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# Sustainable valorization and conversion of e-waste plastics into value-added products

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**Abstract**

The rapid development of the electrical and electronic equipment industry has resulted in the generation of large amounts of waste electrical and electronic equipment plastic, causing an increasing environmental problem for their disposal. E-waste is considered as one of the fastest growing waste streams; however, it is a complex waste stream and comprises a mixture of hazardous heavy metals, plastics, and additives such as flame retardants and plasticizers. Although technologies have been developed for recycling polymer fractions in e-waste, the high cost related to separation and sorting techniques associated with these methods usually leads to the landfilling or incineration of plastics. In this review, we give an account of the recent developments in the field of beneficiation of e-waste plastics. This includes studies on mechanical, chemical, and thermal recycling of e-waste plastics. Additionally, the use of e-waste plastics in composite applications as well as in construction sector has been elaborated.

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**Keywords**

E-waste, Legislations, Recycling, Composites, Construction.

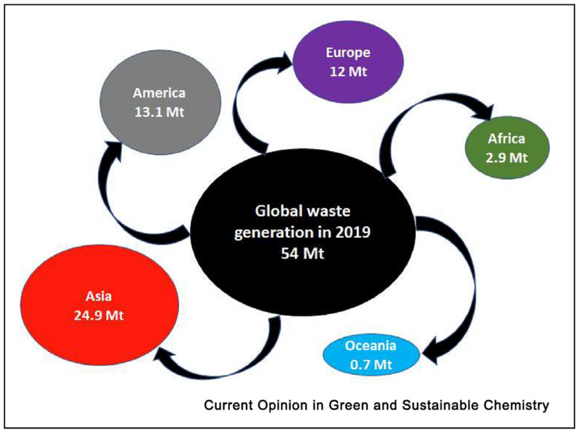
## Introduction

In recent years, the advances of information and communication technologies have increased the demand in the production and use of electrical and electronic (EE) devices [1,2]. E-waste covers a wide scope of EE devices which include, toys, household appliances, medical devices, electrical tools, mobile phones and computers. Amongst the different countries, Asia is the major contributor of e-waste followed by America, Europe, Africa and then Oceania [3] as depicted in Figure 1. The main challenges in recycling include a complicated process of separating the large number of plastics in waste electrical and electronic equipment (WEEE) and subsequent conversion to form value-added products. Additional problems include removing brominated flame retardants (BRFs) and colour compounds (cadmium) present in WEEE.

According to The Global E-waste Monitor 2020, it was reported that in 2019, about 54 million metric tonnes of e-waste was annually produced of which only 17% was collected and recycled. The rest (estimated to have a monetary value of US $ 64 billion) is dumped in landfills or illegally exported to African and Asian countries where it is managed/recycled by informal workers. Majority of these workers are women and children and are at risk of exposure to harmful chemicals such as lead, mercury, nickel, BRFs, and polycyclic aromatic hydrocarbons, which can lead to a hazardous effect on their health [4]. The contamination of soil and ecosystems in e-waste areas by heavy metals and organic chemicals is also another pertinent issue. It is predicted that by 2030, the production of e-waste will increase to 74.7 million metric tonnes as the use of computers, mobile phones, and other electronics continues to expand, alongside their rapid obsolescence [3]. One of the solutions to will enable a circular economy for the electronics sector and in the long run will contribute to mitigating climate change. A recent study by Global E-waste Statistics Partnership showed that in 2019, recycling of 17.4% of e-waste prevented almost 15 million tonnes of carbon dioxide equivalents from being released into the environment. The WHO report on “Children and Digital Dumpsites” indicates that appropriate collection systems, and recycling of e-waste is crucial to protect the environment and reduce greenhouse gas emissions [5].

