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REVIEW ARTICLE

Environmental contamination and public health effects of electronic waste: an overview

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Abstract

Purpose In recent years, electronic waste has become the fastest growing waste stream globally with potential deleterious environmental and public health effects from its hazardous constituents. This review aims at providing an up-to-date information on the environmental and public health effects of e- wastes, and also identify research gaps that could form basis of further innovative studies on this important subject.

Methods We carried out literature survey using several search engines. All available literature which reported directly on environmental contamination of air, soil, and water by e-wastes, and their effects on exposed plants, animals, and humans were used in other to generate an updated information.

Results High production volume coupled with indiscriminate disposal and informal recycling has made electronic waste (e-waste) to become a global public and environmental health issue. E-waste is made up of different hazardous substances such as heavy metals and persistent organic pollutants with the capacity to contaminate the environment if processed or recycled inappropriately. Humans and animals become exposed to e-waste constituents via ingestion, inhalation, and dermal contact. Several health effects have been linked to e-wastes. The most susceptible were children, pregnant women, and workers in primitive recycling sites. Generation of e-waste is predicted to increase drastically in the next decade with the potential complex interactive effects of its constituents.

Conclusion This review is an up-to-date assessment of studies and reports on e-waste environmental contamination and public health effects. The review has shown that e-waste contains constituents that caused adverse environmental effects and toxicity to the biota. However, there is an enormous data gap between exposure quantification and possible health effects. More studies are needed to elucidate and provide holistic information on environmental and public health dangers posed by e-waste constituents.

Keywords Electronic wastes · Persistent organic pollutants · Heavy metals · Environmental perturbation · Public health outcome

Introduction

There is a constant increase in the demand for new and sophisticated electronics, which has also greatly increased the rate of generating and the quantity of generated electronic wastes (e-wastes). E-wastes have contributed significantly to the world's growing waste problem [1] with a yearly worldwide generation of about 20–50 million tonnes [2]. In 2019, the global e-waste generated was about 53.6 million metric tons (Mt), which is an equivalent of 7.3 kg per capita. By the year 2030, the amount of e-waste generated is expected to exceed 74 Mt. Thus, e-wastes global quantity is annually increasing at an alarming rate of about 2 Mt [3]. This has made e-waste the fastest growing waste stream in the world, fueled majorly by an increased rate of consumption of electrical and electronic equipment (EEE), shorter life span, and few repair

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options. In 2019, Asia generated the largest amount (24.9 Mt) of e-waste, followed by America (13.1 Mt), Europe (12 Mt), Africa (2.9 Mt), and the Oceania (0.7 Mt), respectively [3].

E-wastes contain hazardous chemicals with potential deleterious effects on environmental and public health; these include persistent organic pollutants (POPs) such as polybrominated diphenyl ethers (PBDEs), polychlorinated biphenyls (PCBs), polyaromatic hydrocarbons (PAHs), etc., and heavy metals such as nickel (Ni), lead (Pb), copper (Cu), chromium (Cr), arsenic (As), and cadmium (Cd). The chemical constituents and complexity of the design of e-wastes make them difficult to reuse and recycle for economic and technical reasons [4, 5], thereby making their disposal a global environmental issue.

Many countries deal with their e-wastes by incineration or landfilling [6], both of which have been reported to greatly contaminate the environment. However, a significant bulk of generated e-wastes especially from developed nations have been reportedly shipped to developing countries under the disguise of bridging the digital gap [7, 8]. This has led to informal recycling, indiscriminate disposal on/in municipal dumpsites, informal dumpsites, streets, rivers, canals, and homes in many of these developing countries. Recently, e-wastes have been reported as major components of many municipal solid waste (MSW), especially in developing countries. This has contributed to the presence of toxic, harmful and complex chemicals in MSW, hence, making MSW a threat to the environment and public health during landfilling and incineration [9]. This development complicates the management of MSW and increases the public and environmental health importance of e-waste. There have been reports of contamination of air, soil, water, sediment, plants and animals, and public health damages by exposure to e-wastes and their constituents. This is therefore a global public health issue that calls for a concerted effort from all and sundry, to protect the environment from further damage and preserve plant, animal, and human lives. Although several individual reviews exist on the public health effects of e-waste and its environmental contamination, the present review provides an updated account of studies and reports related to e-waste environmental contamination and public health effects from across the world.

What is electronic wastes?

E-waste, often referred to as Waste Electrical Electronic Equipment (WEEE), is a term used for unwanted EEE that are obsolete, discarded, or at the end of their lives [2, 3]. EEE on the other hand includes a wide range of products utilized by businesses and consumers including equipment that depend on the electric current or electromagnetic field to efficiently function, such as equipment for the generation, measurement, and transfer of such currents or fields. This is applicable to products using a voltage rating of not more than 1000 and 1500 V for alternating and direct currents, respectively [10, 11]. There are 10 categories of wastes from EEE as listed by the European Union WEEE Directive (Table 1).

E-waste is now a problem of unprecedented proportion due to two major characteristics:

i. Hazardous nature: E-waste contains over 1000 potentially toxic substances which are of serious environmental and public health concern when disposed;
ii. High rate of generation: E-waste is generated at an alarming rate because of obsolescence; therefore, it is generated at an unprecedented volume in comparison with other consumer goods.

