small equipment. Large appliances, like refrigerators and washing machines, require scheduled pickup services, while smaller items can be dropped off at collection centers.

The third category caters to businesses, government institutions, and recycling agencies, providing details on bulk disposal, scheduled collection services, and auction events where recyclers can acquire valuable raw materials. The final category introduces a reward-based system, allowing consumers to earn points based on the recyclability of their devices. These points can

be redeemed for discounts, purchases, or monetary benefits through partnered stores.

By leveraging technology, this system can enhance e-waste collection, improve recycling efficiency, and minimize environmental hazards. A well-structured approach encourages responsible disposal practices and contributes to a more sustainable electronic waste management framework.

4.2 Recycling Processes of Different Types of E-Waste

In Egypt, twelve Waste Electrical and Electronic Equipment (WEEE) management firms have received environmental approval from the Egyptian Environmental Affairs Agency (EEAA) and operational permits from the Industrial Development Authority. These firms operate within the formal sector, with ten located in the Cairo governorate and two in Alexandria. Among them, four firms specialize in dismantling, while two conduct full-scale recycling, employing both mechanical and chemical processes. Firms focused on dismantling primarily collect, disassemble, and sort e-waste, reselling extracted components in the local market. Some materials that cannot be processed locally are exported to countries such as China, Korea, the USA, Belgium, and Italy for further refining. Specialized facilities in these countries carry out shredding, smelting, and chemical processing to recover valuable metals from exported e-waste (United Nations Development Programme, 2015).

Egypt faces significant challenges in e-waste recycling due to insufficient policies, inadequate legislation, and a lack of a centralized e-waste database. Hazardous disposal methods, including illegal incineration and dumping, contribute to severe environmental and health risks by releasing toxic pollutants such as furans, dioxins, and other harmful gases. Additionally, limited technical expertise and insufficient recycling infrastructure hinder progress in local e-waste management (Abdelbasir et al., 2018). Economic constraints also play a role, making local recycling more costly than exporting e-waste or metal concentrates. As a result, only 15–20% of Egypt's e-waste is recycled domestically, while the remainder is either exported, incinerated, or sent to landfills (United Nations Environment Programme, 2015).

To improve e-waste management, Egypt needs to enhance public awareness, develop a national e-waste database, and implement stricter regulations. Expanding technical expertise, investing in advanced recycling facilities, and adopting best environmental practices (BEP) and best available technologies (BAT) can help create a more efficient and sustainable e-waste management system (Abdelbasir et al., 2018).

Recycling of e-waste involves three significant steps (Atia et al., 2019): dismantling, upgrading, and refining. Dismantling is the primary process, focusing on identifying and separating valuable or hazardous components for specialized treatment. Upgrading involves the use of metallurgical and mechanical processing techniques to refine desirable materials in preparation for further treatment. Refining is the final step, where recovered materials are purified through

chemical and metallurgical processes to restore them for functional reuse. Disassembly and mechanical processing are commonly employed for pre-treatment to enhance the concentration of valuable materials. However, mechanical recycling alone is inefficient for recovering precious metals (Cui & Forssberg, 2003; Matsukami et al., 2015). To extract these metals, pyrometallurgical and hydrometallurgical techniques are applied, which involve melting or dissolving metals to remove impurities through chemical reactions (Cui & Forssberg, 2003). This review examines various recycling approaches, including methods for processing lithium-ion batteries, recovering precious metals from mobile phones, and extracting copper from computer-printed circuit boards, providing insights for future research in optimizing e-waste recycling techniques.

