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E-plastic Waste: A Review of Waste Stream Management Challenges and Opportunities for Environmental Sustainability

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Abstract

E-plastic waste receives little attention despite itzas significance as a proportion of e-waste at 20-40%, depending on specific equipment. The waste stream is characterized by low re-use and recycling, following its perceived; low value, limited recycling technology, sagging global prices for recycled products and associated intrinsic toxicity. Unlike the lucrative precious metals in e-waste, e-plastic waste is viewed as a residual waste after recovery of valuable e-waste components. Thus, the waste stream receives little attention often associated with crude disposal methods such as burning and open dumping oblivious of potential health and environmental impacts. The global sharp rise in e-plastic waste necessitates advocacy and campaign for efficient and effective disposal methods sensitive to environmental sustainability. The growing technology in manufacturing Electrical and Electronic Equipment (EEE) that is not easily recyclable, repairable, or reusable, aggravates the challenge of e-plastic waste management. Currently, the common e-plastic waste management techniques include; recycling, incineration, bioremediation, pyrolysis, landfilling and re-use in construction as aggregates. This study evaluates the challenges and opportunities around e-plastic management practices such as; recycling, pyrolysis, incineration, land filling, bioremediation and use in aggregates while analyzing sustainability of the techniques. The study recommends up scaling of regulatory framework and policies for efficient management of e-plastic waste to avert the looming health and environmental impacts.

Keywords: E-plastics; E-waste; Recycling; Toxicity; Environment; Sustainability

Introduction

The soaring e-waste management challenge is becoming a global concern as e-waste transits international boundaries from developed nations into developing world [1]. The composition of the e-waste is largely metals (e-metals) and plastic (e-plastic) [2]. While e-metals have been recycled to a reasonable degree, following interest placed on its value, e-plastic component has attracted very little interest from recyclers and re-users [2,3]. Commonly, most developed nations dispose off their e-plastics by landfilling, thermal treatment or overseas export for alleged recycling or reuse [4,5]. Either way, the methods are potentially unsafe considering worker's exposure and toxic components released into the environment [6,7].

E-plastic waste is considered one of the fastest-growing waste streams globally, whereas the waste is an environmental time bomb that has received little attention [8]. The waste stream forms a significant fraction of various obsolete home appliances, accounting for an average of 20-40% [9]. For example, in waste mobile phones, the plastics account for approximately 25-55% by mass content of each unit [3,10]. Overall, the proportion represents the largest fraction compared with other parts of the waste devices [10]. A considered growth in demand for technological innovation in the mobile phone industry poses a glaring commensurate growth of e-plastics [11]. Thus, after the recovery of metals, which is a priority for e-waste recycling, e-plastics becomes the most important material potential for recycling [12]. In many countries such as; Ghana, India, Nigeria, and China, e-plastics has raised concern due to challenges imposed at e-waste recycling sites, where open burning of the waste is practiced as a precursor to recovery of valuable metals [6,13]. The resultant environmental impact has led to declaration of towns where such practices occur, the most polluted places on Earth [6,14].

The nature of e-plastics is described by complex composites with copolymers as a matrix and mineral particles (like Calcium carbonate, carbon black, silica, etc.) as fillers [15,16]. The complex matrix imposes a challenge of a possible recycling [17,18]. E-plastics are comprised of more than 15 different types including acrylonitrile–butadiene–styrene (ABS), high-impact polystyrene (HIPS), polypropylene (PP), polystyrene (PS), styrene-acrylonitrile (SAN), polyesters, polyurethane (PU), polyamide (PA), blends of polycarbonate (PC)/ABS, and blends of HIPS/poly (1,4-phenylene oxide) (PPO) [19,20]. Of these, ABS, PP, PS, and HIPS form the major constituents found in e-waste, with ABS and HIPS considered the most predominant components of e-plastics [21]. Although ABS is a block copolymer with good mechanical performance, its cost is not as low as other plastics such as HIPS, a factor that limits its use and wide presence in e- plastics [15,22]. However, both copolymers are styrenic resins in e-plastic waste, whose separation can be very difficult owing to component similarities [15]. ABS is commonly found in computers, computer monitors, and printers [23]. PP is an alternative to polyvinyl chloride (PVC) in insulation for electrical cables [24], while HIPS is the predominant plastic in television housings [25]. Introduction of small amounts of ABS in electrical and electronic plastic improves the tensile mechanical properties of the corresponding properties of the major component in the blend [15,26].

The complexity of e-plastic waste revolves around the inherent complexity of the waste stream [8,27]. The type of plastic, the downstream market and corresponding re-use of the parent electronic devices are factors that complicate handling and disposal of e-plastics [28,29]. Sorting, recycling and marketing the e-plastics content in end-of-life devices can be complicated and economically challenging [5,28]. Many institutions avoid handling the material while only fewer domestic plastics reclaimers are willing to buy it [28]. Thus, there is a growing concern to find a lasting solution to handling the end-of- life for e-plastics following the rising use of plastics in electronics [13]. With the growing effort to champion for recycling, landfilling remains the most popular technique in handling e-plastics despite its perceived delicacy and risks to the environment.

Methods

This review was conducted by evaluation of several studies on the subject matter. Scientific data related to the subject of study were collected from scientific databases of Google Scholar, Research gate, PubMed, and other relevant online scientific websites. This study conducted a review of e-plastic, focusing on the; composition, variability, generation ends, and the health and environmental risks associated with the waste generation, handling and management. Through a review, the study analyzed hazardous substances in e-plastic waste gadgets such as mobile phones and modelling the life cycle impact assessment (LCIA) to determine the impacts on human health and the ecosystem. The review further evaluates the general practices around the management of e-plastics and the best practices adoptable for posterity. The study was motivated by the noted growth in technology associated with development of numerous EEE all over the world. One such gadgets are those in the telecommunication industry. Notably, there is very low collection and recycling rate of e-plastics, posing considerable threat to the environment and human health. Knowledge about the e-plastics is critical to developing its handling and general management.

