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Review

Environmental impacts of hazardous waste, and management strategies to reconcile circular economy and eco-sustainability

Zhen Zhang [a], Muhammad Zeeshan Malik [b,*], Adnan Khan [c], Nisar Ali [d], Sumeet Malik [c], Muhammad Bilal [e]

[a] Zhejiang Provincial Key Laboratory of Evolutionary Ecology and Conservation, Taizhou University, Taizhou, Zhejiang Province 318000, China
[b] School of Electronics and Information Engineering, Taizhou University, Taizhou 318000, Zhejiang, China
[c] Institute of Chemical Sciences, University of Peshawar, Peshawar, Khyber Pakhtunkhwa, Pakistan
[d] Key Laboratory for Palygorskite Science and Applied Technology of Jiangsu Province, National & Local Joint Engineering Research Center for Deep Utilization Technology of Rock-salt Resource, Faculty of Chemical Engineering, Huaiyin Institute of Technology, Huaian, China
[e] School of Life Science and Food Engineering, Huaiyin Institute of Technology, Huaian 223003, China

HIGHLIGHTS

- Toxic effect of waste to human health and environment is discussed comprehensively.
- Waste management strategies to reconcile circular economy and eco-sustainability are outlined.
- Sustainable approaches for effective management of hazardous wastes.
- Sources of wastes are delineated.

GRAPHICAL ABSTRACT

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ABSTRACT

The rise in living standards and the continuous development in the global economy led to the depletion of resources and increased waste generation per capita. This waste might posture a significant threat to human health or the environmental matrices (water, air, soil) when inadequately treated, transported, stored, or managed/disposed of. Therefore, effective waste management in an economically viable and environmentally friendly way has become meaningful. Prominent technology is the need of the day for circular economy and sustainable development to reduce the speed of depletion in resources and produce an alternative means for the future demands in the different sectors of science and technology. In order to meet the potential requirements for energy production or producing secondary raw material, solid waste may be the prime source. The activities of living organisms convert waste products in one form or another in which electronic waste (e-waste) is a modern-day problem that is growing by leaps and bounds. The disposal protocols of the e-waste management need to be given proper attention to avoid its hazardous impacts. The e-waste is obtained from any equipment or devices that run by electricity or batteries like laptops, palmtops, computers, televisions, mobile phones, digital video discs (DVD), and many more. E-waste is one of the rapidly growing causes of world pollution today. Plenty of research is available in the scientific literature, which shows different approaches being set up and followed to manage and dispose of waste products. These strategies to manage waste products designed by the states all over the globe revolves around minimal production, authentic techniques for the management of waste produced, reuse and recycling,

* Corresponding author.
E-mail address: 202106g@tzc.edu.cn (M.Z. Malik).

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etc. The virtual survey of the available literature on waste management shows that it lacks specificity regarding the management of waste products parallel to ecological sustainability. The presented review covers the sources, potential environmental impacts, and highlights the importance of waste management strategies to provide the latest and updated knowledge. The review also put forward the countermeasures that need to be taken on national and International levels addressing the sensitive issue of waste management.

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1. Introduction

The everyday increasing population, urbanization, industrialization, is the contributing factors towards the rise in pollution. The growing pollution has detrimental effects on the environment, climate, animals, plants, and human beings (Bhat et al., 2021; Kabirifar et al., 2020; Khan et al., 2021a). The collective impact of pollution has raised significant concerns among the research and scientific authorities (Abdullah and Anwar, 2021; Sultan et al., 2021). The root cause of the pollution is the solid waste obtained from multiple sources. The waste products exist in different forms depending upon their sources (Fig.1), like municipal solid waste, sludge, plastics, industrial wastes, electronic waste, glass waste, fly ash, etc. (Esparza et al., 2020; Khan et al., 2021b). Technology is majorly based on the use of electronic equipment in every walk of life. According to a survey, the global market of electrical and electronic equipment (EEE) has grown exponentially in recent times. Although the EEE business is flourishing rapidly across the world, the lifespan is becoming shorter and shorter (Kang et al., 2020; Abdullah and Anwar, 2021; Ali et al., 2021). The rising of solid waste especially e-waste profile with the passage of time has provoked concerns about waste management. The e-waste is obtained from any equipment or devices that run by electricity or batteries like laptops, palmtops, computers, televisions, mobile phones, digital video discs (DVD), and many more. E-waste is one of the rapidly growing causes of world pollution today (Nnorom and Odeyingbo, 2020).

Fig. 1. Major environmental problems of solid waste.

Solid waste is the initiating factor behind vector-borne diseases (Luttenberger, 2020; Yang et al., 2021). The solid waste acts as a feed for insects and pests, nourishing them and promoting their growth. Another unpleasant feature of the solid waste is the offensive odor that makes the air unfit for breathing (Fig. 1). Considering these facts, measures towards solid waste management have been taken since one of the practices is landfilling, which revolves around the disposal of the solid wastes into the pits, preferably in the far-flung areas, to avoid discomfort towards the people. The landfilling process of waste disposal has failed to excel due to the high costs and poor biodegradability of the waste products (Sher et al., 2020; Aslam et al., 2020; Todaro et al., 2021; Ali et al., 2020a). The combustion of the wastes has also remained a common practice towards the management of the waste. But the combustion process may also contribute to global warming; hence, it is not a much reliable practice (Cunha et al., 2020; Aldaco et al., 2020; Ali et al., 2020b). Another practice commonly observed is the incineration of waste products. The incineration process belongs to burning down the waste products getting ash, flue gas, and heat as the final products. The products obtained because of incineration can further be used for useful purposes like construction (Gollakota et al., 2020; Leifsson and Lindvall, 2021; Ali et al., 2020c).

Although the disposal and decomposition of solid wastes have been given much attention, a more beneficial practice is recycling waste for valuable purposes. The waste products can be recycled and reprocessed by physical or biological means (Tomić and Schneider, 2020; Ali et al., 2020d). The heat of the content obtained from the reprocessing can be used to generate electricity. In short, the management of waste products has remained a major issue for scientists and researchers since earlier times (Sher et al., 2016a, 2016b; Bao and Lu, 2020; Ali et al., 2020e). The whole waste management system can be combined as a set of steps like collecting the waste materials, their transport, processing, recycling, and monitoring, etc. (Fig. 2). Solid waste management is a worldwide issue that associates ecological contamination, social and economic decline, and disturbs environmental sustainability. Many reports are available scientific literature shows that both the underdeveloped and developed areas of the world suffer from hazardous waste management (Zhang et al., 2019; Zand and Heir, 2021; Vardopoulos et al., 2021). The nature of the problems faced by the developing and developed countries are somewhat different, but in cases, negative social, economic, technical, and legislative impacts are suffered (Saleem, 2021). Many scientists have covered solid waste management issues and provided the necessary measures that need to be taken. But still, there are some gaps left that require to be handled more keenly and based on scientific findings (Dastjerdi et al., 2021; Kanwal et al., 2021). The presented review comprises three portions that cover sources, effects, and ultimate management of the waste materials more focus on e-waste. The compiled literature's novelty could be significant because it deeply discusses the multifarious sources of waste products, their social, economic, and health impacts, and then discusses the most suitable strategies available for the management of solid wastes with some necessary modifications.

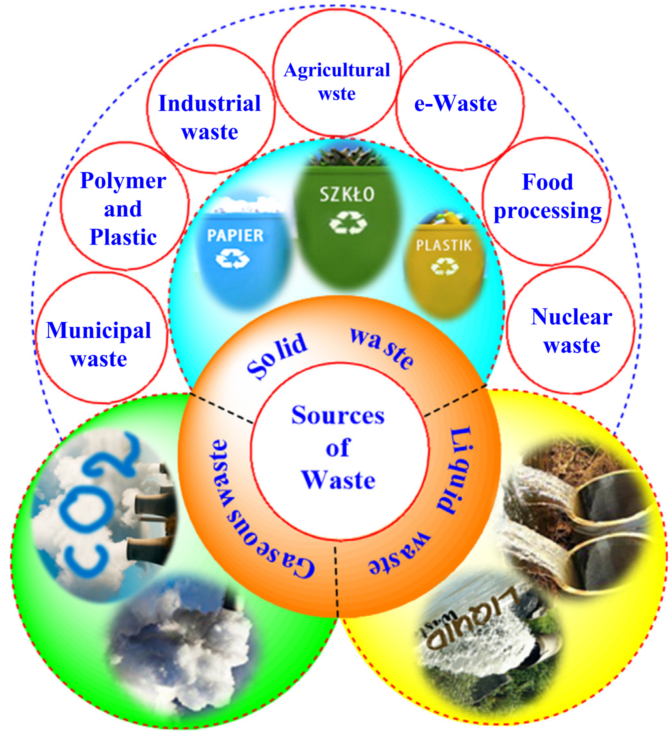

Fig. 3. Different sources of waste.