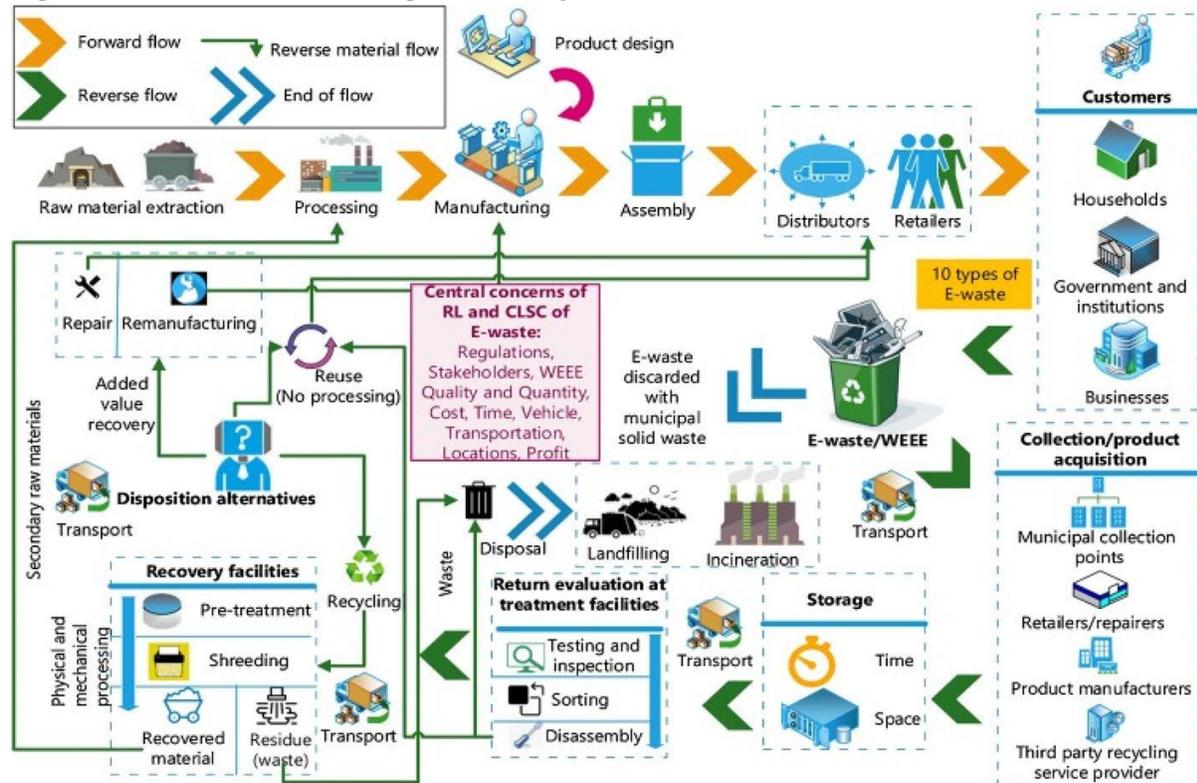


Fig.3: Closed Loop E-Waste Supply Chain (Islam & Huda, 2018) with Elsevier license

5 APPLICATION OF MATERIALS EXTRACTED FROM ELECTRONIC WASTE IN GREEN TECHNOLOGIES

The sustainable management of electronic waste (e-waste) remains a significant challenge for researchers. By 2030, global e-waste production is projected to

reach 74.4 million metric tons (Forti et al., 2020). Traditional disposal methods, such as landfilling, contribute to environmental issues, as landfill sites release substantial amounts of methane—a greenhouse gas that is 21 times more potent than carbon dioxide over a 100-year period (Pariatamby et al., 2015).

Landfilling alone accounts for approximately 14% of global methane emissions (Das et al., 2019). Furthermore, conventional disposal methods, including incineration and exporting e-waste, are becoming less viable due to stringent environmental regulations (Das et al., 2019). Given the increasing demand for raw materials and the challenges in accessing them, recovering valuable metals from e-waste presents an economically and environmentally sustainable alternative. Extracted metals can be repurposed for various applications, such as water-splitting catalysts used to produce hydrogen under specific conditions. Sustainable recycling not only addresses raw material shortages but also reduces energy consumption in raw material production while mitigating the environmental risks associated with hazardous waste from e-waste streams (Das et al., 2019). Since fossil fuel combustion accounted for 33.1 gigatons of CO₂ emissions in 2018 (Zedalis, 2017), transitioning to alternative clean energy sources is crucial for reducing global carbon emissions.

energy conversion and storage applications. By integrating these recovered metals into clean energy solutions, such as batteries, fuel cells, and renewable energy systems, e-waste recycling contributes to a more sustainable and circular economy. The following section explores how these recovered materials are utilized in energy-related technologies, highlighting their potential role in advancing sustainability and reducing reliance on conventional fossil fuels. Waste-to-Hydrogen focuses on producing hydrogen by recycling waste materials. Governments and industries are increasingly interested in hydrogen as a clean alternative to fossil fuels due to its zero greenhouse gas emissions when combusted (Lui et al., 2020). However, around 96% of hydrogen production still relies on fossil fuels, contributing 560 million tons of CO₂ emissions annually (Zedalis, 2017). To address this, renewable sources like wind and solar are being used for hydrogen production. Electrochemical water splitting, which generates hydrogen and oxygen using electricity, offers a sustainable solution for reducing carbon emissions.