Components and constituents of e-wastes

Different natural and man-made materials are used in the production of electronic equipment with potential toxicity to the environment if not processed properly [13, 14]. The varieties of substances in e-waste can be categorized either as "non-hazardous" or "hazardous" (Table 2). Used electronics are a mixture of non-degradable, bio-accumulative, and carcinogenic lethal toxins. E-waste consists of 50% iron and steel, 21% plastics, 13% non-ferrous metals and several other constituents. These pollutants are found in different parts and components of used electronics in varied quantities as a result of the use to which they are put (Table 3).

Plastics

E-waste contains complex mixture of substances including wide variety of different, often incompatible, polymer types [17]. A total of 8–12 different plastic types are present in consumer electronics [18], used for noise reduction, insulation, housing, interior functional and structural parts, sealing, etc. [19]. In the production of electronics, major resins such as high-impact polystyrene made up 56%wt of the electronics while acrylonitrile butadiene styrene and polyphenylene ether are responsible for 20 and 11%wt, respectively. The rest 13%wt is a combination of other resins like poly carbonate, polyphenylene oxide, and polyvinyl chloride (PVC) [20]. PVC, a chlorinated plastic is used for wires and cables insulation in electronics products. The production and incineration of PVC can contaminate the environment with chlorinated furans and dioxins, where they are very persistent and are very toxic even at very low concentrations [21]. There is a great variation in the quantity and types of plastics in electronics, for example in consumer equipment and ICT, not up to 30% of plastics are present while more than 70% plastics can be present in electronic toys [22].

Table 1 Waste EEE categories according to the directive on WEEE by EU

S/No.	WEEE Category	Example
1	Small household appliances	Vacuum cleaner, iron, toaster, coffee machine, clock
2	Large household appliances	Electric stove, washing machine, refrigerators, freezers, air conditioner
3	IT and Telecommunication equipment	Personal computer, laptop computer, phone, cellular phone
4	Consumer equipment	Televisions, radios, VCD, DVD
5	Lighting equipment	Luminaries for fluorescent lamps, straight fluorescent lamps, compact Fluorescent lamps.
6	Electrical and electronic tools	Drills, saws, sewing machine, equipment for turning, milling, sanding, etc. for processing of wood, metal, and other materials
7	Toys, Leisure & spots equipment	Electric trains and car racing sets, video games, etc
8	Medical devices	Radiotherapy equipment, Cardiology, Dialysis, and Pulmonary ventilators etc.
9	Monitoring and control instruments	Smoke detector, heating regulators, Thermostats etc
10	Automatic dispensers.	Automatic dispensers for hot drinks, hot or cold bottles, or Cans

Source: Antrekowitsch et al. [12]

Metals

E-waste is made up of both trace and metallic elements. Trace elements are used in electronic equipment as dopants. Silicon-based chips contained trace elements which include indium (In), phosphorus (P), gallium (Ga), antimony (Sb), and As incorporated into their matrices. Also, during the production of semi-conductors like arsenide, indium phosphide, or Ga, these trace elements are used. Many substances utilized as dopants have been classified as probable or known human

Table 2 Some of the hazardous substances present as e-waste constituents

Substance	Presence in e-waste
Halogenated compounds	
PVC (polyvinyl chloride)	Cable insulation
PBDE (polybrominated diphenyl ethers) PBB (polybrominated biphenyls) TBBA (tetrabromo-bisphenol-A)	TBBA is presently the most widely used flame retardant in printed wiring boards and casings. Fire retardants for plastics (thermoplastic components, cable insulation)
Chlorofluorocarbon (CFC)	Insulation foam, Cooling unit
PCB (polychlorinated biphenyls)	Transformers, Condensers
Heavy metals and other metals	
Arsenic	Small quantities in the form of gallium arsenide within light emitting diodes
Barium	Getters in CRT
Beryllium	Power supply boxes which contain silicon controlled rectifiers and x-ray lenses
Cadmium	Rechargeable NiCd-batteries, fluorescent layer (CRT screens), printer inks and toners, photocopying-machines (printer drums)
Chromium VI	Data tapes, floppy-disks
Lead	CRT screens, batteries, printed wiring boards
Lithium	Li-batteries
Mercury	Fluorescent lamps that provide backlighting in LCDs, in some alkaline batteries and mercury wetted switches
Nickel	Rechargeable NiCd-batteries or NiMH-batteries, electron gun in CRT
Rare Earth elements (Yttrium, Europium)	Fluorescent layer (CRT-screen)
Selenium	Older photocopying-machines (photo drums)
Zinc sulphide	Interior of CRT screens, mixed with rare earth metals
Others	
Toner Dust	Toner cartridges for laser printers / copiers
Radio-active substances Americium	Medical equipment, fire detectors, active sensing element in smoke detectors

Source: ewasteguide.info [15]

Table 3 The composition of a typical desktop Personal Computer (PC) weighing ~60Ibs