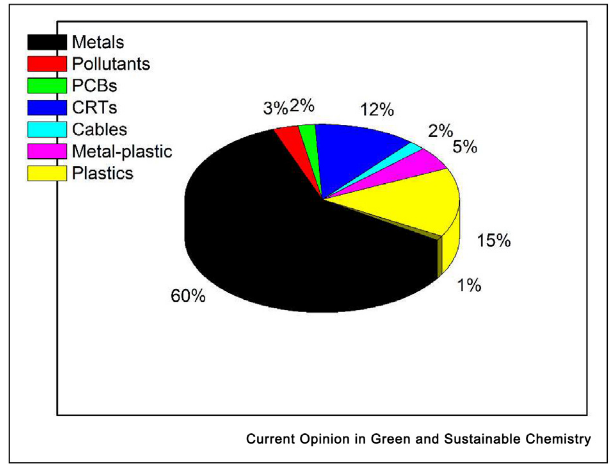
It is apparent that e-waste is one of the fastest growing domestic waste streams, and the rising volumes of e-waste have become a serious concern for governments and environmentalists especially in developing countries. Other concerns include improper disposal, inadequate infrastructure for e-waste management, and informal processing of e-waste thereby posing a serious threat to

Figure 1




Quantities of e-waste globally and e-waste quantities per continents.

Figure 2




Components of e-waste. Redrawn from Ilankoon et al. [8].

the environment [6]. Also, there are several actors involved in an informal e-waste value chain [7] such as:

- Distributers – who buy new/used equipment to consumers directly
- Consumers
- Collectors – also known as waste pickers e-waste and usually work in unhygienic conditions
- Repairers and refurbishers
- Dismantlers or segregators – involved in breaking down equipment into marketable components
- Recyclers – convert e-waste to secondary raw materials, products which are sold to suppliers of manufacturing industries.
- Downstream vendors – buy the different components that have been separated, dismantled, and recovered by recyclers

When compared to other solid waste, e-waste comprises a variety of components such as plastics, glass, and heavy metals of which plastics constitute about 15% as seen in Figure 2 [8]. There is also the presence of persistent organic pollutants like BRFs which are carcinogenic in nature and need to be separated from the plastic fractions. Additionally, chemical additives such as plasticizers, antioxidants, light and heat stabilizers, pigments, antistatic agents, and thermal stabilizers, may be present [9–13].

This makes the recovery and recycling process very complex and expensive since firstly plastics must be separated from metals followed by sorting of plastics into different groups. Recently, extensive research have been conducted to recycle plastics from e-waste to make them a resource of raw materials for variety of applications [14,15]. The current recycling options of plastic from e-waste include mechanical, chemical, and thermal recycling. However, the recycling levels are low with more than 80% of e-waste plastic ending up in landfills. Therefore, innovative non-destructive technologies to recover and recycle plastics from e-waste are required to complement the existing technologies.

This current review focuses on studies dealing with conversion of e-waste plastics into value-added composite products for applications in construction sector. Additionally, the required policies, legislative framework, and regulations enabling the implementation of circular economy of e-waste have been discussed. This review will also address the gaps between existing recycling methods and recent developments.

## E-waste management, policy, legislations, and regulations

E-waste pollution and its adverse impact on humans and environment is a major concern that needs to be addressed by every country. The regulatory bodies and policymakers of each country are tasked to design and implement policies, legislatures, and regulation for e-waste for proper management and to tackle these concerns legally and formally. The prominent international legislations include the recent Basil Convention which ensures that the transboundary movements of e-wastes (irrespective of if it is hazardous) should be subject to the consent of the importing state and any state of transit [16] and the EU directive on WEEE management [17] which calls for separation and sorting of plastics with BFRs from the other WEEE plastics. While one can learn from waste management practices across the world (EU, USA, Canada, Australia, Japan, Korea and China), it is important to modify these practices and adapt to their local situations with regards to e-waste generation rates, recycling capabilities, the presence of "producers" and expectations of stakeholders for example, 13 countries in Africa have an e-waste policy, legislation or regulation in place which focuses on individuals—rather than on entities—involved in importing and manufacturing electronics. In many developing countries, e-waste management is still in infancy, and there are no legislations dedicated to e-waste and therefore e-waste is poorly managed. As a result, there are huge quantities of e-waste that are not accounted for and has led to the thriving of informal and illegal recycling centres [18–21]. As a starting point, it is imperative for developing countries to have new e-waste legislations that focus on the following [22]:

- Promoting the principles of extended producer responsibility (EPR) which will force the manufacturer to be responsible for the product after end of service life.
- To encourage cradle to cradle circular economy as depicted in Figure 3 to avoid the incessant use of raw materials and reducing post-consumer waste products.
- To promote 9Rs (Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover) with a view to closing material loops.
- Formalize e-waste management system by developing drop off centres, collection banks as well as buy-back centres whereby households and business are encouraged to dispose their unwanted e-waste and they can trade in for profit.
- Standardizing the system by monitoring and rewarding the different stages of e-waste management.
- To ensure that the e-waste legislations are enforced, and latest technologies are implemented.