Results & Discussion

E-waste composition and its plastic component

The diversity in e-waste components can range up to more than 1000 different substances, many of which fall under "hazardous" category [6]. Generally, the components consists of ferrous and non-ferrous metals, plastics, glass, wood & plywood, printed circuit boards, concrete and ceramics, rubber and other items [30,31]. Quantification of the components broadly places Iron and steel, plastics and non-ferrous metals at 50, 21, and 13% respectively [32]. Table 1 summarizes the constituents in e-waste.

The non-ferrous metals include; copper, aluminum and precious metals like silver, gold, platinum, palladium etc. Elements such as; lead, mercury, arsenic, cadmium, selenium, hexavalent chromium and flame retardants are considered hazardous waste in levels beyond the limiting thresholds which varies in different countries [33,34]. Some of the plastic components in E-waste such as phthalate plasticizer and brominated flame retardants (BFR) are considered hazardous [32]. When incinerated, BFR can emit dioxins that are known for toxicity, thus, plastics with such components have limited recycling efficiency [17].

The growth of e-waste based on growing demand for electronic gadgets proportionately results in growth of e-plastics. According to Forti et al. [35] the projected volume of e-waste will be 74.7 million metric tons by 2030, up from 53.9 metric tons in 2019. Comparatively, the volume of e-plastic will be 22.4 million metric tons by 2030 up from 16.3 million metric tons, assuming e-plastic is 30% of the general e waste [35]. Figure 1 below presents a graphical illustration of the projected e-waste and its possible associated e-plastic growth between the years 2019 and 2023.

Complexity and toxicity of e-plastics

The complexity of e-plastics revolve around presence of specific chemical compounds, considered hazardous to human and animal health [9]. Understanding the composition of such chemical components forms the basis of handling and disposal of such plastics [36]. Such knowledge also allows for monitoring, definition of the toxicity limits for plastics and ultimate establishment of environmentally safe handling and treatment processes [37]. Components of e-plastics such as; fillers or additives used on the equipment to enhance their technical standards [38], such as flammability, necessitate inclusion of flame retardants like BFR's which ultimately complicate end of life

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(EoL) management [39]. Circulation of electric currents, heating of internal components, together with the inherent flammability of most plastics and the widespread use of EEE in households and offices, necessitate the addition of flame retardants in order to comply with flammability standards [38,40]. Commonly, flame retardants (FRs) including halogenated compounds in form of organo-halogen flame retardants with either chlorinated or brominated FRs are used in EEE globally [41,42]. A strategy EoL management and considerations for environmental and health impacts are critical subjects to consider right from the manufacturing stage [40].

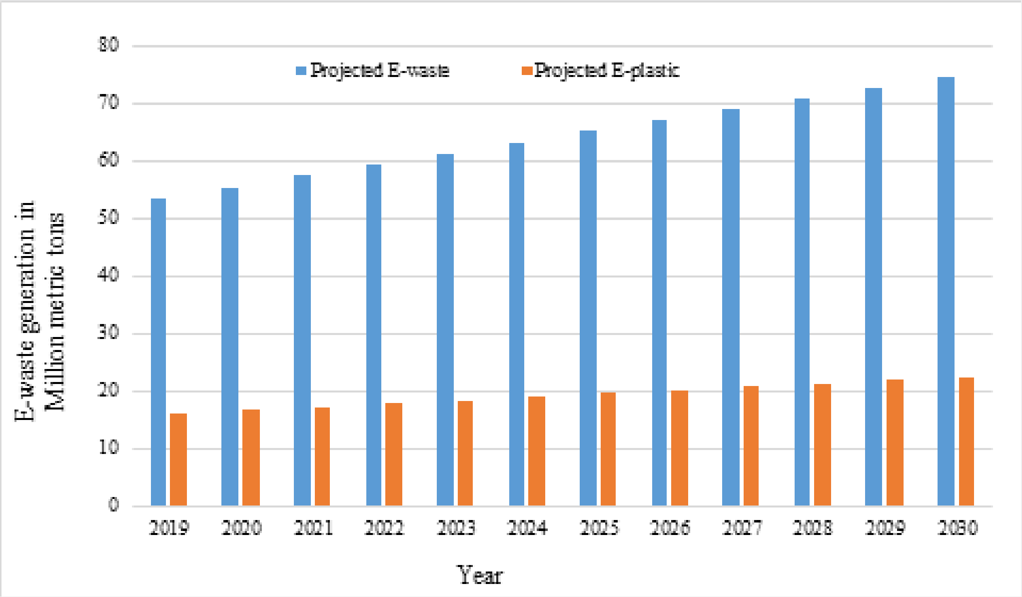

Figure 1: Projected E-waste and E-plastic growth [35].

The presence of toxic components in e-plastics in form of organic and inorganic additives, poses numerous challenges to its recycling, recovery and management [9]. The aspect of additive content in e-plastic has largely been ignored despite being a critical parameter of concern under environmental impacts of e-waste treatment and re-use [7,43]. Generally, the proportion of additives to e-plastics constitute around 10% of the weight of plastics and can account for 5-40% of source greenhouse gas (GHG) emissions [17,22]. Following complexity associated with e-plastic mixtures, limiting its sorting, handling, recycling and management due to limited technologies, estimated 40 to 50% of captured plastics in WEEE are improperly disposed through unsafe practices in the informal sector [45]. Coupled with low recyclability, e-plastic waste component is characterized by high presence of hazardous components including potentially toxic elements (i.e., lead, cadmium, mercury) and flame retardants [40].