2. Sources of wastes

Solid waste products are more dependent upon urbanization. The inclination of industrialists towards setting up more industries has awakened the rise in waste materials production (Filimonau et al., 2020; Ali et al., 2020f). The heavy contributor of wastes is the industrial sector. The emissions from factories and industries escalate the pollution ratio. These industries dump their waste products into rivers and streams, thus polluting the surface water (Fig. 3). The waste products like plastics, glass scraps, dyes, drugs, chemicals, etc., are mostly obtained from related industries (Vlachokostas et al., 2020; Aziz et al., 2020; Gatto et al., 2021).

As far as the production of e-waste is concerned, the developed countries are the major producers of e-waste. The developed countries including America, Europe, and Australia (Fig. 5) have the highest rates of industrialization and urbanization (Sartaj et al., 2020; Gollakota et al., 2020; Sher et al., 2020). Hence, these developed countries completely depend on the usage of electronic devices for fast and better performance. Eventually, these countries produce high amounts of electronic wastes. The e-waste is then transported to developing countries like Pakistan, India, China, Nepal, Bangladesh, etc. The reason for the transportation of e-waste to developing countries is the availability of open space for dumping and low-cost labor for recycling purposes (Sharma et al., 2020). The developing countries, unfortunately, lack the proper knowledge and techniques required for the management of e-waste. The developing countries improperly handle e-waste management through “backyard recycling” or “informal recycling”. Such primitive recycling activities followed by the developing countries expose the people to toxic health risks (Baidya et al., 2020; Zhang et al., 2019).

Some commercially obtained waste materials like paper and plastics are also a part of the overall waste material. While the commercial sectors like colleges, universities, offices, schools, cafeterias are the main sources behind such garbage. Another important source of waste material is household/domestic wastes (Awuchi et al., 2020; Sartaj et al., 2020; Asante-Duah, 2021). Household activities, including cleaning, cooking, etc. are given rise to massive waste products. The common domestic waste products include vegetable and fruits peels, leaves, excreta, etc. (Tulebayeva et al., 2020; Thakur and Kumar, 2021; Ali et al., 2020g). The agricultural sector is also a huge contributor towards the waste products. The agricultural activities produce weeds, husk, cattle

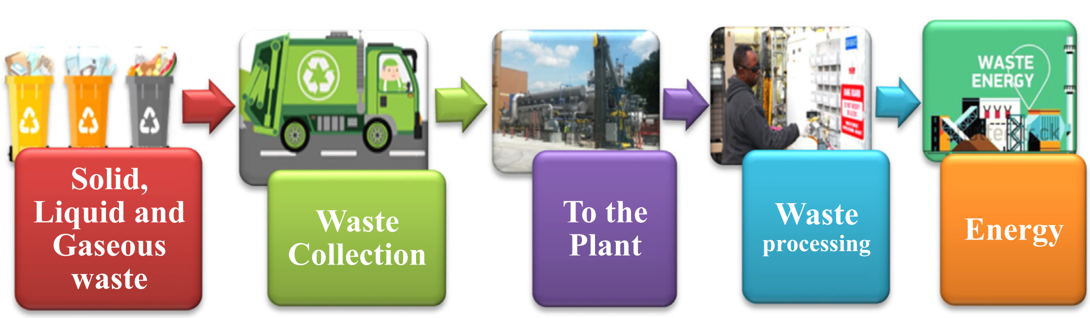

Fig. 2. Different steps from collection of waste materials, transportation, processing, and conversion to different energy sources.

wastes, etc. All the said sources are considered the major causes behind the production of waste products (Vaneeckhaute and Fazli, 2020; Ali et al., 2020h). The fact that these sources of waste products are indispensable and cannot be avoided at any cost is worth mentioning. The industries, agricultural activities, household, and domestic practices are necessary for keeping up with a healthy and better lifestyle, but the associated perks like waste products need to be accepted as per se. A rough estimation shows that 50-80% of the waste products are related to household activities while the rest of the 10-30% is dependent on commercial sources, i.e., industries, institutes, streets, etc. (Kumar and Gao, 2021; Ali et al., 2020i). The sources of solid waste are also important because it is the principal cause that specifies the chemical characteristics and nature of the waste products. Mostly, the waste products are heterogeneous, making it harder to utilize them for a certain purpose (Gaustad et al., 2020; Ali et al., 2020j). The usual components of these waste products are rubbers, leather, food wastes, plastics, inert materials, batteries, textiles, etc. Hence, the fractionation and separation of these products before further treatment and management are necessary (Stiborova et al., 2020; Ali et al., 2020k).

The recent outbreak of the COVID-19 pandemic has also multiplied e-waste production. The coronavirus broke out in Wuhan, China in December 2019 and spread over the whole world within 2-3 months (Cesaro and Pirozzi, 2020; Cunha et al., 2020). A lockdown was implemented throughout the world to control the spread of COVID-19. This lockdown prevailed for longer periods depending upon the situation of the pandemic in the particular state. This lockdown promoted the trend of online working and studies from home (Ahmad et al., 2021; Gong et al., 2014a, 2014b). Online activities upsurged the use of laptops, mobile phones, computers, etc. while decreased waste transportations. The increased use of electronic devices to fill the gaps imposed by the lockdown in the business and education centers has had many consequences (Agamuthu and Barasarathi, 2021; Sher et al., 2021a, 2021b). The increased usage of electronic devices has also increased e-waste production due to their disposal and poor management. The transportation system has also suffered during the pandemic situation which has made it harder to transport the e-waste (Shammi et al., 2021). The classical e-waste management strategies were also not being practiced properly during the pandemic. Due to this unimagined situation faced by the whole world in the last two years, one of the many problems that arouse is the hype in e-waste production. A complete and proper set of the management of e-waste should be the utmost priority at the present moment (Scheinberg et al., 2020; Sher et al., 2016a, 2016b).

The proper recycling of e-waste requires advanced equipment and sophisticated procedures which are lacking in developing countries. However, some of the e-waste recycling is also being done according to the formal methods following the legislations and norms given by Governments (Kang et al., 2020). In Germany, 17.4% of the total e-waste is handled through formal recycling techniques while the rest is either dumped, traded, stored, or recycled informally. The burning down of e-waste has also been considered as an option in many areas but it cannot be adopted due to associated respiratory problems (Shittu et al., 2020).

According to estimation, the urban areas of states are more responsible for waste production. The economic status of a state also affects the management of waste products. The economically unstable states have poor waste management strategies, which give rise to additional garbage and waste production across the world (Berktas et al., 2020; Khan et al., 2019a).

3. Environmental and climatic impact of the wastes

With the rise in population and modernization all across the globe, there is an increased demand for food and goods, which ultimately causes a hype in pollution, whether it's air, water, or land pollution (LaTurner et al., 2020; Ali et al., 2019). To meet the growing demands of the increasing population, technology, food and other essentials have also increased. This increased production of essentials ultimately produces tons of garbage in the form of worn-out products. These waste products, if not properly handled and dissipated, can cause great damage. The waste products dumped into landfills must be collected and transported properly to the final dump sites (Klugmann-Radziemska and Kuczyńska-Łażewska, 2020). The improper disposal of the waste products thus leads to harmful impacts on the surrounding environment (Fig. 4).