Name	Content (% of total weight)	Weight of material in computer (Ibs)	Use/Contents
Plastics	22.9907	13.8	Includes organics, oxides other than silica
Lead	6.2988	3.8	Metal joining, radiation shield/CRT
Aluminium	14.1723	8.5	Structural, conductivity/housing, CRT, PWB, connectors
Germanium	0.0016	<0.1	Semiconductor/PWB
Gallium	0.0013	<0.1	Semiconductor/PWB
Iron	20.4712	12.3	Structural, magnetivity/(steel) housing, CRT, PWB
Tin	1.0078	0.6	Metal joining
Copper	6.9287	4.2	Conductivity/CRT, PWB, connectors
Barium	0.0315	<0.1	In vacuum tube/CRT
Nickel	0.8503	0,51	Structural, magnetivity/(steel) housing, CRT, PWB
Zinc	2.2046	1.32	Battery, phosphor emitter/PWB, CRT
Tantalum	0.0157	<0.1	Capacitors/PWB, power supply
Indium	0.0016	<0.1	Transistor, rectifiers/PWB
Vanadium	0.0002	<0.1	Red phosphor emitter/CRT
Beryllium	0.0157	<0.1	Thermal conductivity/PWB, connectors
Gold	0.0016	<0.1	Connectivity, conductivity/PWB
Europium	0.0002	<0.1	Phosphor activator/PWB
Titanium	0.0157	<0.1	Pigment, alloying agent/(aluminium) housing
Ruthenium	0.0016	<0.1	Resistive circuit/PWB
Cobalt	0.0157	<0.1	Structural, magnetivity/(steel) housing, CRT, PWB
Palladium	0.0003	<0.1	Connectivity, conductivity/PWB
Manganese	0.0315	<0.1	Structural, magnetivity/(steel) housing, CRT, PWB
Silver	0.0189	<0.1	Conductivity/PWB, connectors
Antimony	0.0094	<0.1	Diodes/housing, PWB, CRT
Chromium	0.0063	<0.1	Decorative, hardener/(steel) housing
Cadmium	0.0094	<0.1	Battery, glu-green phosphor emitter/housing, PWB, CRT
Selenium	0.0016	0.00096	Rectifiers/PWB
Niobium	0.0002	<0.1	Welding allow/housing
Yttrium	0.0002	<0.1	Red phosphor emitter/CRT
Mercury	0.0022	<0.1	Batteries, switches/housing, PWB
Arsenic	0.0013	<0.1	Doping agents in transistors/PWB
Silica	24.8803	15	Glass, solid state devices/CRT, PWB

Adapted from Microelectronics and Computer Technology Corporation [16]

carcinogens and very toxic. As, Al, In, and Ga have been shown to be carcinogenic [23–25]. Other metallic elements present in e-waste include: beryllium (Be), cobalt (Co), barium (Ba), selenium (Se), zinc (Zn), yttrium (Y), europium (Eu), gold (Au), platinum, iron (Fe), aluminium (Al), tin, germanium, tantalum, vanadium, ruthenium, tanialum, rhodium, americium, palladium, manganese, silver, bismuth, niobium, silica, lithium, tritium, terbium, etc. [23–28]. Heavy metals like Pb with known toxicity is present in most electronic devices in large quantities [29]. Typical printed wire boards (PWB) have been reported to contain approximately 50 g and 0.7% of tin-lead solder/m^2 and the total weight of a PWB, respectively, while color CRTs is made up of an average of 1.6–3.2 kg Pb [30]. Yousefzadeh et al. [31] also reported different quantities of recoverable Cu from circuit boards of electronics using different hydrometallurgical methods.

Persistent organic pollutants (POPs)

Different POPs that are mostly used as flame retardants in the production of consumer electronics are found in e-wastes. The most commonly used are brominated flame retardants (BFR) because their small quantities can ensure very high fire safety [32]. In 2004, about 1000 tons of a BFR called tetrabromobisphenol-A (TBBPA) was used in the

manufacturing of 674 million mobile phones. There has been a report that this chemical might be neurotoxic [33]. Three main classes of BFR pose a hazard: polybrominated biphenyl (PBB), TBBPA, and PBDEs. PBDEs are mixed into plastics and components during the production of electronics, however, no chemical bond exists between the plastics and PBDEs which makes it possible for PBDEs to leach into the environment from the surface of e-waste components. Other organic constituents of electronic products as well as products of their low-temperature combustion include: chlorofluorocarbon (CFC), polyhalogenated aromatic hydrocarbons (PHAHs), polychlorinated dibenzofurans (PCDFs), polychlorinated dibenzo-p-dioxins (PCDDs), and polycyclic aromatic hydrocarbons (PAHs) [34, 35]. Until the later part of the 1970s, PCBs were universally used in PVC and other polymer applications as flame-retardant plasticizers, and in electrical capacitors and transformers as insulating fluids [36, 37]. Also present are the polychlorinated naphthalenes (PCNs); these are the precursors to PCBs, and share many of their properties [36]. They contain inorganic and organic halogens such as nitrogen, phosphorus, and minerals containing compounds that possess strong varieties of individual sets of properties. Also present in e-wastes are dioxin-like compounds (DLC), which is a general name for planar aromatic hydrocarbons that are chemically and structurally related, and are capable of binding to the aryl-hydrocarbon receptor inducing dioxin-like toxicity [38]. Among the most toxic DLC in e-waste are dioxin-like polychlorinated biphenyls, dibenzofurans, and 2,3,7,8-polychlorinated dibenzo-p-dioxins [38].