Studies conducted on life cycle assessment (LCA) of e-waste indicate that very little effort has been put on understanding; recycling, handling and management of e-plastics considering its potential toxicity and dangers to the environment [13]. Among the few studies on toxicity of e-plastics, a study conducted by Bientinesi & Petarca [46], compared the environmental impact of two thermal treatment systems designed for e-plastic. The study investigated combustion in a MSW plant in Germany and the gasification in a gas turbine system in the Netherlands. The study demonstrated that waste EEE thermal treatment for energy and matter recovery is an eco-efficient method for disposal of e-plastics [46].

Similarly, another study conducted by Singh et al. [9] evaluated the toxicity of e-plastics and the potential repercussions on human health. The study characterized the toxic substances in e-plastics from waste mobile phones and highlighted the possible consequences of having these plastics at e-waste recycling units. Although the study concluded that the levels of Pb, Cd, Be, Cr, Sb, As, Hg and BFRs in the plastics of discarded mobile phones would not pose a major danger if collected and recycled properly, the content of Hg, Cr, Pb, Sb, and Br held a potential danger to the environment and human health, particularly under open burning as commonly practiced in the developing countries [9]. Hg from plastic of mobile phones is potentially carcinogenic and poses a major risk to human health [47]. Similarly, exposure to high levels of Pb may cause anemia, body weakness, and kidney and brain damage whereas, very high Pb exposure can be fatal [48]. In another study conducted by Butturi et al. [17] environmental and

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human health risks caused by the unregulated treatment practices of e-plastics containing BFRs, could be resolved by some tailored EoL options including well managed and controlled incineration and landfilling [17].

Management and disposal techniques for e-plastics

This section discusses the management techniques for e-plastics including; recycling, pyrolysis, incineration, bioremediation, re-use in concrete and landfilling. The section highlights the merits and demerits of the methods including derived benefits from process by-products.

Recycling

The challenges associated with e-plastic management necessitates a considered demand for extended producer responsibility (EPR) imposed by different countries across the world [49]. The principle of EPR places a recycling and recovery responsibility on the original equipment manufacturers (OEM) for products they put on the market [50]. Implementation of EPR, however faces a challenge considering the OEMs responsible for the recovery cannot bear the responsibility of e-waste collection [51].

The formal process of e-waste treatment occurs in material recovery facilities (MRF) where recycling/recovery is conducted under controlled conditions, often in developed countries [52,53]. There are three main recycling options for e-plastics which include; chemical recycling, mechanical recycling and thermal recycling [54,55]. Mechanical recycling involves treatment of the waste without influencing the polymer length substantially [56]. The recycling technique involves component recovery, pre-treatment, size reduction, separation and the reprocessing of waste, in a manner compatible with selected operations in MRF [28]. The recycling process, involves the use of waste plastics as raw materials for petrochemical processes or as reductant in a metal smelter [57]. On the other hand, chemical recycling involves de-polymerization which is the degradation of polymers to low molecular weight products that can be reused in fuels or as raw materials in the generation of new polymers [54,58]. Thermal recycling process employs eddy current to separate non-ferrous metals used as alternative fuel for energy recovery [59]. Generally, plastics are known to have high calorific value, which is equivalent to or greater than coal [60], thus, plastic materials can be combusted to produce heat energy in cement kilns [61]. Figure 2, summarizes the recycling routes for e-plastics.

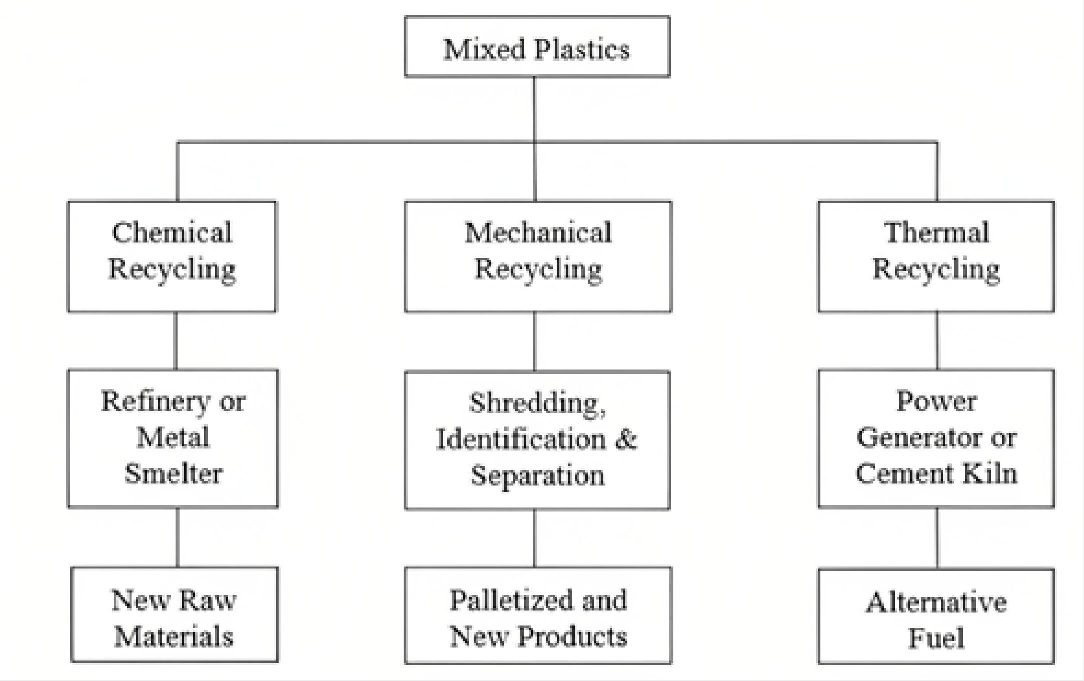

Figure 2: Recycling routes for managing e-plastics from end of life electronics.