One of the factors affecting the environment is that leachates of the dumpsites may percolate deep down the soil and contaminate the groundwater. The wastes present on the dumpsites may be dislocated by the animals and scavengers, which may spread the garbage and cause aesthetic inconvenience (Jeswani and Azapagic, 2020; Khan et al., 2019b). The wastes like plastics, rubbers, and textiles are often burnt, causing fumes and release of noxious gases to the atmosphere, promoting air pollution. The unpleasant odors coming out of the waste products also become a factor in air pollution. Massive waste production also has a negative impact on the health of individuals (Xiao et al., 2020; Khan et al., 2019c). The vectors like insects and rats find their living onto the dumps of garbage, thus spreading multiple diseases. The improper transportation of drugs and wastes from hospitals can also spread various diseases. The flies invading food and water bodies also promote diseases like diarrhea and dysentery (Nor Faiza et al., 2019). The rats-promoted diseases include salmonellosis, plague, trichinosis, etc. (Fig. 6). Pathogenic diseases like jaundice, cholera, hepatitis may also spread via contaminated wastewater.

The drains are also choked by the garbage providing a perfect environment for the nourishment of the mosquitoes (Shooshtarian et al., 2020; Ali et al., 2018a). The breeding of mosquitoes favors the spread of malaria and dengue. The colored plastics also contain color pigments that are high in toxic heavy metals ratio like cobalt, copper, lead, chromium, mercury, etc. These heavy metals have toxic impacts on the health of individuals, thus causing great concerns (Behrooznia et al., 2020; Sohni et al., 2018). The excess of toxic chemicals like mercury, biphenyls, and cyanides may also cause the deaths of individuals.

3.1. Environmental impacts of plastic-based waste

The process of plastic depolymerization while using UV, heat, or other physical methods generates some undegradable products that seriously affect the outer environment, both land, water, and atmosphere. Different factors affect the production of these by-products, such as the type of plastic used, strain specious; two different plastics were selected to generate by-products through two different kinds of bacteria (Shahnawaz et al., 2019). It was noted that under the same operating condition, the behavior of each strain is different for Polyethylene degradation and generates different kinds of by-products. The generated by-product was checked for their toxicity, and it was found that most of the by-product was low or no toxic for the outer environment. About 20 different chemical compounds were identified by incubating polyethene terephthalate (PET) and *Streptomyces* sp. It was noted that except o-xylene and ethylbenzene, the rest of reported byproduct was found safe for the environment (Farzi et al., 2019).

Different kinds of fungi and bacteria strains were used for the evaluation of byproducts obtained from the incubation of mixed polymers, i.e., polystyrene, polyethylene, and polyethylene terephthalate. The test was performed with activated sludge and soil. The colorimetric method was used for the evaluation of the toxicity of the generated byproduct. It was found that the toxicity there is no inhibition in the microbial activity and growth (Taghavi et al., 2021). Some of the byproducts are mentioned in Table 1 generated through the biodegradation of polymers. The direct ingestion of plastic and its eco-toxicity can be evaluated directly as micro or nanoparticles by its contact with some other chemicals associated with the particles of the soil or water (Szymańska and Obolewski, 2020). But there are very limited studies are available for the toxicity of the polymer micro and nanoparticles;

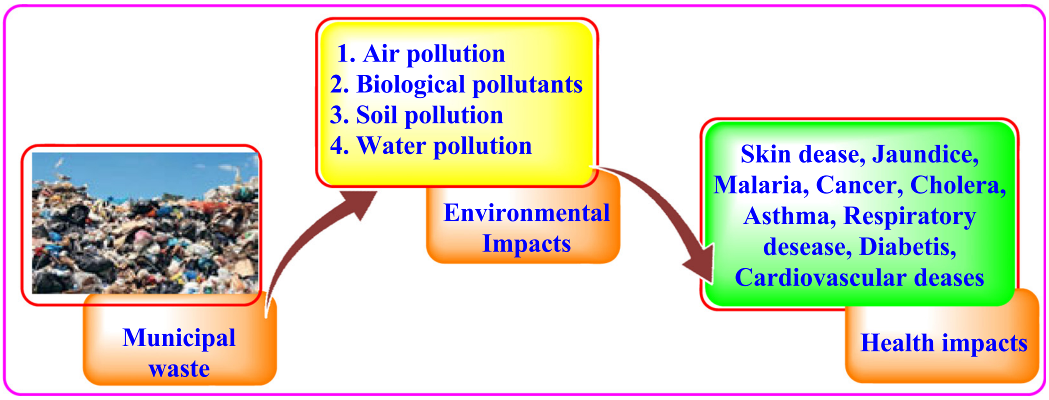

Fig. 4. Environmental and health impacts of solid municipal waste.

there is some data about the adverse effect of the micro and nanoparticles in land and aquatic animals at very high concentrations (Yong et al., 2020).

3.2. Environmental problems of cereal-based waste

The high amount of organic pollutants in the waste from cereal processing plants, which might be the source of both land and aquatic pollution and cause serious health issues (Table 2) (Kumar et al., 2017). The waste of cereal processing plants is yellowish or brown in color with a very bad smell. The COD is composed of phenol, lignins, cellulose, and some other materials in the waste effluent leading to serious environmental problems (Kumar et al., 2016). The waste effluents from cereal processing plants are the main source for algae growth on the water's surface, and high COD; BOD prevents the body growth of much aquatic life. Especially, the effluents from the processing of the corn industry mainly increase the acidic properties of the nearby land water and alkaline soil (España-Gamboa et al., 2018). The main focus of waste management is to recover the water and soil resource efficiency and prevent and guard their environment, by the significant research work in the last few decades (Kumar et al., 2017).

3.3. Environmental impacts of e-waste

The e-waste can be considered as a heterogeneous mixture of plastics, glass, metals, and resins. The e-waste contains toxic metals like

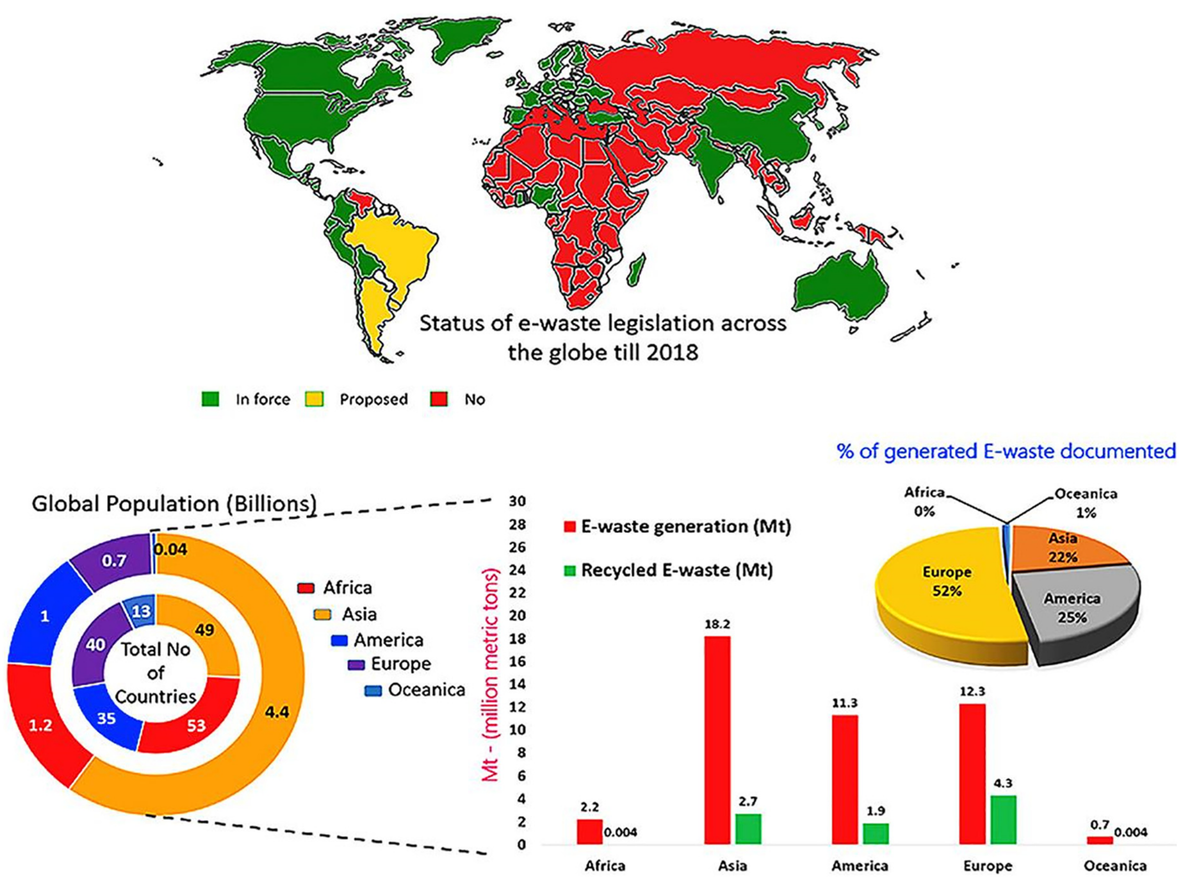

Fig. 5. *E*-waste production and possible management in developing nations (Reproduced from Gollakota et al. (2020) with permission of Elsevier.