Environmental contamination by e-waste

Data from different countries has shown a wide magnitude of environmental contamination by e-wastes. The level of contamination calls for environmental health concerns and the need for urgent attention and remediation. Environmental contamination by e-waste has increased due to informal dismantling and recycling of e-waste, the so called "backyard activities". These crude recycling activities are taking place in Asia and Africa, aimed at material recovery from e-waste. Gold and silver are among the major e-waste constituents sort after during this informal recycling. Report has shown that for every 1 million cell phones that are recycled, the following amounts of precious metals can be recovered: 16,000 kg of copper, 350 kg of silver, 34 kg of gold, and 15 kg of palladium [39].

Soil contamination by e-waste

Several studies have shown evidence of heavy metal pollution of soil from various electronic activities ranging from production, sales, repair, disposal, and recycling processes. Soils have been contaminated heavily by chemicals in electronic goods and those generated through the informal and indiscriminate disposal of electronic components that are non-recyclable [40, 41]. Pollutants have been reported in the soils directly at e-waste processing area and the one located at a considerable far distance from the main processing area. These pollutant's mobility through different environmental compartments is dependent on several environmental parameters especially adsorption-desorption process, organic matter content, degradation process, pH, uptake by biota, temperature, the intrinsic chemical characteristics of the substance, and complexation [42].

In Bangalore slum, Asia, the soil of an e-waste recycling site contained 957 mg/kg Sn, 2850 mg/kg Pb, 4.6 mg/kg In, 39 mg/kg Cd, 49 mg/kg Hg, 2.7 mg/kg Bi, and 180 mg/kg Sb [43]. Bottom ashes of e-waste recycling facilities in New Delhi were reported to contain 3560–6450 mg/kg dw of Pb [8], 254–461 times higher in comparison with the concentration of Pb present in the bottom ash of major power plants in the same country [44]. The soil of an acid leaching site at an e-waste processing area contained PBDEs at a concentration of 4250 ng/g [45]. Studies on the metal contents of soil from e-waste informal recycling areas in metro Manila showed an elevated level of Co, Zn, Pb, Ni, Cu, Mn, and Cd [40, 41]. A similar study from Guiyu, a major recycling site in China, showed an elevated level of heavy metals compared to those of Bangalore [46]. The report of Luo et al. [47] showed that soil from farmland about 2 km away from a workshop where informal e-waste recycling takes place contained 191–9156 ng/g (dry weight) of PBDE. PCBs, PCDD/Fs, and PAHs were also recorded at 330, 100, and 20, 000 ng/g, respectively, from the soils of this region [48]. In another study by Hoa et al. [49] in northern Vietnam, unsubstituted and methylated PAHs were found to heavily contaminate about 60% of soil and river sediment samples from an e-waste informal recycling village. Mutagenic and carcinogenic PAHs in the soil samples were significantly higher in comparison to the soil of the control site. Meanwhile, concentrations of anthracene, benzo[*a*]pyrene, benz[*a*]anthracene, fluoranthene, and phenanthrene in the e-waste contaminated soil samples were above the maximum permissible concentrations, an indication of possible ecotoxicological risk.

Similar reports from Africa showed contamination of soil by e-waste activities. Reports of high vegetation and soil contamination by PAHs, heavy metals, and PBDEs from e-waste activities at an informal recycling site in Agbogbloshie, Ghana, have been documented [50–52]. Bridgen et al. [53] showed that several chemical contaminants were found in soil samples contaminated with ashes of e-waste open burning at both Agbogboloshie and Korforidua in Ghana, where Pb, Cd, and antimony were present at concentration over 100 times typical background levels for soils. In a recent report by Moeckel et al. [54], PCDD/Fs concentrations in surface soils

from Agbogbloshie were up to hundreds of nanogram per gram while those of PBDD/Fs up to thousands of nanogram per gram (dry weight). The WHO-TEQ concentrations at open burning areas were up to 24 times greater than the USA action level, whereas those for non-burning areas exceeded the USA screening level [55]. The study of Fosu-Mensah et al. [52] on soil from vegetable farmland contaminated with e-waste burning around Korle Lagoon, Accra, Ghana, showed that Cd (103.66 mg/kg), Sn (705.32 mg/kg), Ni (72.00 mg/kg), Cu (202.99 mg/kg), and Pb (184.44 mg/kg) concentrations were higher than the WHO/FAO thresholds for agricultural soils.

Alabi and Bakare [56] reported a high level of Ni, Pb, Cr, Cu, Mn, Cd, and Fe in raw leachates and soil from e-waste informal dumpsites at Alaba International and Computer village markets in Lagos, Nigeria. Assessment of the same sites a year later by Alabi et al. [57] in comparison with e-waste recycling site in Guiyu, China, showed an increased concentration of heavy metals in the soil and leachate compared to the previous report. Their report also indicated a higher heavy metal concentration in Nigeria's e-waste contaminated soil compared to Guiyu soil. The soils from both countries were contaminated heavily with toxic PBDEs, PCBs, and PAHs from e-waste activities. A similar result on the same site in Nigeria was reported by Olafisoye et al. [58]. They also noted that concentration levels of heavy metals were affected by a change in season and depth of soil. Adesokan et al. [59] assessed heavy metal contamination of soil from the low, medium, and high e-waste informal recycling activities in Ogunpa, Ibadan, Nigeria. Their results indicated that Cu and Pb were several times higher compared to the control soil. The study of metal speciation showed that in the presence of slight changes in the natural conditions, about 88% and 65% of the Cu and Pb, respectively, will be liable to possible mobility.