The general mechanical process for e-plastic recycling commences from sorting to the final stage of pelletization [62]. In the first process of sorting, contaminated plastics such as laminated and/ or painted plastics are removed from the collected materials before passing it over to the shredding stage [28]. Various techniques that may be used for sorting include; grinding, cryogenic method, abrasion/ abrasive technique, solvent stripping, and high temperature aqueous based paint

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removal method [63,64]. The shredding process involves size reduction commonly conducted by shear shredders and hammer mills which also liberate metals before granulation and milling for further size reduction [65,66]. Granulators use a fixed screen or grate to control particle size whereas hammer mills allow particles between hammers and the walls to exit the mills [64]. Magnetic separators are used for ferrous metals separation, while eddy current separators are used for nonferrous metals separation [59]. Metal remaining after magnetic and eddy-current separation can be separated from plastics by vibration systems or by electrostatic separation [67,68]. Air separation system is used to separate light fractions such as paper, labels and films [69,70]. The process of recycling preparation is summarized in Figure 3.

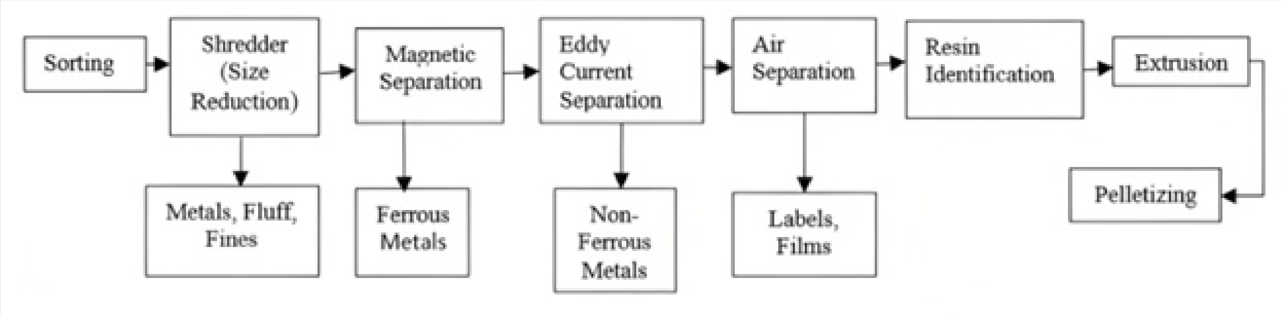

Figure 3: Detailed E-plastic mechanical recycling process.

Considering mobile phones plastic waste management, incineration and mechanical recycling are considered the most common practices globally [56]. Mechanical recycling provides the separation of various types of plastics that can be used for closed-loop recycling systems [28], while incineration is the method used to generate energy from waste plastics by burning [71]. The recycling of e-plastics from mobile phones can be a difficult process compared with other electronic equipment due to presence of tinny waste components associated with heavy metals and BFRs [2,40]. Additionally, the heavy metals and BFR components can complicate their processing associated toxicity [72]. Inclusion of toxic substances such as heavy metals and BFRs to e-plastics is a common practice that needs to be regulated and limited to make re-use and recycling possible while saving impacts on environment and health [11].

Pyrolysis

Pyrolysis is a technique of converting plastic waste to fuel by subjecting it to very high temperatures [73]. Traditionally, the process has been used to convert gases and fatty oils to recover crude petrochemicals and obtain hydrocarbons [74]. The process of recovery of crude petrochemicals can be used to generate renewable energy from the plastic wastes [75,76]. Based on the energy level injected into the process to destruct the plastic connections, pyrolysis can be categorized as; high, medium and low temperature processes [77,78]. The injected heat is used to degrade the polymeric plastic molecules into light gas and liquid hydrocarbons in the absence of oxygen, in a reactor designed to withstand such conditions [79]. The pyrolysis material is subjected to a temperature range between 600-800°C, or higher depending on material properties and desired product [80]. Thus, the pyrolysis product depends on different factors such as; reactor type, residence time, plastics properties, condensation arrangement, feeding arrangement, and temperature applied [77,81]. There are two primary methods of pyrolysis which can either be thermal or catalytic [82]. The thermal pyrolysis involves application of high temperature and pressure on the plastic, leading to destruction of the molecule by a mixture of scission [83]. The process leads to breakdown of carbon chain and cyclization of linear structures [73]. On the other hand, catalytic pyrolysis involves the use of a catalyst to enhance the efficiency of the degradation while lowering the energy input [83]. Figure 4 presents the various melting temperatures for various e-plastics identified in this study. Pyrolysis products may be classified into three distinct classes, including; gaseous product, liquid hydrocarbons and char [85]. The gaseous products are mostly composed of lighter hydrocarbons formed through successive successful cracking [82], as well as some volatile impurities. from char [83]. These gaseous products include; methane, butane, ethane, and propane, which can be used to generate electricity [86]. Liquid hydrocarbons are other products of pyrolysis that can essentially be utilized as a direct fuel or mixed with gasoline, motor oil, or diesel, depending on the required fuel characteristics [87]. The most common pyrolysis liquid products include; paraffin (octane, heptane, and butane), olefins, isoparaffins, propane, and aromatics [88]. Apart from the gaseous and liquid pyrolysis products, char, is a carbonaceous solid substance produced as a by-product of the manufacturing process for liquid oil and natural gas [89]. The use or application of char from pyrolysis of plastic waste depends on the source material composition, which also affects the characteristics and properties of the char [83]. Depending on its properties such as surface area and porosity, char is commonly used as an adsorbent material. Such application can be enhanced through treatment to improve its surface properties and advance its application effectiveness [90].