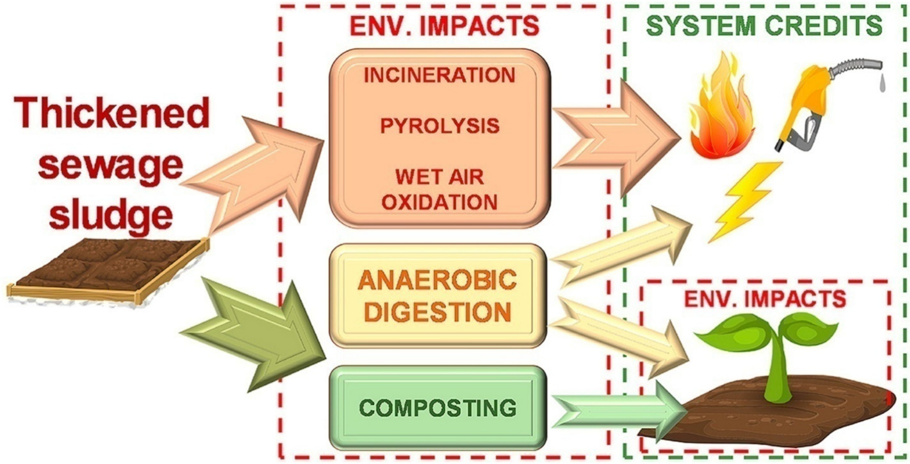

Fig. 6. Sewage sludge treatment methods their life cycle, environmental impacts for resource recovery of Eco toxicity of personal care, pharmaceutical products, and heavy metals. Reproduced from Tarpani et al. (2020); an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

arsenic, copper, cobalt, lithium, chromium, cadmium, palladium, mercury, etc. It also contains some non-hazardous metals like steel and iron, and some rare earth materials such as indium, tantalum, neodymium, etc. Some other organic and inorganic materials are also present in the e-waste which have the capacity to pollute the environment (Nithya et al., 2021). In general, the e-waste consists of 30% ceramics (alumina, mica, silica, etc.), 30% organic matter (glass fiber, polymers, retardants), and 40% inorganic matter (metals). The presence of toxic materials, especially heavy metals raise great concern about e-waste management. The cathode-ray tubes (CRTs) reportedly contain 468-732 mg/kg of copper and 429-9900 mg/kg of lead (Sahle-Demessie et al., 2021). While in printing writing boards the level of copper and lead may rise to 83,100-705,300 mg/kg, which exceeds the permissible limits. The combustion of liquid crystals in the liquid crystal displays (LCDs) emits polyaromatic hydrocarbons (PAH). All these toxic elements present in the e-waste have toxic impacts on the environment as well as human beings (Zeng et al., 2021). The most common health hazards related to e-waste include respiratory issues, damage to CNS, orthopedic complications, skin-related problems, cancer, etc. Based on these problems, proper e-waste management is the most significant matter at the moment.

The highly toxic material of the e-waste mainly depends on the EEE type. The toxic components emission to the outer environment depends on the processing technique used for the processing and reuse. Ingestion, inhalation, or dermal contact is the exposure routes to toxic emissions of the e-waste or another way through polluted water, air, soil, or food items. The toxic effect of e-waste is more for workers working in recycling units, such as children, older people, and pregnant women (Ohajinwa et al., 2019). Especially, infants and children with a high possibility of high breathing, intense activity, utero exposure, breastfeeding frequently and meal intake, and the removal of toxicants at a slow rate are most considered vulnerable groups for exposure to e-waste (Xu et al., 2018). *E*-waste exposure and its adverse health impact on humans can be assessed through exposure evaluation and the biomarkers effect, population control, and morbidity analysis pattern. One of the comprehensive reviews on the health impacts of e-waste exposure to different toxicants generated from e-waste recycling was reported (Grant et al., 2013). The release of e-waste, which mainly consists of toxic chemicals, causes atmospheric damage. While the release of e-waste into the pits and landfills causes' surface and ground water pollution. This eventually leads to hazardous health effects on marine animals and humans. The burning of e-waste is a common practice to obtain useful metal like copper. But the e-waste burning causes chronic diseases and even cancers (Hijazi et al., 2021). Table 3 illustrates the potential health effects of heavy metals and persistent organic pollutants (POPs) produced from e-waste.

3.4. Environmental impacts of food lost waste

The processing, production, and transportation for utilization need some input resources such as water, energy, land, pesticides, and fertilizer. The production of food generated some pollutants and contributed

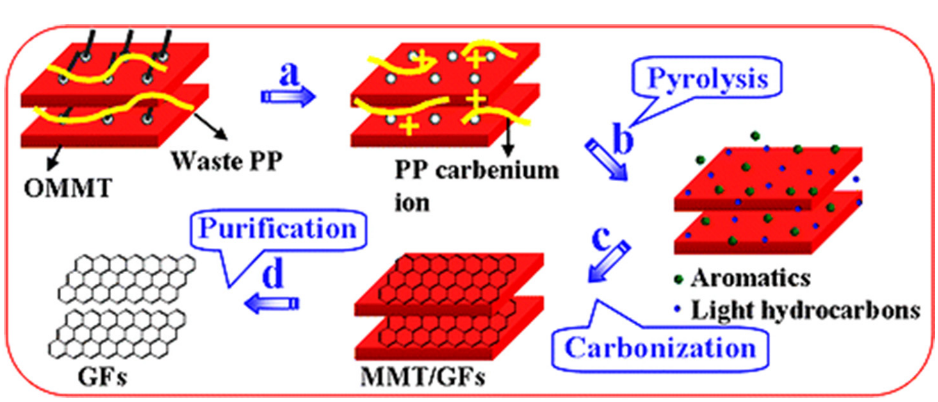

Fig. 7. Schematic explanation of the organically modified montmorillonite method for the recycling of waste polypropylene into graphene. Reproduced from Gong et al. (2014a, 2014b) with permission of American Chemical Society. Copyright © 2014, American Chemical Society.