Study by Taiwo et al. [60] showed that soil samples from three e-waste dumpsites in Nigeria had higher bacterial and fungal counts than the control soil. Eleven bacterial and five fungal isolates were obtained from the dumpsites with the highest frequencies from *Bacillus spp* (29.8%) and *Aspergillus spp* (79.9%). The soil's Zn, Pb and Cu concentrations were above the WHO and Nigeria Federal Environmental Pollution Agency permissible limits.

Atmospheric contamination by e-waste

The release of e-waste contaminants into the air through dust is a major pathway for human exposure through inhalation, skin absorption, and ingestion [61]. Different studies have established severe ambient air contamination by heavy metals, brominated and chlorinated compounds in the surroundings of e-waste recycling in China. Open burning of e-wastes has resulted in the presence of elevated air concentration of total PBDEs of up to 16,575 pg/m^3 in Guiyu, which was 300 times higher than in nearby Hong Kong [62]. PBDEs contamination of ambient air in Guiyu is higher than 11, 000 pg/m^3 at daytime, and about 5, 000 pg/m^3 during the night time [63]. Detection of elevated levels of heavy metals including Cu, Zn and Cr at 483, 1038 and 1161 ng/m^3, respectively, in Guiyu were between 4 and 33 times higher compared to the levels recorded in other Asian countries, while PAHs at concentrations of 22.7–263 and 40–347 ng/m^3 in PM2.5 and TSP, respectively, and PBDD/Fs at a concentration of 8.12–61 pg/m^3 were also recorded in the same site [64]. The highest concentration of PCDD/Fs in ambient air worldwide was reported in Guiyu at 64.9–2365 pg/m^3 [65]. The range of atmospheric phthalates esters (PAE) concentrations is 200–1200 ng/m^3 near e-waste recycling sites, which is about 1–2 times higher in comparison to nearby urban areas [66, 67].

The concentrations of Cr, Bi, Mn, Co, Sn, Ti, In, Pb, Cu, and Sb in ambient air around an e-waste recycling site in Bangalore, India, was reported to be higher compared to the reference site [42]. A comparative report of the air concentration of PBDEs (BDE-17, 28, 47, 49, 66, 85, 99, 100, 153 and 154) in e-waste storage facility in Thailand and China showed that the PBDE concentrations of the indoor and outdoor air of the storage facility in Thailand was reported to be 46–350 and 8–150 pg/m^3, respectively, but were lesser than the concentration of PBDEs in indoor and outdoor air in China [68]. A study from an e-waste processing facility in Canada showed that the ambient air of the workbenches was contaminated with BDE-209 (156 ng m^{-3}) and Tris (2- chloroethyl) phosphate (59 ng m^{-3}), while the dust was contaminated with BDE-209 (96,300 ng g^{-1}) and Triphenyl phosphate (47,000 ng g^{-1}) compared with the control site [69].

In Africa, PBDEs have been detected in the dust samples of e-waste workshops in South Africa at levels greater than those recorded in Guiyu, China. PCBs 28, 153 and 180 were also detected in the sampled dust with PCBs 153 and 180 as the most predominant [70]. In Westminster electronic market in Lagos, Nigeria, Adaramodu et al. [71] reported a high concentration of Fe, Cr, Pb, Cd, and Zn in surface dust from workshops (indoor), and around the market areas (outdoor). In another study, Getachew et al. [72] reported the contamination of surface dust by heavy metal at maintenance workshops for electronic and electrical equipment in Nekemte, Gedo, and Ambo towns, Ethiopia. The concentrations of heavy metals in the surface dust from the three sites followed a decreasing order of Pb > Fe > Cu > Cr > Zn > Co > Ni > Cd, an indication of the presence of an elevated concentration of Pb in the surface dust samples.

Aquatic system contamination by e-waste

E-wastes can contaminate aquatic systems through leaching of the constituents from the dumpsites where unprocessed or

processed e-wastes have been dumped. Furthermore, informal processing of e-waste such as hydrometallurgical processes can lead to acid disposal into soils and water bodies, while open burning of e-waste can release air pollutants which can eventually result in aquatic system contamination [35].

Sediment from lagoon adjacent to the disposal and burning areas in Agbogboloshie market in Ghana was found to contain an elevated level of Cu, Pb, Zn and Cd [53]. Report from Accra showed that PCB levels in e-waste contaminated sediment was 0.57–32.2 ng/g dw, which was lower than the levels reported in large e-waste sites in China, but comparable or higher than the levels documented in Vietnam, the Philippines, Indonesia, India, Japan, and Senegal [73]. The highest concentration of PCB recorded in this study (32.2 ng/g dw) exceeded the maximum acceptable level in the sediment quality guideline (22.7 ng/g) set by US National Oceanic and Atmospheric Administration [74]. Bakare et al. [75] documented that the concentrations of Pb, As, Cu, Cd and Cr in underground water near a major e-waste market in Alaba International market, Lagos, Nigeria, were significantly higher than the maximum allowable for drinking water by regulatory organizations, and the water was cytogenotoxic in *Allium cepa* and mice. In a comparative study of e-waste contamination of underground water in computer village and Alaba international market, Lagos, Nigeria, Alabi and Bakare [76, 77] reported a high level of Cd, Cr, Cu and Pb and some POPs in underground water from both locations. However, the underground water at Alaba international market had higher concentrations of POPs and heavy metals, which was attributed to the duration of operation and larger volume of e-waste at this location.