## Recycling of plastic from e-waste

The first step in the recycling of e-waste plastics is the collection of electronic devices, manual sorting, dismantling, ad shredding. The shredded e-waste is subjected to mechanical separation of metals and non-metallic components (glass, ceramics, and plastics) as seen in Figure 4. The different plastics that can be recovered from e-waste include polycarbonate (PC), acrylonitrile-butadiene-styrene (ABS), high impact polystyrene (HIPS), polyamides (PA), polypropylene (PP), polyethylene (PE), and polyesters; these need to be sorted into grades followed by recycling into products and/or converting to energy. Although e-waste comprises of high value engineering plastics such as ABS, the recycling of e-waste plastics is not well established due to the presence of large variety of polymers, BRFs, chemical additives such as plasticizers [12] and lack of awareness of compatibility of different plastics during melt extrusion process. Additionally, for the recycling process to be well established, large quantities of sorted plastics and proper recycling infrastructure are required [23].

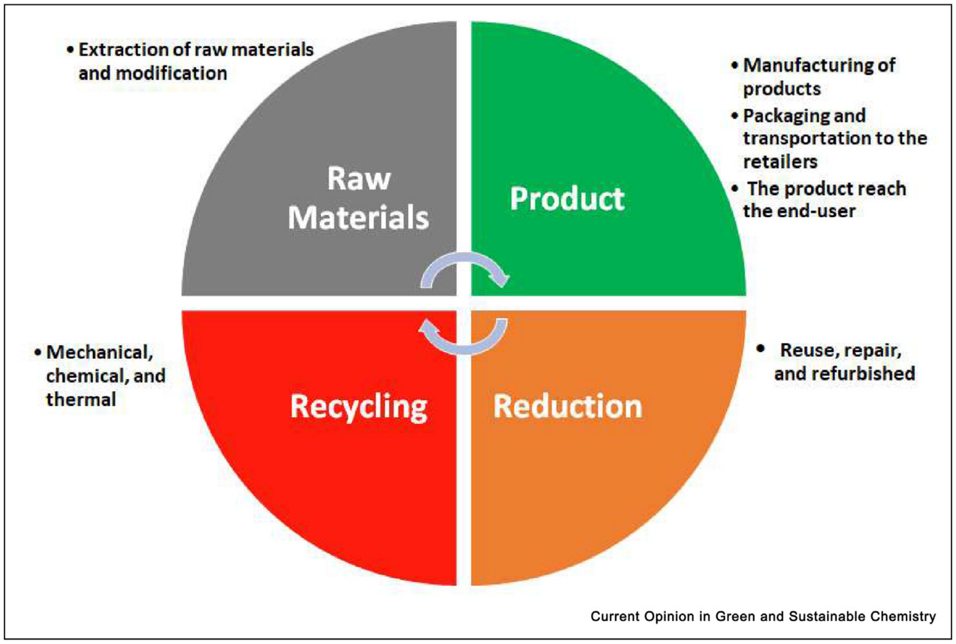
### Primary and secondary (mechanical) recycling

Mechanical recycling process is the widely used process which deals with melting the e-waste plastics and moulding to form new products. In primary recycling, the recovered plastic is used to fabricate similar products with performance characteristics that are equivalent to those made using virgin plastics. Secondary recycling is when the recovered plastic is used to develop different products and have less performance requirements than the original materials [24]. When the plastic fractions have been separated from the e-waste, the next step involves size reduction by granularizing plastics into small pieces or pellets, cleaning, and sorting (either manual sorting using eddy-current separators, magnetic separators or optical sorting depending on the target end-product). The sorted plastics are then subjected to melt processing techniques such as melt extrusion, hot pressing, and injection moulding [15,23,25]. There are numerous reports [25,26] on mechanical recycling of e-waste plastics. The use of sustainable processing techniques such as additive manufacturing to convert e-waste plastics into sustainable products is on the increase [15]. Several studies [27,28] have shown the potential of transforming e-waste plastics into sustainable 3D printing filaments. In an interesting study, Gaikwad et al. [28] converted PC derived from e-waste into 3D printable elements. It was observed that the filaments and 3D printed products exhibited up to 83% of tensile strength when compared to 3D printed ABS counterparts. As expected, the multiple heating cycles resulted in decreased thermal stability. Life cycle assessment studies on the filament production process showed a 28% reduction in $CO_2$ emissions on using e-waste plastics as feedstock as compared to virgin plastics. Another recent study examined the 3D printing characteristics of ABS derived from e-waste plastics. The authors found that though tensile and compression results revealed a slight reduction in mechanical properties compared to virgin ABS, recycled e-waste ABS exhibited sufficient properties for manufacturing commodity products [27].