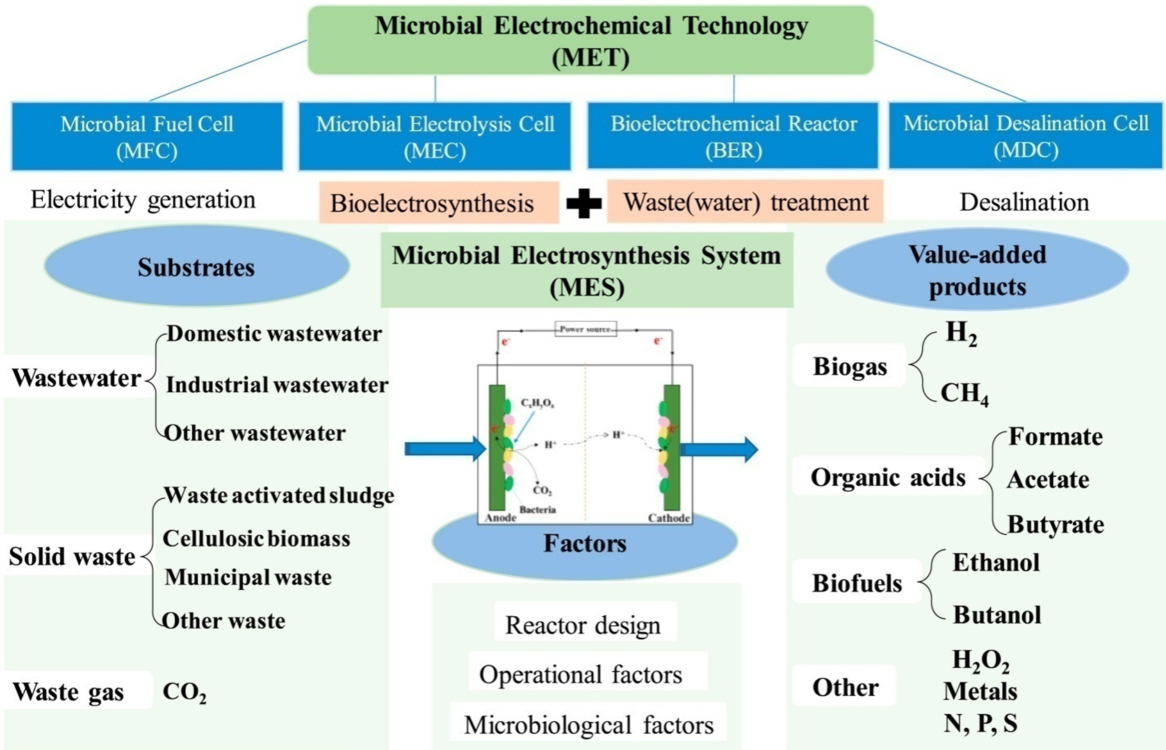

Fig. 8. Illustration of microbial electrochemical synthetic method and their application for bio-electrosynthesis of some useful products. Reproduced from Kong et al. (2020) with permission of Elsevier. License Number: 5127080037727.

to the destruction of the environment. Famous greenhouse gas carbon dioxide CO_2 is emitted during the different steps of food processing and production. The source of CO_2 is the food supply's transportation activity, which consumes gasoline and diesel for the combustion of the engine (Boehm et al., 2018). Food lost waste is also associated with the production of CO_2, which directly contributes to the acidification of water channels and has a negative effect on marine life (Anthony et al., 2008). The oxides of nitrogen NO_x are also directly linked to food lost to waste. Food waste reacts with some volatile organic molecules and generates smog and ozone (O_3). Furthermore, the processing, production, and supply of food release soot and particulates to the outer atmosphere, severely impacting human health (Vinikoor-Imler et al., 2011). Table 4 explains some of the contaminants from the food matrix.

4. Treatment of the waste materials

The detailed discussion about the waste products, their production, and their hazardous impact has highlighted the importance of proper waste management (Table 5). On an average scale, the waste products can be divided into two categories (Hossain et al., 2020; Ali et al., 2018b). Some of the wastes are biodegradable wastes, including the waste produced from household chores. These waste products have the ability to decompose themselves over a certain period of time (Niinipuu et al., 2020; Shah et al., 2018). While some of the wastes

Fig. 9. Explanation for the risk of antibiotic resistance and microbiological safety at large scale and at sustainable farm composting toilet systems and open-air composting. Reproduced from Liu et al. (2021) with permission of Elsevier. License Number: 5127080399885.

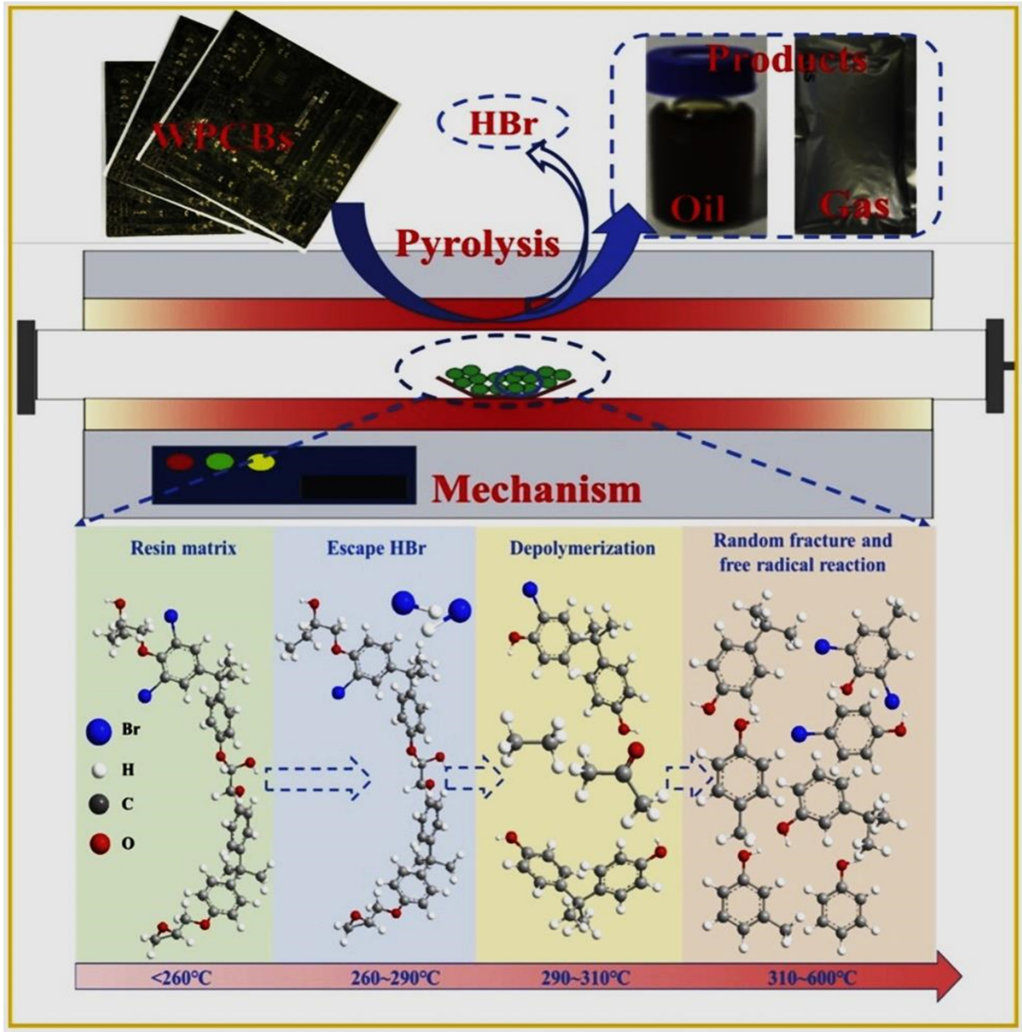

Fig. 10. Mechanism of pyrolysis and thermal decomposition mechanism process from macromolecules to a small molecule of waste printed circuit board. Reproduced from Gao et al. (2020) with permission of Elsevier. License Number: 5127080768353.

Table 1
A list of by-products generated through plastic biodegradation.