Recycling e-waste supports the development of green technologies by repurposing extracted materials for

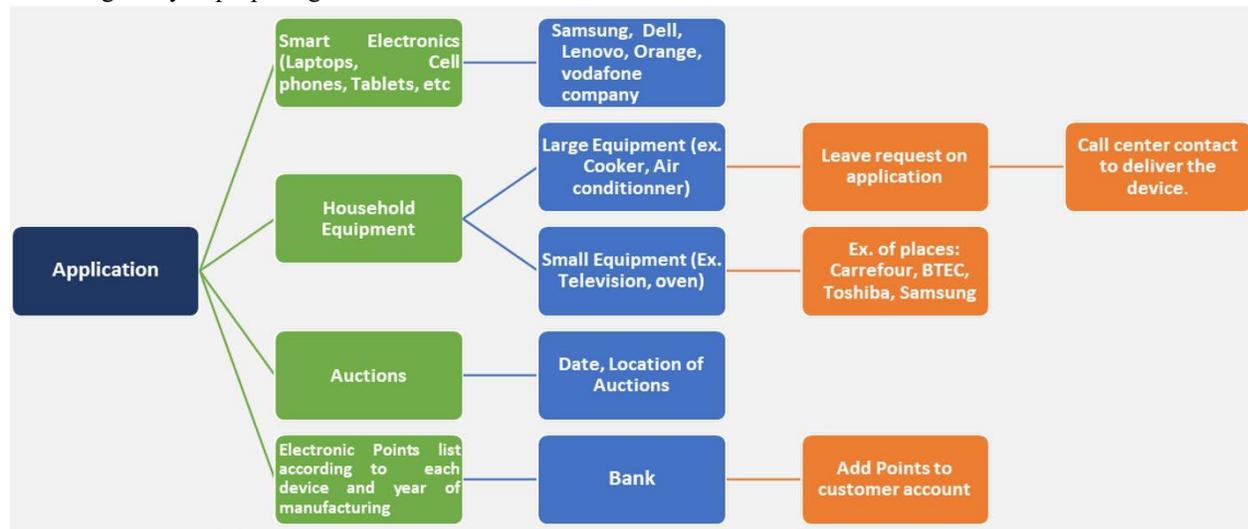


Fig. 4: Architectural application for e-waste collecting

5.1 Sustainable Hydrogen Production from E-Waste-Derived Materials

Water electrolysis is an efficient method for hydrogen production but requires an external power source, making it costly. Using renewable energy sources like solar, wind, and tidal power can reduce dependence on external electricity (Wang et al., 2019). Solar cells and

thermoelectric devices can convert sunlight into energy, while triboelectric nanogenerators (TENGs) harness wind and tidal energy to drive water splitting (Li et al., 2020).

Nickel (Ni), Copper (Cu), and Iron (Fe) recovered from e-waste exhibit excellent catalytic properties for hydrogen production (Karthik et al., 2022). Non-noble

metals like Ni and Molybdenum (Mo) offer hydrogen evolution activity similar to noble metals, making them sustainable alternatives. Recycled e-waste catalysts have shown promising performance with stable hydrogen evolution (Jothi et al., 2018). Many

essential elements in electronics, such as In, Ag, Zn, and Ga, face future supply risks, highlighting the importance of sustainable e-waste recycling for green hydrogen production (Karthik et al., 2022).