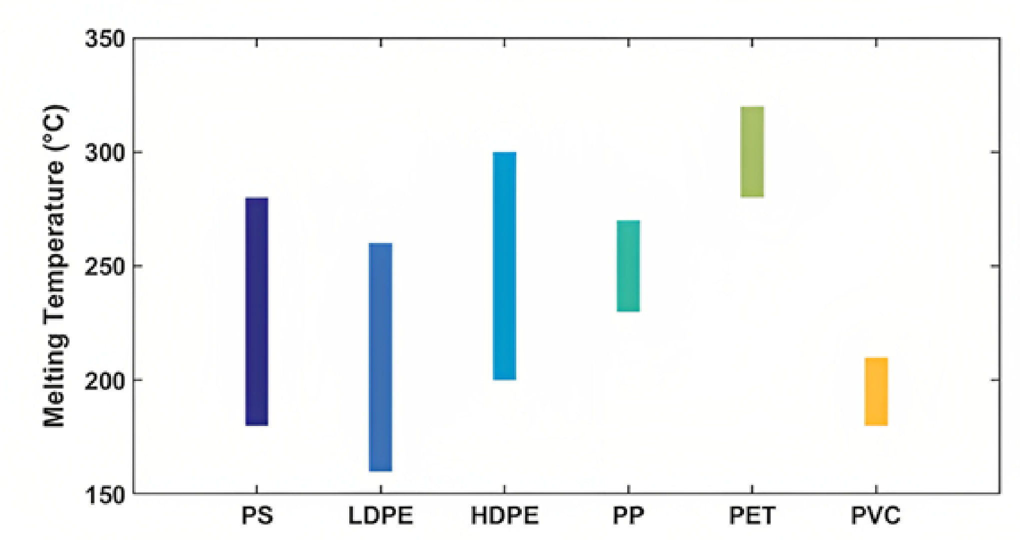

Figure 4: Melting temperature range for different e-plastics [84].

Pyrolysis, as a chemical treatment process for waste plastics, is propelled by the principle of good waste management and proper accumulation of plastic wastes in the waste management industry [36]. Despite its demand for high capital cost, the method is an efficient technique for plastic waste management [91]. Figure 5, presents a general layout of a pyrolysis process for plastic waste.

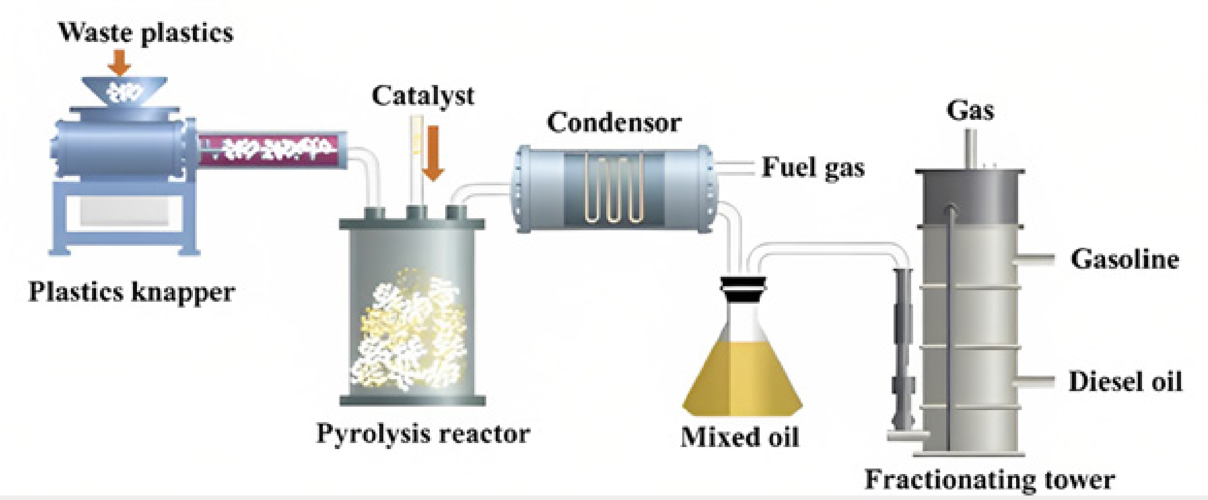

Figure 5: Typical factory layout for plastics pyrolysis plant [92].

Incineration

Incineration is a feasible e-plastic waste treatment technology involving destruction of the waste at controlled high temperatures above 800ºC [93]. Unlike pyrolysis in which combustion of the feed material is conducted in the absence of oxygen, incineration occurs in the presence of oxygen [92,93]. According to Al-Eryani et al. [94] incineration can be applied in disposal of different material wastes including; hazardous waste, municipal solid waste, infectious medical waste, wastes from nanotechnology research and development, among others [94].