Polymer type	Time for degradation (days)	Biological strain	Generated by-product	References
Polyethylene terephthalate	18	*Streptomyces* sp.	Ethylbenzene, o-Xylene, 1,2-βPinene, p-Menthan−3-one.	Farzi et al. (2019)
Poly styrene	56	*Cephalosporium*sp.	Pyridine, Benzene, chloro, Methane,	Chaudhary and Vijayakumar (2020a); Chaudhary and Vijayakumar (2020b)
Poly styrene	60	*Exiguobacterium indicum* HHS31	2-Pentanone,4-hydroxy-4methyl, (*R*)-(-)-2,2-Dimethyl1,	Yang et al. (2015)
Polyethylene	60	*Aspergillus sydowii* strain	1,4-Benzenediol, Dibutyl phthalate	Sangale et al. (2019)
Polyethylene	90	*Streptomyces sp.*	1,4-epoxynaphthalene 1(2 h) -methanol,4,5,7-tris(1,1-dimethylethyl) −3, 2-t-butyl-5-chloromethyl-3-methyl-4-oxoimidazolidine-1-carboxylic, tetrapentacontane	Abraham et al. (2017)
Poly styrene	56	*Mucor* sp	*n*-Hexane, Cyclohexane, Benzene, Pyridine,	Chaudhary and Vijayakumar (2020a); Chaudhary and Vijayakumar (2020b)
Polyethylene	112	A5 *Aspergillus oryzae*	4,4-Dimethy; 2-pentene	Muhonja et al. (2018)
Polyethylene	60	*Lysinibacillus fusiformis* VASB14/WL	Hexadecanoic acid, Trimethylsilylmethanol,	Shahnawaz et al. (2016)
Polyethylene	140	*Pseudomonas aeruginosa* PAO1	Tetrachloroethylene, Benzene, 1,3-dimethyl, Octadecane, methyl, Benzene, Hexadecanoic acid, Octadenoic acid, Eicosane,	Kyaw et al. (2012)
Polyethylene	31	*Enterobacter sp. D1*	Monobenzyl phthalate, 6-methyls-5-hepten-2-ol, N-Acetylglutamic acid	Ren et al. (2019)

Table 2
Impact of the cereal processing waste.

Waste type	Processing condition	Treatment	Product obtained	Reference
Rice mill wastewater	60 min, 120–122 °C, in autoclave	Acid hydrolysis (H_2SO_4)	Bio-based hydrogen	Ramprakash and Muthukumar (2014)
	Acid hydrolysis, 60 min, 120–122 °C in autoclave, enzymatic hydrolysis: 5 days of incubation at 27–35 °C	Combined hydrolysis (Acid & Enzymatic)		Ramprakash and Muthukumar (2015)
	139 rpm agitation, in shaker, 303 k, 122 min, 16 min centrifuged at 10,000 rpm	Adsorption by using ADS & ADC	COD removal was 39.3% and 48.1%	Kumar et al. (2016)
	5 min agitation, chitosan dose 605 mg/L, pH 4.6, settling time 20 min	Adsorption by application of chitosan	Pollutants removal was >95% removal as TTS and COD	Thirugnanasambandham et al. (2013)
	Anodic feed 50 mM phosphate buffer, pH of 6.0, 7.0, 8.0	Dilution twice: 93% COD removal at pH 8, Without dilution: 89%, 92% and 96%, COD removal at pH of 6, 7 and 8, respectively.		Behera et al. (2010)
	Catalyst 4 g/L, H_2O_2 at 4.12 g/L, incubation at 303 K, pH 3.1, 12 min at 10,000 rpm centrifugation	Fenton-like process, the catalyst of rice husk ash-based silica- iron	COD removal 70%,	Kumar et al. (2016)
Parboiled rice effluent	4 °C, pH 2.0, 1800 *g* centrifuged for 10 min.	Pichiapestorisa X-33 supported bioremediation		Gil de los Santos et al. (2012)
Removal of PRE by cyanobacteria and microalgae	5 g at pH 7.5, at 28 °C and 12 h stored in simple light, followed by 36 days stored in dark.	100% ammonia–nitrogen and 94% phosphorus removal, 92%, 91.7% and 98.5%, reduction in COD, BOD and TSS, respectively		Mukherjee et al. (2016)
	105 and 300 mg/L concentrations of inoculum, air flow at 1VVM, 105 °C drying, filtration	Treatment by *Cyanobacterium AphanothecemicroscopiaNägeli*	Biomass of Protein	Bastos et al. (2015)
Corn wet milling steep water	NaOH as electrolyte at pH 12	EO-EA treatment	95% and 93% removal of COD after repeated treatment of EO-EA	Yasri et al. (2015)
Rice washing drainage and rice bran	Lipase enzyme and protease pretreatment, 3 min ultra-sonication, 14 days fermentation	Fermentation (by using *S. cerevisiae*)	Ethanol	Watanabe et al. (2009)
Corn by-product	41 mesh particle size, 26 mL g^{-1} liquid and solid ratio, 180 W ultrasonic power, for 80 min	Ultrasonic-assisted extraction	Fiber	Wang et al. (2013)
	NaOH 2 wt% which contain 6 M urea, freeze at −20 °C, then dried at 45 °C overnight	Treatment with NaOH urea solvent	Hemicelluloses	Yoshida et al. (2012)
	72 h, at 30 °C, (*Bacillus* sp.) 0.5 mL inoculum	Solid-state fermentation	α-amylase and Proteases	Salim et al. (2017)
	alkaline 2.5%, fermentation for 8-day, 5000 rpm centrifuged, 10 min	*A. niger* and *S. cerevisiae* used for fermentation	Bioethanol	Herring and Narayanan (2016)
	176 °C, 2.5 min come-up time, 18 min heating time, 1/20 (g/mL) solid to liquid ratio	Microwave-assisted extraction		Yoshida et al. (2010)
Corn industry wastewater	35 °C, pH 6, 24 h, 0.305 nmoles laccase dose	Enzymatic oxidation (Laccase oxidation)	COD reduction	García-Zamora et al. (2015)
Maize processing effluent	Wastewater checking in plabrt	Aerobic activated sludge	700 mg/L of COD found in the treated effluent and 400 mg/L of BOD, which was enough according to standards	Abdel-Fatah et al. (2015)

like glass, plastics, etc., cannot decompose themselves and thus become problematic for the environment. Here comes the need to properly manage the waste products either through decomposition or recycling (Gong et al., 2014a, 2014b) (Fig. 7). The recycling of waste products is based on converting waste products into useful ones that can be reused (Yuan et al., 2020; Saeed et al., 2018). The recycling process is a convenient method for controlling pollution by minimizing the hazardous impacts of waste products with minimal energy expenditure. The commonly found waste items like plastics, glass, paper, etc., can be recycled to obtain useful products out of them, ultimately conserving natural resources and energy (Kong et al., 2020; Wahid et al., 2017).

Another sustainable field is microbial electrosynthesis, which presents a huge potential in the energy sector and the source of wastes and wastewater treatment. Microbial electrosynthesis can generate valuable and useful products by treating waste material through microbial catalysis (Kong et al., 2020). The important thing is the bio electrosynthesis mechanisms in the production of useful products. Also, the main advantage is microbial electrosynthesis with the reuse of waste materials such as solid waste, wastewater, and gaseous waste (Fig. 8). Another common practice for the management of waste products is the decomposition of waste products. The waste is decomposed into simpler organic matter by different methods, as per the convenience of the circumstances (Vermeşan et al., 2020; Neelofar et al., 2017). The common practices of waste management like composting, recycling, and decomposition are discussed in detail as follows.

4.1. Waste composting

Considering the absolute need for the proper management of waste products obtained from different origins, many steps have been taken by the concerned departments. A look over the literature shows that composting is a promising practice for waste products management (Wei et al., 2020; Khan et al., 2017). Briefly, the composting process could be defined as a controlled conversion of the waste products into harmless stable products by the action of microorganisms (bacteria and fungi). The composting process is aerobic in nature that successfully converts the waste products into organic/inorganic by-products (Tang et al., 2020; H. Khan et al., 2016; S.U. Khan et al., 2016).

Table 3
Potential health effects of heavy metals and persistent organic pollutants produced from e-waste.