### Tertiary (thermal and chemical) recycling

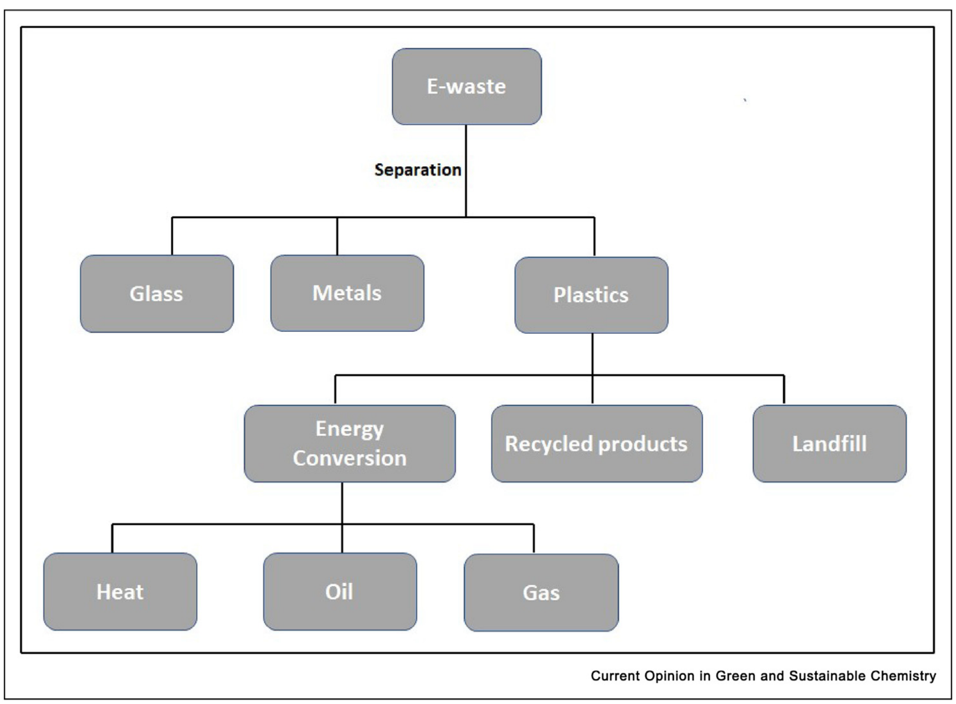
In this process, plastics from e-waste are subjected to chemical and thermal treatments to recover chemicals and fuels through depolymerization techniques [29]. In the case of e-waste plastics, chemical recycling allows the processing of contaminated plastics without elaborate pre-treatment steps. The plastic fractions then undergo repurposing to form useful products. Common techniques include dissolution, hydrogenation, gasification, pyrolysis, and catalytic cracking. In pyrolysis process, the sample is heated to high temperatures (between 400 and 800 °C under inert conditions) to convert it into products like oil, combustible gases, and char; pyrolysis emits less pollutants compared to traditional thermal treatment. The products obtained from

**Figure 3**




A circular model for electronic products.

**Figure 4**




Management of plastic recovered from e-waste.

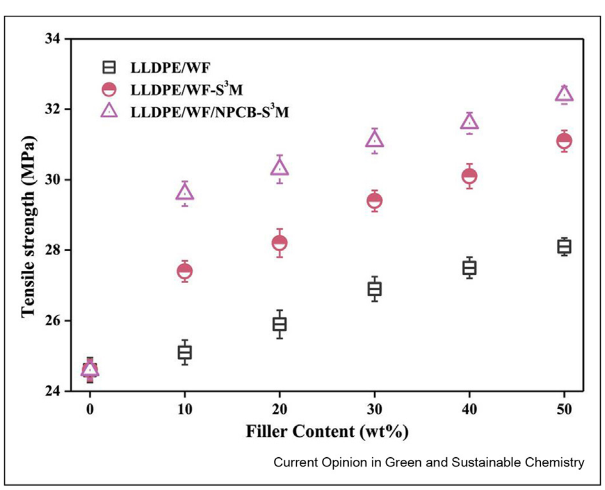
pyrolysis depends on optimized processing parameters such as temperature, composition of the feedstock, time, and heating rate [30]. Catalytic pyrolysis whereby temperature and residence time are shortened can be used to obtain high-value products [31]. Studies have explored the formation of monomers by using super-critical fluids (SCF) [30,32] and dissolution techniques [33] with various solvents such as water, acetone, carbon dioxide; however, these are all at laboratory scale. A significant technology with potential for up-scaling is the CreaSolv technology that deals with extraction of BRFs from e-waste by use of solvents followed by precipitation of polymers which can be reprocessed by extrusion technologies [34].