Disposal of e-waste by incineration commences from an initial stage of collection and manual or mechanical sorting to separate recyclable e-plastic component from metallic portion of the waste [95]. The e-plastic material is then shredded into smaller size particles that are easier to manage during combustion [96]. Subsequently, the shredded material is dried up and divided into manageable batches that allow for optimum combustion of waste. Each batch is then passed through the combustion chamber in the presence of oxygen, at temperatures ranging between 850-1200ºC [94]. The combustion process induces heat that is used to generate steam subsequently usable for power generation. Additionally, the combustion process generates ash collected for safe disposal at both the combustion chamber and the heat recovery boiler [97]. From the combustion chamber, exhaust gas (flue gas) is generated, majorly containing sulphur oxides, nitrogen oxides, carbon monoxide and particulate matter, in the form of dust [98]. According to Miller [37], the generated gas is subjected to a thorough purification process in the flue gas purification system [37]. In this chamber, the gas is treated with filters, precipitators and scrubbers to ensure optimum removal of potential pollutants, prior to discharge to the atmosphere [99]. A summary of the incineration process is as illustrated in Figure 6 below;

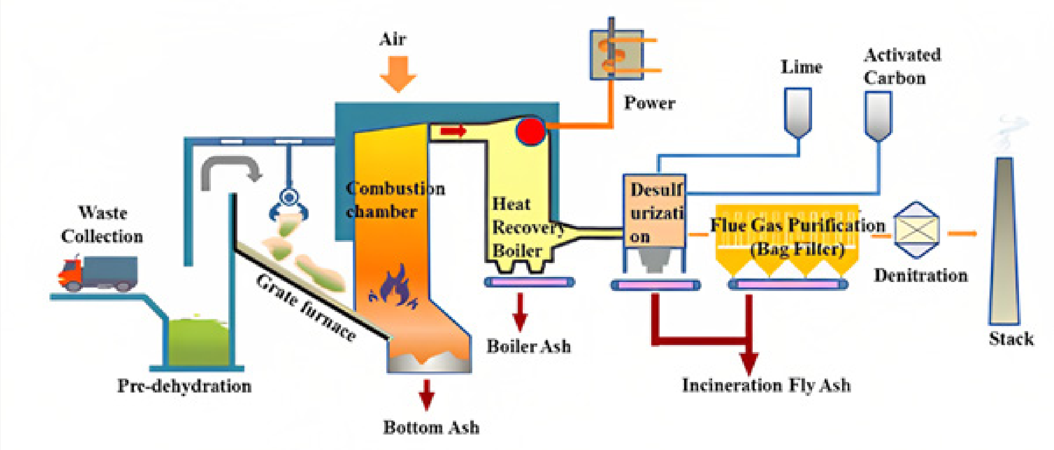

Figure 6: The flow chart of a typical modern incineration plant [97].

Incineration for e-plastics can efficiently and significantly reduce the surging volumes of e-waste that would otherwise occupy large spaces, for instance, in landfills [100]. Additionally, the process offers beneficial gains through generation of power and other useful by-products such as fly ash. Lee et al. [101] conducted a Life Cycle Assessment (LCA) between sanitary landfills and Waste to Energy (WTE) incineration as methods of solid waste management. The study proved that WTE incineration had a more preferable net green-house gas emission as compared to sanitary landfills, essentially due to the generation of clean electricity through WTE incineration as opposed to the conventional power production methods [101].

However, according to Tait et al. [102] incineration has been associated with significant contribution towards air pollution through toxic emissions [102]. The emissions resulting from incineration of e-plastics contain Persistent Organic Pollutants (POPs) among them being dioxins, furans, mercury and Polychlorinated Biphenyls [102,103]. POPs have a negative impact on human and environmental health including; respiratory ailments, cancer and neurological damage [103]. Although newer waste technologies have been employed to reduce adverse environmental impacts [102], pollutants are still produced, thus, management of the pollution levels remains a regular requirement. Reduction of e-plastic waste generation, re-using and recycling are therefore deemed more efficient methods of e-plastic waste management.

Bioremediation

Bioremediation is a technique that uses living organisms or biological processes to clean up contaminated environments through the action of metabolic abilities of microorganisms, converting contaminants into harmless products [90,104,105]. The technique is an evolving environmental biotechnology for detoxification and decontamination using the microorganisms [106], with a potential for optimization for better performance [107]. The degradation process employs a number of microorganisms to break down plastic and produce bioplastics

[108]. Some of the microorganisms identified for high potential plastic degradation include; *Pseudomonas putida, Bacillus subtilis, Bacillus amylolyticus, Pseudomonas fluorescens, and Bacillus firmus* [109,110]. The break down in molecular chains during biodegradation leads to decrease in the total length of macromolecules that make the polymer and the degree of polymerization [111]. The process requires optimization of different conditions for culture medium such as; nutrients, enzymes, pressure, light and temperature, together with the action of any biological agents such as fungi and bacteria to facilitate the growth of the microorganisms [112,113].

Under natural degradation, plastics like polyvinyl chloride result in monomers of phthalates like vinyl monomers, dioxins, and CFCs [36]. Plastic polymers can be separated and biodegraded when subjected to heteroatomic molecules [36,82]. Such plastics are considered eco-friendly in nature and are commonly used in packaging industries [36]. Generally, plastic has been identified as one of the highly persistent pollutants that is stubborn to biodegradation [114]. Additionally, the material proves to be resistant to the attack of most microorganisms to remain non-degradable [115]. Buildup of e-plastics in the environment can be hazardous with numerous related environmental challenges [3]. According to a study by Jumaah, which evaluated the rate of breakdown of plastic material for a period of one month using submerged fermentation, the microorganism associated with degradation effectiveness included two gram negative and three gram positive bacteria [116].

The buildup of e-plastics on the environment is alarming with a considerable eco-logical disturbance [3,5]. Mitigation of such ecological threats necessitates isolation of beneficial microorganisms capable of e-plastic biodegradation [3,117]. A study by Muthukumar & Veerappapillai [118], suggested bioremediation of plastic using non-conventional techniques to manage microplastic and plastics commonly used in packaging and as commercial polymers [118]. Such plastics are considered the most abundant form of e-plastic wastes [5]. Figure 7 illustrates the microbial and enzymatic aerobic bioremediation for plastics. The process is a promising strategy to depolymerize e-plastics into monomers for recycling or mineralization into CO_2, H_2O and new biomass.