Pollutants from E-waste	Pollutant level	Population exposure	Health impacts levels	Reference
Heavy metals	3.47 μg/dL vs BPb: 4.86	Preschool children	Level of alivary sialic acids: 17.57 vs 9.58 mg/dL	Hou et al. (2020)
	BMn: 14.9 vs 20.6	School children	FVC in 8−9-year-old boys: 2121vs 1859 mL, increased the level of malondialdehyde and superoxide dismutase,	Zheng et al. (2013)
	HPb: 0.073 vs 0.155, HMn: 0.018 vs 0.130,	6−9-year-old children	Cognitive performance noted poor in children	Soetrisno and Delgado-Saborit (2020)
	BCd: 0.57 μg/dL vs 0.58 BPb: 3.57 *vs*5.53	5–6-year-old preschool children,	Haemoglobin noted 131.49 vs 128.17 g/L,	Zeng et al. (2017)
	BCd: 0.50 vs 0.58, BPb: 4.75 vs 6.24, BCr: 7.49 vs 7.65	3–6-year-old children	Blood Lead noted >5 μg/dL with asthma.	Zeng et al. (2016)
	BPb: 9.94 vs 15.3 μg/dL,	< 6-year-old children		Huo et al. (2007)
	BPb: 3.85 vs 4.94 μg/dL	3–7-year-old preschool children	Loss of Hearing: 13.6 vs 28.8%.	Liu et al. (2018)
	PCPb: 165.82 vs 301.43 ng/g,	Mother-baby pair		Guo et al. (2010)
		Mother-baby pair		Xu et al. (2012)
	UCBCr: 93.89 and 306.2 μg/L vs 24.00 abd 18.10 μg/L	Mother-baby pair	DNA damage significantly in exposed group	Li et al. (2008)
Blood lead (BPA)	Serum: 2.8 vs 3.2 ng/mL	Elderly population	FBG noted abnormal (<6.1 vs > 3.9 mmol/L):	Song et al. (2019)
	PDBE Serum: 158 vs 382 ng/g lipid	Recycling workers		Yuan et al. (2008)
	PCBs: 0.0041 vs 0.022 pg	Pregnant women	TSH serum: 2.65 vs 1.15 nmol/L, levels negatively correlate with body burdens PCBs and PCDD/Fs.	Zhang et al. (2010)
Dioxins		Recycling workers, occupationally, non-occupationally		Wang et al. (2010)
	BDE-209: 2.54 vs 4.19 BDE-99:0.24 vs 0.65 ng/g lipid	Mother-baby pair	Premature delivery	Wu et al. (2010)
Polycyclic aromatic hydrocarbons (PAHs)	BaA: 0.43 vs 0.83 ppb, Chr: 1.05 vs 1.57 ppb	Mother-baby pair	Adverse birth results.	Guo et al. (2012)
Polychlorinated biphenyls (PCBs)		Mother-baby pair	Reduced neonatal weight, height, gestational age. Use of workshop and house as mothers' involve in the activities of recycling contributed to the UCB-PCBs total levels.	Wu et al. (2011)

The byproducts obtained as a result of composting process also contain humic-like compounds, and they can be used as bio-fertilizers which are beneficial products. As a result of composting method, not only the harmful byproducts are deteriorated, but soil-fertility enhancing bio-fertilizers are also obtained (Ma et al., 2020; Rahim et al., 2016). One of the benefits of using compost is that it does not contaminate the groundwater in case of landfilling. The soil productivity is also increased as a result of this process by using the byproducts of the composting process as bio-fertilizers (Sun et al., 2020; H. Khan et al., 2016; S.U. Khan et al., 2016). Apart from the agricultural aspects, other benefits are related to bioremediation, pollution control, plant disease control, weed control, erosion control, landscape restoration, etc. The composting process differs from the ordinary decomposition process due to the controlled environment it is performed (Grasserová et al., 2020; Khan et al., 2015a). Although composting is a safe technique for managing waste products, some of the issues regarding this method are releasing greenhouse gases (SO_2, NO_2, CO_2). Composting is called the vermicomposting process, which utilizes red worms to convert waste products into organic/inorganic matter (Liu et al., 2021; Khan et al., 2015b).

The evaluation of risk at antibiotic resistance and microbial safety of ecological farms at the sustainable level on a large-scale green system of composting toilet systems (CT) and open-air composting system (OC). Liu et al. (2021) analyzed different samples from different biological sources such as compost, livestock manure, soil, rainwater, and vegetables to design excellent treatment methods for the said wastes and design the land application risk assessment (Fig. 9).

4.2. Waste recycling

The recycling of the waste components with some reuse value is another concept greatly utilized in the waste management process. Recycled products have great economic value due to conservation of resources, minimal energy usage, and a decrease in pollution (Nguyen et al., 2021; Khan et al., 2011a). The recycling process offers many benefits over the usual methods of waste decomposition. The recycling of waste products decreases the massive production rate by recovering useful products from the waste materials. The recycling process helps in energy recovery and also reduces huge volumes of waste products (Aboelmaged, 2021; Khan et al., 2011b).

Based on these assumptions, recycling seems to be the best option for the waste management process. The waste recycling process mainly consists of multiple steps, including collecting the waste products, their separation, and processing, followed by marketing (Li et al., 2021). The waste materials are first collected and then separated depending upon their origin to get a clean and homogenous matter. The recovery process is categorized as chemical recycling, mechanical recycling, and energy recovery (Arain et al., 2020). In the primary recycling process, the waste products are collected, ground, or melted, extruded and then re-granulated to obtain useful products.

In case of e-waste, the collection of e-waste occurs through drive programs and take-back schemes. The collected e-waste is passed through the phase of pre-processing which gives a homogenous mixture of similar materials followed by the fractionation of refined metals (Ádám et al., 2021). After this step, the useful metals can be extracted from the homogenous mixture through metallurgical processes,

Table 4
Contaminants evaluation in the food by-products.

Food matrix	Processing	Contaminants	Possible comments	Reference
Palm oil waste products	Bleaching, deodorizing,	Dioxins, polychlorinated biphenyl	Crude oil processing accompanied with contamination of Dioxin	Taverne-Veldhuizen et al. (2020)
Microalgae and Coffee waste product	–	Hg, Pb, Cd, As, Ni	Biomass use in both food and feed	Truzzi et al. (2020)
Waste of pufferfish skin	Electrodialysis	Tetrodotoxin, Heavy metals	Contaminants found for human exposure under safety limits	Chen et al. (2019)
Olive leaves-based waste	Extraction	Pesticides	–	Žuntar et al. (2019)
Wastewater from Olive mill r	Flocculation and nanofiltration	Organic toxic pollutants	Determination of carbohydrates content	Alfano et al. (2018)
Durum wheat by-products	TAG: Soxhlet	Free fatty acid	Pharmaceutical, animal feeding, cosmetic	Cardenia et al. (2018)
(Spent yeast and spent grains) Brewing products	Filtration of mash			Mastanjević et al. (2019)
Waste of grape skin	Freezing drying	Ochratoxin A, pesticides, metals	By-products evaluation from grape	Moncalvo et al. (2016)
Soybean by-product	Soxhlet, hydrolysis		Undesirable compounds produced in and the bio-active molecules enrichment	Nemitz et al. (2015)
Strawberry products (cake, flesh, seed,)	LLE + HPLC-UV	Pesticides	Contaminants were found in human after exposure	Sójka et al. (2015)
Grape bagasse waste material		Fungicides	Bioactive compounds enrichment for food, cosmetic and pharmaceutical applications	Celeiro et al. (2014)
Various by-products		Pesticides, dioxins, metals, PAHs	Contaminants transfer was noted in milk and meat and from animals feeds	Mortensen et al. (2014)
Coffee wastes		Ochratoxin A	Bioactive compounds enrichment for food, cosmetic and pharmaceutical applications	Toschi et al. (2014)
Fish oil			The decontamination of fish oil waste used as a feed.	Olli et al. (2013)
Cocoa shell wastes		Aflatoxins	Cocoa waste used for candies preparation	Copetti et al. (2012)
Fish waste products		Pesticide, metals, organochlorine	PAHs found in higher concentration in the sample of alternative fish.	Berntssen et al. (2010)
Fish oil waste		Polychlorinated biphenyl, organochlorine pesticide		Berntssen et al. (2010)
Fish oil waste		Polychlorinated biphenyl and dibenzofurans		Olli et al. (2010)
Fish oil waste		Polychlorinated dibenzo-p-dioxins, polychlorinated dibenzofurans, polychlorinated biphenyl	By-product decontamination.	Kawashima et al. (2009)

chemical processes, or heating. The most commonly employed post-processing metallurgical processes for the separation of metals include shredding/crushing, magnetic separation, eddy current separation, ball milling, gravity separation, etc. The issues faced informal are the generation of post-processing by-products (Li and Achal, 2020). These by-products need to be further treated through landfilling or incineration. To avoid such issues, green computing is the newest approach that encourages reduce, reuse, recycle and recover practices. The green computing approach provides several options like energy saving modes in electronic appliances, awareness towards the disposal of e-waste, production of eco-friendly electronic devices, etc. (Dhir et al., 2021).