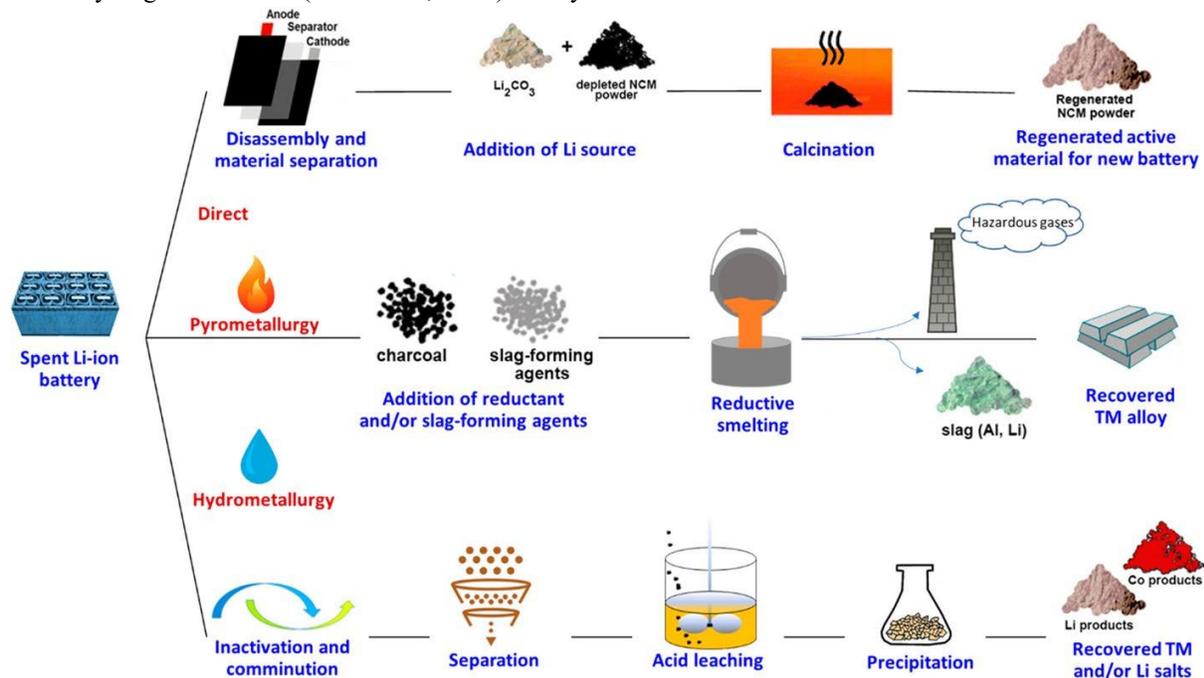


Fig.5: Typical techniques for recycling battery active materials include hydrometallurgical, pyrometallurgical, and direct recycling (Baum et al. 2022). Permission from the American Chemical Society.

5.2 Recovered Metals from E-Waste for Hydrogen Production and Energy Storage

Research has demonstrated that metals extracted from e-waste can serve as efficient catalysts for hydrogen production. Yi et al. (Jothi et al., 2018) utilized copper recovered from discarded electrical cables as a cost-effective current collector for water-splitting reactions. By electrodepositing a nickel–cobalt phosphide (NiCoP) catalyst onto scrap copper wire (SCW), they achieved superior electrocatalytic performance for both hydrogen and oxygen evolution reactions (HER and OER). The catalyst exhibited remarkable stability and efficiency in an alkaline medium, surpassing conventional catalysts such as $\text{IrO}_2/\text{RuO}_2$ and Pt.

Similarly, Slabon et al. (Lee et al., 2012) developed a cobalt-aluminum borate (AlBCoO_3^{2+}) electrocatalyst using materials recovered from waste lithium-ion battery cathodes. The catalyst, supported on graphene and copper tape, achieved a hydrogen production rate of $49.3 \text{ L(H}_2\text{) min}^{-1} \text{ g}^{-1} \text{ Co}$ at 70°C , with a high turnover number of 1.2×10^7 molecules per cobalt atom. The presence of carbon in the catalyst significantly enhanced its activity.

Beyond hydrogen production, recovered nanomaterials from e-waste play a crucial role in energy storage. With the growing demand for advanced nanotechnology, recycling these materials ensures a sustainable supply of raw materials while promoting efficient waste management (Klaine et al., 2012).