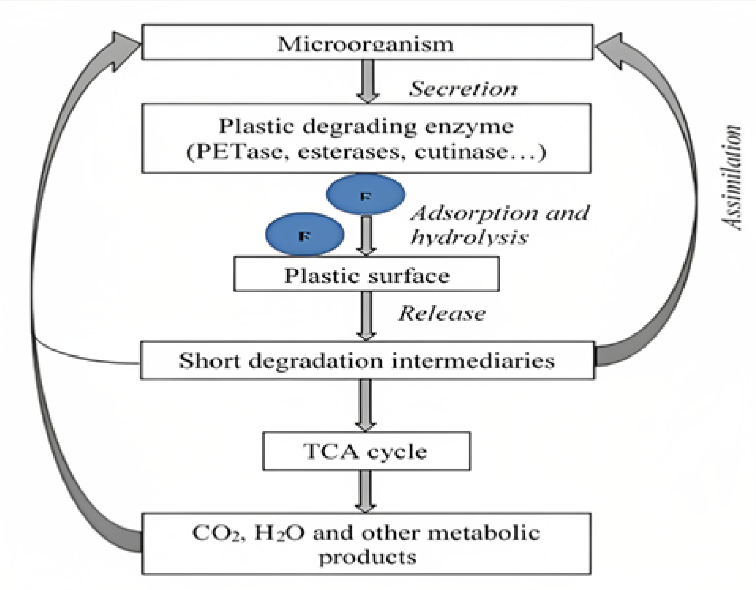

Figure 7: Summary process for microbial and enzymatic degradation of plastics under aerobic conditions [119].

Re-use of e-plastic as aggregates in concrete

Construction industry is continuously adopting e-plastic waste for use as a complementary aggregate or fiber in concrete [120]. The use of e-plastics in the construction sector in partial replacement of course aggregates in concrete has been studied as a feasible route to e-plastics recycling in developing countries [121]. According to Lamba et al. [122] e-plastics possess properties such as; low permeability, low density, smooth surface, and good acid resistance [122]. Such properties have been considered appropriate for its reuse application in construction industry, particularly where lightweight material is desired [27,123]. Research efforts on re-use of e-plastics in construction sector have focused on application such as; making light weight concrete blocks and pavement concrete block materials [122]. Plastics have low degradation in the environment [124]. thus, its application

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as construction material can potentially save the environment while reducing the impacts of excessive mining and usage of natural resources, such as aggregates, bricks and natural stones [122,123]. Similarly, re-use of e-plastics as a complementary construction material can potentially eliminate environmental impacts and the human health risks associated with exposure to toxic components embedded in the material [17,40]. On a recycling front, re-use of e-plastics in construction industry can complement recycling effort to e-waste while preserving health and the environment [125]. Moreover, the use of plastics in construction can complement the effort of developing low cost housing in response to the growing housing demand due to rapid urbanization [28,126].

Table 1: E-plastic Composition in Selected Electrical and Electronic Appliances [30,32].

Appliances	Refrigerators and Freezers	Washing Machine	Personal Computer	TV Sets	Cellular Telephones
Average weight (Kg)	48	40-47	29.6	36.2	0.08-0.100
Plastic Component (% weight)	13	1.5	23.3	22.9	59.6

Previous studies have demonstrated the potential applications of e-plastics such as cathode ray tube wastes in development of green concrete and bituminous mixes considered applicable to low-income economies [127]. A study by Parsons & Nwaubani [128], investigated e-plastics derived from various waste electronic gadgets and found that e-plastic substitution of aggregates up to 30% produced a viable structural strength concrete. Thus, the partial replacement of aggregates with e-plastic may reduce the demand for natural or crushed aggregates and reduce the amount of waste disposed off in landfills [128]. A study by Gavhane et al. [129] investigated the use of e-plastic as fine aggregate in concrete with 10% replacement while checking the strength hardened properties of concrete and durability for optimum cement content. The results revealed that replacement of river sand with 10% e-plastic resulted in comparable results to control specimen. The study therefore suggested that utilization of e-plastic in concrete can reduce the requirement for conventional fine aggregates thereby resulting in conservation of natural resources [129]. While investigating the application of e-plastics in pavement construction, Santhanam et al., used e-plastic powder in bituminous-grade VG30 as an alternative to conventional bitumen. The source of e-plastics included; PC boards, phones, and other electronic appliances with other discarded fractions of metals, such as lead, lithium, copper, and aluminum. The results showed that 10% of e-plastic powder with conventional bitumen improved the pavement strength compared with the bitumen alone used as the control [130].

Landfilling

Landfilling is the most basic technique applicable to e-plastic waste disposal [131]. The technology has been attractive for its excellent energy source due to carbon dioxide and methane gas produced during the biodegradation process [36,131]. The operation of landfills involve biodegradation and decomposition of organic molecules where plastic waste with long polymers can take approximately ten to a hundred years to degrade [132,133]. The efficiency of the process depends on the material's specific biochemical properties and environmental or climatic conditions [134]. Landfilling has also been regarded as the most cost-effective means of waste management including plastic wastes [36,131,135]. However, the technique has been associated with safety concerns and may not be considered the most preferable option for disposal of e-plastic waste [131].