Another form of e-waste recycling is informal recycling or backyard recycling. Informal recycling is mostly common in the developing countries of the world and is carried out by unskilled people. Unfortunately, about 80% of the e-waste produced is recycled informally (Kim et al., 2020). The stepwise procedure involved in informal e-waste recycling involves its transportation, processing, segregation, repairing, refurbishing, and dismantling. The informal and unscientific collection is performed by local rag pickers and sold to those who are interested in collecting value able materials (Asibey et al., 2020). The crude recycling and manual dismantling techniques cause a reduction in the volume of e-waste. The residues obtained post-recovery ate then dumped into drains, rivers, etc. The informal recycling of e-waste has many adverse effects on the environment and lives of human beings. The heavy metals intake from the e-waste causes multiple abnormalities like cell proliferation, abnormalities of thyroid, negative neonatal effects, mood swings, lungs abnormalities, etc. (Soetrisno and Delgado-Saborit, 2020).

In the case of the chemical recycling process, the waste products are treated using various technological solutions depending upon the quality of the processed product. While in the case of the energy recovery process, the waste products are used to produce heat energy (Zhang et al., 2020).

4.3. Decomposition of wastes

Sometimes, waste management practices like landfilling, incineration, composting, recycling, etc., are not enough or may produce secondary pollutants. This propels the need to decompose the harmful and toxic waste products to avoid their harmful impacts (Gao et al., 2020). One of the most common methods for decomposing solid waste products is the hydrothermal technique (Fig. 10). The common examples are the hydrothermal de-chlorination of the chlorinated plastics, hydrothermal solidification of the radioactive waste products, hydrothermal leaching of the heavy metals containing waste products, etc. Table 5 depicts different strategies for waste management.

Effective e-waste management is a prime requirement as far as a safe and green environment is concerned. Eco-sustainable e-waste management can only be achieved by setting up policies and practicing eco-friendly methods (Safdar et al., 2020; Xu et al., 2020). The purpose of e-waste management should be a sustainable and resilient environment and public awareness about this issue. The e-waste management system must rely on a precautionary principal approach, comprehensive waste assessment, strategic collaboration of entities and team building, amendments in the legislative rules followed by their implementation, continuous monitoring of the e-waste plan (Parajuly et al., 2020). The treatment methods and technologies prevailing like hydrometallurgy and informal practices must be replaced with more advanced, eco-friendly, cost-effective, and sustainable measures. The collection of the e-waste through secondary sources and its segregation must be assessed (Chen et al., 2020). The practices like resource recovery, recycling, reuse of functional gadgets, and proper disposal must be included in the system by the Governments. The policies like advance

Table 5
Different strategies for waste management.

Process	Wastes products	Positive impacts	References
Composting	Greenhouse gas emissions	Economic, environmental, and social benefits, Cheap, wealth creating, sustainable Prevents erosion, Suppress plant diseases, Energy recovery, Soil enrichment, etc.	Couth and Trois (2012)
Composting	Solid waste, garbage		Taiwo (2011)
Composting	Waste from palm oil mill		Singh et al. (2010)
Home composting	Biowaste		Mihai and Ingrao (2018)
Composting	Industrial wastes		Smith and Aber (2018)
Windrow composting	Horticultural waste		Gavilanes-Terán et al. (2016)
Home composting	Municipal organic waste		Takahashi et al. (2019)
Windrow composting	Solid waste		Vigneswaran et al. (2016)
Home composting	Food waste		Margaritis et al. (2018)
Composting	Organic waste		Moqsud et al. (2011)
Recycling	Glass waste	Eco-efficient, energy recovery process, Environmental sustainability, etc.	Blengini et al. (2012)
Recycling	Solid wastes		Atienza (2011)
Recycling	Solid wastes		Godfrey and Oelofse (2017)
Recycling	Municipal solid waste		Ramayah et al. (2012)
Recycling	Electronic waste		Chatterjee (2012)
Recycling	Plastic waste		Putri et al. (2018)
Recycling	Solid waste		Moh (2017)
Recycling	Municipal solid waste		Sanneh et al. (2011)
Recycling	Solid waste		Oke and Kruijsen (2016)
Recycling	Food waste		Paritosh et al. (2017)
Decomposition	Food waste	Reduces wastes volumes	Fujii and Kondo (2018)
Decomposition	Solid waste		Chen et al. (2014)
Decomposition	Biowaste		Gold et al. (2018)
Decomposition	Municipal solid waste		Tan et al. (2017)
Decomposition	Solid waste		Unnikrishnan and Singh (2010)
Decomposition	Municipal solid waste		Bareither et al. (2012)
Thermal decomposition	Poly vinyl chloride		Huang et al. (2018)
Decomposition	Solid waste		Vadera and Gudi (2013)
Decomposition	Rice stubble		Borah et al. (2016)
Incineration	Medical waste	Efficiency, saves transportation, control over odor of waste products, etc.	Windfeld and Brooks (2015)
Incineration	Municipal solid waste		Assamoi and Lawryshyn (2012)
Incineration	Solid waste		Johnson (2013)
Incineration	Municipal solid waste		Havukainen et al. (2017)
Incineration	Solid waste		Rajaeifar et al. (2015)
Gasification	Solid waste	A more advanced strategy towards efficient waste management	Ojha et al. (2012)
Gasification	Solid waste		Ng et al. (2019)
Integrated plasma gasification	Solid waste		Galeno et al. (2011)
Gasification	Industrial waste		Valdés et al. (2020)
Land-filling	Municipal solid waste	Simple approach	Kamaruddin et al. (2017)
Land-filling	Solid waste		Abduli et al. (2011)

recycling fee (ARF), extended consumer responsibility (ECR), tax credit, etc. should also be strengthened by the law and legislative authorities (Srivastava and Pathak, 2020). The transportation of e-waste to developing countries for the sake of trade is also a major issue. There is a need to develop proper channels under the supervision of experts for safe transportation and disposal of e-waste (Bimir, 2020). The informal sector must also be formalized to maintain the eco-sustainable management practices of e-waste throughout the world. Active collaboration between the researchers and stakeholders can come off as handy towards the development of a proper e-waste management system (Leclerc and Badami, 2020). In short, there is a long way to go for the proper management and eco-sustainable of e-waste in the coming times.

5. Conclusion and future prospects

The issue of waste production and its subsequent management is worth noticing in both under-developed as well as developed regions of the world. The production of waste products is something that cannot be hindered completely. But the proper knowledge about their products, their harmful impacts on the environment and human beings, and their control should be provided on a priority basis. The presented review has tried to cover the different sources of waste products and their management strategies. Plenty of literature is available on waste production and its consequent management, highlighting the importance of this sensitive issue. Furthermore, the awareness about e-waste in developing countries is almost negligible. The informal treatment of e-waste is causing even bigger problems in terms of environmental deterioration and human health decline. The estimated rise in the usage of electronic equipment in the times to come, and the associated rise in e-waste is an alarming situation.

Futures prospective for waste management is the disposal and reuse, which include the proper adaptation of modern technologies, especially in the under-developed countries. A proper e-waste management policy builds upon laws and legislation passed by the Governments is the dire need of the time. In addition, there is a need for proper product design at an advanced level for landfilling, recycling, and burning or incineration technology, because the reuse of produced waste with proper product design can effectively reduce the toxicity level of the waste. Also, advancement in recycling technology improves the material type that can be recycled to more useful material. Eco-sustainable e-waste management can help cover the gaps between the informal and formal treatment methods, economic growth, resilient environment, and improve the health and safety of people, along with providing better job opportunities. The future landfills with modern technology will help in the faster and complete degradation of wastes, and the recover gases from these landfills will be the sources of energy. The future incineration activities will be less pollutant or have very low environmental impacts and generate more and more energy.

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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