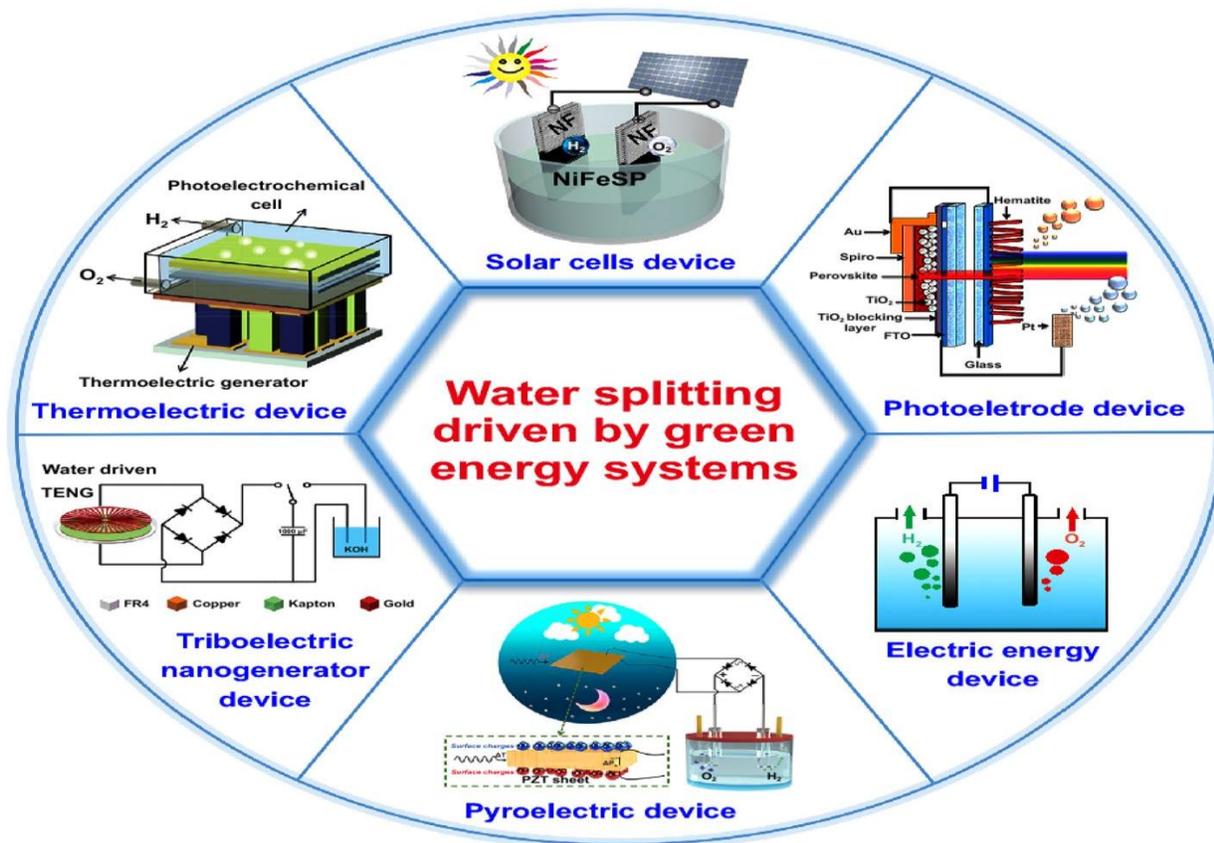


Fig. 6: Water splitting driven by different green energy systems (Li et al., 2020)

5.3 Utilization of Recovered E-Waste Materials for Energy Storage

The continuous advancement of nanotechnology necessitates a steady supply of raw materials, making the recovery of nanomaterials from e-waste essential for sustainable resource management (Klaine et al., 2012). Energy storage devices, such as supercapacitors and rechargeable batteries, depend on these materials, many of which are costly. For instance, the price of cobalt oxide rose from \$20/kg in 1998 to \$60/kg in 2017 (Freitas & Garcia, 2007).

Metal oxides play a crucial role in electrical energy storage due to their high capacitance properties. Ruthenium oxide, known for its high surface area and conductivity, was one of the earliest materials investigated, achieving a capacitance of 1340 F g⁻¹, close to its theoretical maximum of 1400 F g⁻¹ (Aboelazm et al., 2021; Hu et al., 2004). Various transition metal compounds, such as CuO, Co₃O₄, V₂O₅, MnO₂, MoS₂, Fe₃O₄, and NiO, have been studied for their supercapacitor applications (Atef et al., 2018; Nathan et al., 2008). Among these, Co₃O₄ and MnO₂

demonstrated significant theoretical capacitance values of 3560 F g⁻¹ and 1360 F g⁻¹, respectively, due to their multi-valence states (Gomaa et al., 2018). The ultra-layered Co₃O₄ catalyst further exhibited a capacitance of 548 F g⁻¹ (Sumanta et al., 2011).

Recovering nanomaterials from e-waste is an economically viable and environmentally sustainable alternative for producing catalysts used in energy storage applications. Manganese dioxide (MnO₂) has proven to be an effective pseudocapacitive material, offering a cost-efficient and less toxic substitute for ruthenium oxide. Although manganese is naturally abundant, recycling it from waste materials helps conserve natural resources and supports sustainable technology development. The United States Environmental Protection Agency (USEPA) reported that approximately 160,000 tons of batteries are discarded annually, with potential Mn recovery reaching up to 20,000 tons (María et al., 2013). Additionally, Mn recovered from waste batteries has been successfully used in supercapacitor electrodes (Sayilgan et al., 2009). Studies have demonstrated that

MnO₂ nanoflowers recovered from spent Zn–C batteries exhibit high electrochemical performance, with capacitance values reaching 309 F g⁻¹ and maintaining 93% stability over repeated cycles (Gomaa et al., 2014, 2017).