Wastewater from India [8, 78] and Guiyu [8, 79] were reported to have Pb concentrations ranging from 17 to 247 times higher than in other areas with no known electronic activities. The report of Wang and Guo [80] showed that a river located downstream of an e-waste recycling plant in Guiyu was contaminated with 0.4 mg/L Pb, which is 8 times higher than the local standard of 0.05 mg/L for drinking water. In nearby Lianjing river, a significantly high level of Se, Mo, Ag, Sb, Li, and Cr were reported by Wong et al. [81]. Sediments collected in a cyanide leaching area [78], Lianjing river [8] and near open burning sites [82] in China contained heavy metals especially Pb in concentrations higher than other non-electronic activity sites. Also, PBDE bioaccumulation has been reported in Nanyang river near Guiyu [83]. Higher concentrations of PCDD/Fs in Lianjing riverbank [84] and Suzhou Creek, China [85], and in sediments collected from the Elbe river, Europe [86] have been documented. The authors concluded that these higher concentrations were due to the prevalence of electronic activities in the study locations.

E-wastes contamination and toxicity in plants

Evidence have shown plant contamination by e-waste constituents. High levels of PCBs and PBDEs in plants from Guiyu and the surrounding areas have been documented [87]. Study has shown that there can be translocation of PBDE to plant from the soil. Leaves of Eastern daisy fleabane (*Erigerun annuus* L.), spider fern (*Pteris multifida* Poir), Japanese dock (*Rumex japonicus* Huntt.), sorghum (*Sorghum bicolor* L.), and bracken fern (*Pteridium aquilinum* L.) contained PBDEs at concentrations of 326, 116, 278, 162, and 144 ng/g (dry matter), respectively, when grown in soil that contained 25, 479 ng/g PBDEs [88]. Plant uptake of such contaminants can be a possible route through which these contaminants enter the food chain, even though the bioaccumulation coefficient is less than 0.01 [35].

Study on e-waste contamination of rice grown in Taizhou, an e-waste processing town in eastern China, showed the concentrations of Cd and Pb to be 2–4 times greater than the Chinese maximum allowable limits (0.2 mg/kg) of these metals in food samples [89]. In another study, paddy soil located adjacent to an e-waste recycling site in Zhejiang province was reported to cause a reduced rate of rice germination [90]. In addition, vegetables harvested from e-waste sites contain elevated PAE levels [91]. Alabi et al. [57] showed that edible *Amaranthus* species grown on e-waste contaminated soil in Nigeria contained elevated levels of Cd, Pb, Cr, Ni, Cu, PAHs, PCBs, and PBDEs. The concentrations of Cr, Ni, Cd, and Pb in the leaves, stems, and roots of *Ipomea batatas* and *Eleusine indica* from three e-waste dumpsites in Lagos, Nigeria were found to be significantly high with positive correlation to the metals in the soils from where the plants were collected [92].

There are limited studies on e-waste induced toxicity in plants. In Nigeria, Bakare et al. [75, 93] showed the cytogenotoxic effects of Alaba International electronic market's raw and simulated e-waste leachates and e-waste contaminated underground water in *A. cepa*. The authors concluded that Cd, Fe, Cu, Mn, Cr, Ni, Zn, Pb and As present at different concentrations in these samples were responsible for the observed cytotoxicity and genetic damage. Babatunde and Anabuike [94] reported similar findings in *A. cepa* but with e-waste leachates from south-south Nigeria. Likewise, the micronuclei (MN) assay in *Vicia fabia* suggested that e-waste contaminants in soils can induce significant damage to the DNA of the exposed plant [90].

E-waste contamination and toxicity in animal

E-waste constituents have been reported to be present in aquatic and terrestrial animals found in and around the vicinity of e-waste processing activities. Bioaccumulation of PBDEs have been documented in water snake captured in an aquatic

environment close to an e-waste recycling plant [95], peregrine falcons [96], waterfowl [97], Virginia freshwater fishes [98], fishes collected from rivers in Michigan and Illinois, USA [99], and farmed rainbow trout and wild whitefish from Swiss lakes [100]. Elevated concentrations of PCBs and PBDEs in fish [101] and snails [87] in Guiyu and the surrounding areas have also been documented. Analysis of PBDEs in chicken tissues from Guiyu recorded a concentration as high as 18 ng/g of PBDEs, and Liang et al. [102] concluded that the presence of this toxin at this high concentration may pose a threat to the ecosystem and public health.

Aside the animal body burden of chemicals presents in e-wastes, studies have shown the toxicity of exposure to e-waste in different animal models. The first major report by Alabi and Bakare [56] showed that simulated and raw leachates obtained from informal e-waste dumpsites in two major Nigerian electronic device markets induced chromosome aberrations (CA), MN, and abnormal sperm morphology in mice. In another study, Alabi and Bakare [76] reported that underground water contaminated by e-waste processing induced significant MN in the bone marrow and abnormal sperm morphology of mice that drank the water.