## Emerging developments on conversion of e-waste plastics

### Usage of e-waste as a reinforcement in composites

The use of e-waste plastics (e-fillers) as a reinforcement in polymeric materials for composite applications is on the increase. The inclusion of e-filler into polymeric materials is usually seen to improve tensile, flexural, and impact properties of the resultant composites [35,36]. In a recent study, Sun et al. [37] produced composite boards from acrylonitrile–butadiene–styrene (ABS) waste plastic and nonmetal particles from waste printed circuit boards (WPCB). It was observed that at a loading of 30 wt% of nonmetal particles, flexural strength and stiffness of 72.6 MPa and 3.57 GPa respectively were obtained. The presence of compatibilizers such as maleic anhydride-grafted ABS could effectively promote the interfacial adhesion between the ABS plastic and the nonmetal particles. Another recent study examined the development of wood plastic composites using wood fibres and nonmetals from waste printed circuit boards (NWPCB). NWPCB mainly contains phenolic and epoxy resins and the developed composites exhibited high tensile strength (Figure 5) with filler content and storage modulus. The reuse of NPCB in high-strength wood composites was considered as a sustainable solution for both resolving environmental pollution and developing value added products [38].

**Figure 5**




Tensile strength of composites with filler content (Adapted from Yang et al. [38]).

### Usage of e-waste plastics in construction

E-waste plastics is now regarded as a suitable substitute for the coarse and fine aggregates concrete for construction applications [39–41]. The driving forces for the replacement (complete or partial) of concrete with e-waste plastics is the fact it is considered as a solution to e-waste pollution and preventing the depletion of natural materials such as concrete [42]. The advantages of using e-waste plastics over the commercially available concrete is lowering cost of the final product and producing light weight concrete which results in less fuel consumption during transportation and energy savings [43]. Numerous researchers have reported that the partial replacement of concrete with e-waste plastics by incorporating loadings of up to 16 wt.% results in increment in compressive, flexural, and tensile strength [43–46]. It has also been observed that higher loadings of e-waste plastics led to a detrimental trend in compressive, flexural, and tensile properties. The hardness and mechanical properties of the cementitious composites reinforced with e-waste plastics can be improved by addition of nanofillers such as graphite platelets. These nanofillers play a significant role in reducing the porosity and reinforcing the microstructure [47]. The workability and durability properties of the resultant composite materials reinforced with e-waste plastics was significantly improved when compared to traditional concrete [42,48].

Another category of recycling are the emerging "Microfactories" where e-waste plastics can be upcycled into a completely new and higher value product rather than converting it back to a plastic product. Examples include that of the microfactory in Sydney which transforms e-waste plastic into a novel high value product called "Grenew carbon" which is used as an alternative top-charging source of carbon in metallurgical industries [49].

## Conclusions

The generation of e-waste is on the rise with predictions that it will reach 74.7 Mt by 2030. It is clear that there needs to be a concerted approach to tackle this problem which involves all actors across the value chain. The necessary steps for management and of e-waste has been summarized below:

- A legislative framework dedicated to developing proper e-waste management practices to reduce volume of e-waste dumped in landfills in developing countries is required.

- Recycling of plastics from e-waste using mechanical, thermal, and chemical recycling has been discussed in this review. However, most of this is still performed on laboratory-scale and need to be up-scaled. The recycling rates of e-waste are very low and research needs to focus on innovative methods of conversion.
- The research on conversion of e-waste plastics into value-added materials that are sustainable and eco-friendly is on the increase. Examples include that of e-waste plastics used to partially replace concrete for construction application and used as a filler in composite applications.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

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