Cobalt oxide (Co₃O₄) has also been widely explored for supercapacitor electrode design due to its multiple oxidation states and high conductivity. Aboelazm et al. successfully recovered Co₃O₄ nanomaterials from discarded lithium-ion batteries using a magnetic field, achieving a capacitance of 1273 F g⁻¹ with 96% stability over multiple cycles (Eslam et al., 2018).

Furthermore, copper oxide nanoparticles have been recovered from spent circuit boards through acid leaching, filtration, and thermal drying, resulting in an electrocatalyst with a capacitance of 408 F g⁻¹ and 93.1% retention over 3000 charge-discharge cycles (Rajkumar et al., 2022).

These findings highlight the potential of e-waste recycling for nanomaterial recovery, offering a sustainable and cost-effective approach to improving energy storage technologies.

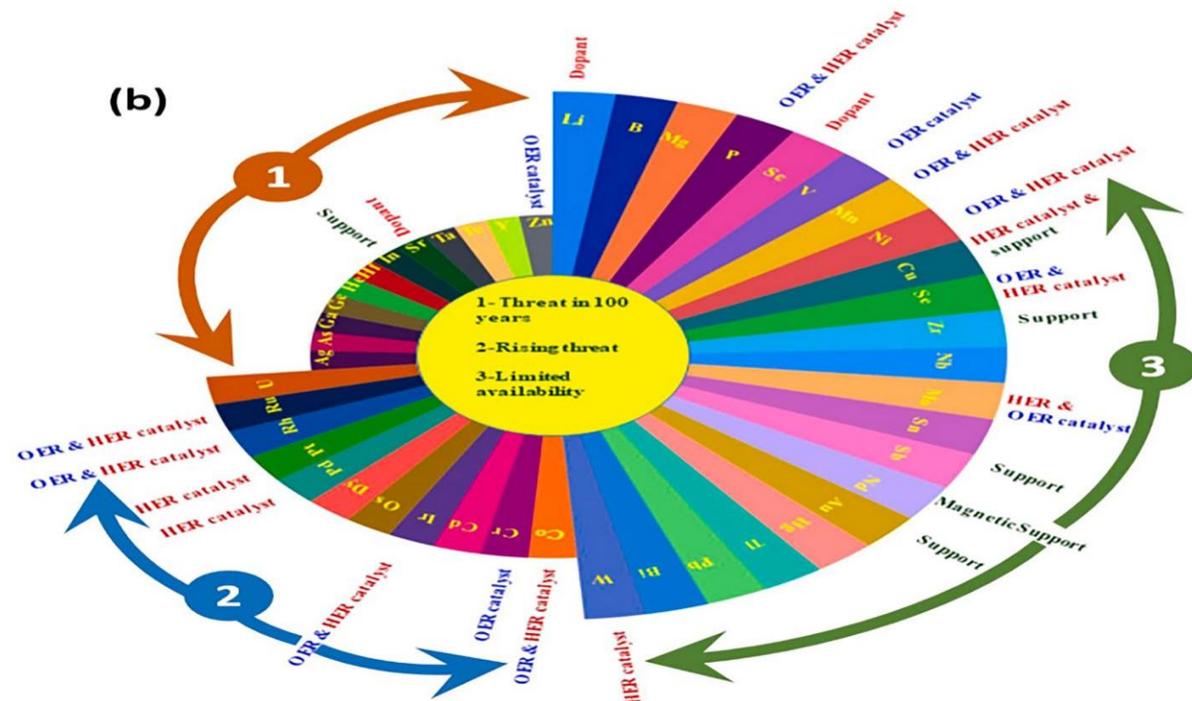
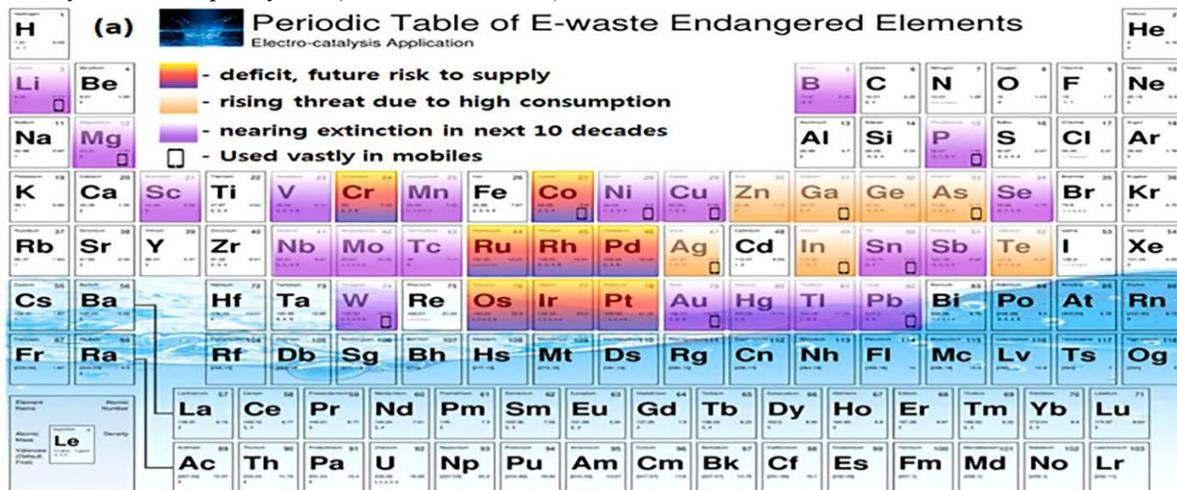