Another study by Song et al. [103] reported that exposure to PBDEs from e-waste activities induced erythrocyte DNA damage and thyroid endocrine dysregulation in juvenile *Crucian carp*. In addition, Bakare et al. [75] reported induction of cytogenetic damage in peripheral erythrocytes of *Clarias gariepinus* after exposure to raw leachates from e-waste dumpsites and e-waste contaminated water. The study linked the e-waste constituents in the water and raw leachate with the observed genetic damage and nuclear abnormalities in the exposed fishes. Assessment of oxidative biomarkers such as lipoperoxidation, catalase, reduced glutathione, and superoxide dismutase levels showed that oxidative stress might be a possible mechanism of observed genotoxicity. The authors concluded that the elevated levels of AST and ALT in *C. gariepinus* were indicative of a hepatic injury after leachates and water exposure.

Human exposure and public health effect of e-wastes

Human exposure routes to e-waste

Inhalation, dermal contact and ingestion are the main human exposure routes to the hazardous constituents present in e-wastes (Table 4). Aside from the direct formal and informal occupational exposure, human exposure to e-waste and its constituents can also occur as a result of contacts with water, soil, air, dust, and food including meat [35, 105]. Pregnant women, fetuses, children, e-waste recycling sector workers, people with disabilities and elderly people have additional exposure risks. Children belong to the most sensitive group due to their changing physiology (e.g., low rates of toxin elimination and high intakes of food, air, and water), high-risk behaviors (e.g., hand-to-mouth activities, and high risk-taking activities in adolescence), and additional exposure routes (e.g., breastfeeding and placental exposures) [106]. Contamination took home by parents working with e-waste on their skin or clothes constitute additional exposure routes for children and much worse when recycling is carried out inside such homes due to direct high-level exposure. Women born and raised in the recycling sites and are now pregnant present a longer history of exposure to e-waste and increased body burden in physiologic deposits compared to women who relocated to the sites at the time of marriage. Lactational and transplacental exposure to e-waste lipophilic organic pollutants and heavy metals is expected [106].

Human body burden of e-waste constituents

The level of PBDEs in human biological samples have been documented in many countries. Analysis of PBDEs in breast milk samples of women in Venice and Rome [107], Pacific Northwest [108], Catalonia-Spain [109], United States [110], Japan [111], and Sweden [112] showed the presence of an elevated level of this contaminant. Elevated levels of PBDEs have been documented in liver tissues from stillborn fetuses [113], human adipose tissues [114], and cord blood [115, 116]. BDE-47, 99, 100, 153 and 154 are the five most prevalent congeners found in human tissues, and are responsible for about 90% of the total human burden [117]. Very high BDE-209 concentration has been recorded in electronic dismantling workers in China [118, 119] with a high concentration of 182 ng/g, 30 ng/g, and 58 ng/g of PCBs, PBDEs, and PBBs, respectively, in samples of human hair [120]. Luksemberg et al. [84] showed that the total concentration of PCDD/F in samples of residents' hair close to Guiyu's e-waste recycling facilities ranges from 16.4–25.6 pg WHO-TEQ/g dw, similar in concentration to the level of PCDD/F recorded in hair samples obtained from people in a Chinese site which was highly contaminated with pentachlorophenol [121], and approximately 29–466 times greater than the PCDD/F concentration of subjects exposed to contaminated ambient air in Ryugasaki and Tsukuba, Japan [122]. PAHs were reported at very high concentrations in the urine sample of pregnant women [123] and children [124–126] at Guiyu. In Southern China, the body burden of PAEs in people exposed to e-wastes showed a total urinary concentration of 11 mPAEs in the e-waste sites ranged from 11.1 ng/mL to 3380 ng/mL, and were dominated by mono-(2-isobutyl) phthalate and mono-n-butyl phthalate [127]. Report of Fobil et al. [128] have also shown the presence of increased concentrations of blood dibenzofurans and polychlorinated dibenzo-p-dioxins, chemicals produced during e-waste burning, in recycling workers.

Table 4 Chemical classification of e-waste components and sources and routes of exposure