Landfilling has been characterized by shortcomings including; partial contribution to climate change and lighting up methane as combustible gas [136]. The method has also been associated with soil and water contamination and general adverse health impacts on wildlife [137]. The objectives of landfill waste disposal must provide a safer means for the e-plastic waste disposal focusing on protection of all dimensions of the environment, such as aquatic, soil and airspace [36,114]. The growing volumes of e-plastic waste indicates growing land mass requirement for development of appropriate landfills [3,13]. Moreover, considered disposal of e-plastic in landfills may exacerbate land shortages and hinder the operations of waste management organizations [131,137]. On health and environmental concern, leachate from e-plastic landfills can contaminate the ground water and surrounding ground environment [138]. Hence, disposal of e-plastic waste on landfill may raise concerns for human health and the environment, since landfills have been recognized for soil contamination [131]. Therefore, the disposal process to landfill must take precautionary measures to avoid the noted secondary side effects like groundwater contamination and soil degradation that can result from poor processing [139]. Following the environmental and health concerns, the choice of the technique in disposal of e-plastics is considered limited and comes secondary to re-use and recycling.

Impediment of e-plastic to e-waste recovery and recycling

The mixed content of e-plastics [40], presence of flame retardants (FR) in form of BFR [140], or organo-phosphorus flame retardants (OPFR), the economic value to recycling [56], and limited recycling options [55], are considered major impediments to e-plastic recycling. Beyond the sheer array of plastics found in consumer electronics, the use of BFR has been a historical

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barrier to recovery [141]. Although many original equipment manufacturers have moved away from using BFRs in their products [40], older equipment, particularly TVs and computers, still contain considerable quantity of the chemical mix [142]. While studies have shown that some BFR may be hazardous to human and animals, most flame retardant chemicals can persist in the environment and remain a long term environmental concern [143]. Thus, reuse and recycling of e-plastics' is adversely affected by the presence of BFR and OPFR [10].

Another major impediment to e-plastics recovery relates to the economic value associated with the recovery effort [56]. Generally, the value of e-plastics is often considered unworthy of the labor required to separate the material unless for derived environmental considerations [144]. In this regard, mixed plastics is one of the lowest and least valuable material category [55], despite being the most voluminous component of EEE [145]. The incredibly low value of this material underscores the challenges in assuming profitable recycling [55]. Indeed, mixed plastics found in TVs, computers and printers have little to no recovery value [28,146].

One essential and fundamental knowledge necessary of all e-scrap professionals revolves around the material variety and complex classification [28,147]. Since late 1980s, the plastics industry has resorted to the resin identification code to distinguish between the various kinds of plastics in use today [148]. The code defines seven different kinds of plastics by resin type. An increasingly wide range of plastic resins have been used in consumer electronics, including; acrylonitrile butadiene styrene (ABS), high impact polystyrene (HIPS) and expanded polystyrene (EPS) [149,150]. Common diversity of resins and plastics in one device presents another challenge associated with recovery effort for e-plastic [28]. For example, printers can have up to four or five different plastics in their structure [151]. Cathode ray tubes (CRT) monitor housings generally contain PC/ABS [152], and (HIPS), while flat panels often use a mix of PC/ABS and HIPS [153].

Significantly, e-plastic waste streams are currently not recycled or reused [55]. Instead, most e-plastics are either disposed of in landfills, thermally treated, or released to poor neighborhoods for informal recycling or reuse [3,5]. A successful e-plastics recycling holds the potential of reducing landfill space requirement, improving operation efficiency and reducing land use requirement in waste disposal and management facilities [28,36]. The practice can also reduce the pressure on other related informal disposal sites such as dump sites [5]. Dumping of old electronic equipment and their components is associated with extended pollution emanating from the need for fresh materials and manufacture new products [7,43].

Selected e-waste guidelines and regulations

In the effort to protect human health and save the environment, certain directives aimed at reducing toxic elements of e-plastics from the source, have been developed by the European Union (EU). In 1995, the EU established the first guideline known as "Packaging Directive"-EC Directive 94/62/EEC, the first known guideline which controls the total amount of toxic metals such as Cd, Cr, Hg, and Pb in plastic materials to less than 100mg/kg [9]. Furthermore, additional Restriction of Hazardous Substances (RoHS) Directive 2002/95/EC in 2006 was developed to regulate the allowable concentration of considered toxic substances in the plastics by the manufacturer. The directive regulates identified toxic substances including; Pb, Hg, Cr(VI), polybrominated biphenyls (PBBs), and polybrominated diphenyl ethers (PBDEs) to a maximum value not exceeding 0.1% by weight and 0.01% by weight in homogenous materials for Cd in their products [154]. The guidelines on e-waste recommends appropriate segregation and sorting of plastics with hazardous substances from the non-electronic plastics [155]. Therefore, the diverse composition of e-plastics necessitate analysis of component hazardous substances and their potential health impacts as a baseline to establishment of toxicity limits for input into sound environmental management.

Conclusion

In conclusion, there is need to revamp a campaign to sensitize stakeholders of the growing challenge in management of e-plastic alongside the general considerations of e-waste management regulations and policies in place. The waste management strategies must consider the toxicity aspect of the waste stream and the pathways of exposure to human and animal health. The growing volume associated with growing appetite for electronic equipment must be an urgent concern before the waste imposes a crisis to solid waste management. Similarly, the management for e-plastic must consider its uniqueness that demands special attention. Furthermore, the existing approaches to e-plastic management must be assessed for value addition and environmental considerations, thereby promoting sustainable techniques such as; recycling, re-use, bioremediation and pyrolysis. Notably, government institutions need to develop and enforce policies and regulations particular to e-plastic management alongside e-waste management policies. To date, very little attention has been given to this waste stream across the world. There is need for further research that shall unearth value in e-plastic, raise interest around it and complement management effort for the waste.

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.

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