Fig. 7: shows the matching Aster plot illustrating the likely water splitting properties, as well as the larger IUPAC periodic table of elements (Karthik et al., 2022). Reproduced with Elsevier's consent.

5.4 E-Waste Recycling for Sustainable Development Goals

In the past two decades, sustainability has emerged as a key global priority. Landmark initiatives such as the Brundtland Commission’s report, the Kyoto Protocol, the Millennium Development Goals (MDGs) in 2000, and the Paris Climate Agreement in 2015 have underscored the necessity of adopting sustainable practices. As a result, businesses have started integrating sustainability into their operational strategies, addressing environmental concerns while also pursuing economic benefits. Companies are increasingly focusing on cost-efficient management, waste reduction, and responsible resource utilization to ensure long-term sustainability (Bhaskar, 2018). The United Nations established the 2030 Agenda for Sustainable Development, which includes 17 goals and 169 specific targets aimed at fostering global sustainability (Kumar et al., 2017b). Organizations worldwide are encouraged to align their business models with at least one of these sustainable development goals (SDGs). However, the broad scope of sustainability often presents challenges in implementation (Dao et al., 2011). The rising demand for electronic devices, coupled with their short lifespan and limited repair options, has led to increased e-waste generation. The COVID-19 pandemic further accelerated this trend due to the widespread shift to remote work and digital transformation (Rautela et al., 2021). Improper disposal of e-waste poses significant environmental and health risks, as it contains hazardous materials. At the same time, e-waste is a valuable source of recoverable metals such as iron, gold, and copper, offering opportunities for resource conservation and economic gain (Sharma et al., 2021).

In 2019, the global e-waste recycling industry was valued at approximately \$57 billion, highlighting the economic potential of efficient waste management (Forti et al., 2020). By maximizing material recovery, the electronics industry can transition towards a circular economy, reducing the reliance on primary raw materials and cutting greenhouse gas emissions (SDG 13). For example, improper disposal of air conditioners and refrigerators alone contributed 98 megatons of CO₂ emissions in 2019, accounting for nearly 0.3% of global emissions (Forti et al., 2020). E-waste management aligns with several SDGs. For instance, SDG 3 (Good Health and Well-being) addresses the health risks associated with exposure to toxic substances found in e-waste. SDG 6 (Clean Water and Sanitation) emphasizes reducing contamination of water sources by hazardous materials. SDG 8 (Decent Work and Economic Growth) supports entrepreneurship and innovation in the recycling sector. SDG 11 (Sustainable Cities and Communities) focuses on minimizing environmental impacts in urban areas, while SDG 12 (Responsible Consumption and Production) promotes waste prevention, reduction, and sustainable product lifecycle management (Sharma et al., 2021). To effectively track progress in e-waste management, more specific indicators are needed, including the adoption of extended producer responsibility models that encourage manufacturers to reclaim and recycle their products (Morseletto, 2020). These initiatives can improve material recovery rates, strengthen customer relationships, and enhance sustainability for future generations.

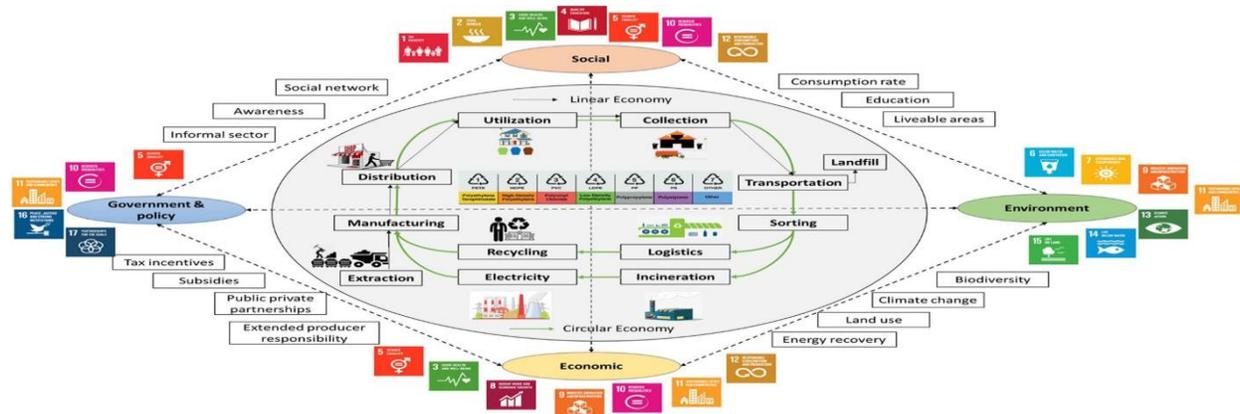


Fig 8: Using the circular economy to manage electronic trash (Sharma et al., 2021) with Elsevier permission

As global energy consumption continues to rise, transitioning to renewable energy sources is crucial. Between 2010 and 2015, energy demand grew from 5.52×10^{20} J to 6.07×10^{20} J, with projections reaching 6.97×10^{20} J by 2030 (IRENA, 2018). The heavy dependence on fossil fuels contributes to climate change, necessitating investment in clean energy alternatives such as solar, wind, hydro, and geothermal power (Acheampong et al., 2016). By 2030, it is estimated that 20% of global energy needs could be met by renewable sources (Acheampong et al., 2016). Expanding infrastructure, improving energy storage technology, and increasing efficiency are key steps toward achieving this goal. Additionally, the renewable energy sector has the potential to create 24 million jobs by 2030, contributing to socioeconomic and environmental progress (IRENA, 2018; Sen & Ganguly, 2016). The global sustainability agenda emphasizes three fundamental pillars: expanding renewable energy sources, improving energy accessibility, and enhancing efficiency. Key targets include ensuring equitable access to reliable and affordable energy, increasing the share of renewables in the energy mix, optimizing energy consumption while maintaining economic growth, fostering international collaboration for technology investment, and advancing green energy solutions for all communities (Acheampong et al., 2016; Bishoge et al., 2018). These efforts will play a critical role in building a sustainable future while addressing the environmental challenges posed by e-waste and energy consumption.

6. CONCLUSION AND FUTURE DIRECTIONS

The rapid expansion of the electrical and electronic equipment (EEE) market has been accompanied by a decline in product lifespan, leading to significant challenges in managing end-of-life disposal. A substantial portion of discarded electronic devices ends up in landfills or recycling facilities, raising environmental and economic concerns. Governments and policymakers are striving to regulate e-waste disposal by introducing policies aimed at minimizing hazardous waste and promoting sustainable recycling practices. Additionally, researchers and global organizations are actively exploring methods to recover valuable materials from e-waste, which can be repurposed for renewable energy applications.

Extracting these materials efficiently can be more economically viable than sourcing them from natural ores. To align with sustainable development goals and climate commitments, policymakers are supporting advanced recycling techniques, particularly hydrometallurgical processes, to recover metals such as lithium, cobalt, and copper from electronic waste. Transitioning towards renewable energy requires a well-structured approach that integrates material recovery, improved energy efficiency, and innovative technological advancements. Creating awareness and investing in technological development will further enhance sustainable e-waste management.

Future research should focus on optimizing the use of metals recovered from e-waste in renewable energy applications. Possible areas of development include utilizing extracted materials as catalysts for CO₂ reduction, ammonia production, and green hydrogen generation. Additionally, these materials could be integrated into renewable energy technologies, such as biogas production, to enhance methane yield. Another promising avenue is the use of recovered metals in water purification and desalination processes, contributing to global clean water initiatives. By advancing e-waste recycling, industries can significantly reduce environmental impact while fostering a more circular economy.

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