Persistent organic pollutants	Component of electrical and electronic equipment	Ecological source of exposure	Route of exposure
Brominated flame retardants	Fire retardants for electronic equipment	Air, dust, food, water, and soil	Ingestion, inhalation, and transplacental
Polybrominated diphenyl ethers	Dielectric fluids, lubricants and coolants in generators, capacitors and transformers, fluorescent lighting, ceiling fans, dishwashers, and electric motors	Air, dust, soil, and food (bioaccumulative in fish and seafood	Ingestion, inhalation or dermal contact, and transplacental
Polychlorinated biphenyls			
Dioxins			
Polychlorinated dibenzodioxins and dibenzofurans	Released as combustion byproduct	Air, dust, soil, food, water, and Vapour	Ingestion, inhalation, dermal contact, and Transplacental
Dioxin-like polychlorinated biphenyls	Released as a combustion byproduct but also found in dielectric fluids, lubricants and coolants in generators, capacitors and transformers, fluorescent lighting, ceiling fans, dishwashers, and electric motors	Released as combustion byproduct, air, dust, soil, and food (bioaccumulative in fish and seafood)	Ingestion, inhalation, and dermal Absorption
Perfluroalkyls	Fluoropolymers in electronics	Water, food, soil, dust, and air	Ingestion, dermal contact, inhalation, and transplacental
Polyaromatic hydrocarbons			
Acenaphthene, acenaphthylene, anthracene, benz[a]anthracene, benzo[a]pyrene, benzo [e]pyrene, benzo[b] fl uoranthene, benzo[g,h,i] perylene, benzo[j]fluoranthene, benzo[k]fluoranthene, chrysene, dibenz[a,h]anthracene, fluoranthene, fluorene, indeno[1,2,3-c,d]pyrene, phenanthrene, and pyrene	Released as combustion byproduct	Released as combustion byproduct, air, dust, soil, and food	Ingestion, inhalation, and dermal contact
Persistent organic pollutants	**Component of electrical and electronic equipment**	**Ecological source of exposure**	**Route of exposure**
Elements			
Lead	Printed circuit boards, cathode ray tubes, light bulbs, televisions (1 · 5–2 · 0 kg per monitor), and batteries	Air, dust, water, and soil	Inhalation, ingestion, and dermal contact
Chromium or hexavalent chromium	Anticorrosion coatings, data tapes, and floppy disks	Air, dust, water, and soil	Inhalation and ingestion
Cadmium	Switches, springs, connectors, printed circuit boards, batteries, infrared detectors, semi-conductor chips, ink or toner photocopying machines, cathode ray tubes, and mobile phones	Air, dust, soil, water, and food (especially rice and vegetables)	Ingestion and inhalation
Mercury	Thermostats, sensors, monitors, cells, printed circuit boards, and cold cathode fluorescent lamps (1–2 g per device)	Air, vapour, water, soil, and food (bioaccumulative in fish)	Inhalation, ingestion, and dermal contact
Zinc	Cathode ray tubes, and metal coatings	Air, water, and soil	Ingestion and inhalation
Nickel	Batteries	Air, soil, water, and food (plants)	Inhalation, ingestion, dermal contact, and Transplacental
Lithium	Batteries	Air, soil, water, and food (plants)	Inhalation, ingestion, and dermal contact
Barium	Cathode ray tubes, and fluorescent lamps	Air, water, soil, and food	Ingestion, inhalation and dermal contact
Beryllium	Power supply boxes, computers, x-ray machines, ceramic components of electronics	Air, food, and water	Inhalation, ingestion, and transplacental

Source: Grant et al. [104]

Reports from Guiyu showed high Pb concentration in the blood of children exposed to e-waste [116]. Further studies in this site observed a high concentration of Cr, Cd, Pb, and Cu in the blood of preschool-aged children and neonates [129, 130]. Similar human studies in China have shown a high concentration of Pb in adults [131] while Cd, Cr, and Mn were reported in pregnant women in Guiyu [132]. Elevated levels of PAH metabolites, Pb, Ni, As, and Co were also documented in urine samples from workers in e-waste processing facilities [128]. Elevated concentration of urinary Cr and blood Pb have been reported in e-waste informal recycling workers in Delhi, India [133].

Human exposure to e-waste in Africa was reviewed by Orisakwe et al. [134]. Open burning of e-waste may pose the highest health risk as individuals involved in this burning tend to record the highest concentrations of blood Pb. Report from Ghana showed increased blood Pb in workers in e-waste processing facilities than non-e-waste workers [135]. Analysis of urine and blood samples from female and male workers in e-waste recycling and processing at Agbogbloshie, showed elevated Pb and Cd in the blood and As in the urine samples [136]. The concentrations of Fe, Cu, Pb, and Al in samples obtained from workers in e-waste plants were higher than the threshold limits set by the American Conference of Governmental Industrial Hygienists [137]. In another study in Ghana, urine Sb, Pb, and Fe from e-waste processing workers were at concentrations of 0.89, 6.06, and 130 lg/l, respectively, which were significantly higher than the control site [138]. Aside from heavy metals, Wittsiepe et al. [139] indicated a direct exposure of workers at the Agbogbloshie to PCDD and especially to PCDF as combustion products. The PCDD/F blood levels were related to the time participants were working at the e-waste site. Similarly, analyses of hexabromocyclododecane, PBDEs and PCBs in the breast milk of Ghanaians exposed to e-wastes showed concentrations of these chemicals to be lower than concentrations reported in similar people in China, however, the concentrations recorded were of public health concern [138]. In Nigeria, Popoola et al. [140] reported a high concentration of blood MN and Pb in scavengers at an e-waste dumpsite in Alaba International Market, Nigeria. Recently, Alabi et al. [141] showed significantly high concentrations of Pb, Ni, Cd, and Cr in the peripheral blood of teenage scavengers at e-waste dumpsites in Alaba international market, Nigeria. The elevated blood metal concentration was found to be dependent on the duration of scavenging the e-wastes.

Epidemiological evidence of e-wastes induced toxicity in humans

There are mounting evidences on the public health impact of e-waste. Evidence from experimental and human studies, on mode(s) of action and main long-term effects from chronic/repeated exposure to e-waste chemicals have been documented (Table 5). These effects were observable in children and adults, males and females, including fetuses. Respiratory diseases have been reported in 80% of children living in Guiyu, with particular vulnerability to Pb poisoning [143, 144]. A significant increase in blood Cd [145] and Pb [116, 146] have been reported in children in Guiyu and its associated reduced cognitive abilities in comparison to the control subjects from a nearby town. Study in Guiyu has shown a positive correlation between elevated Cr concentration in infants' umbilical cord blood, mother's e-waste exposure and DNA damage [147]. In recent studies, e-waste Pb toxicity in preschool-age children has been linked to DNA methylation and hearing loss [130], decreased erythrocyte CD44 and CD58 [129], difficulties in sensory integration [147,148], and cardiovascular endothelial inflammation [149]. Also, e-waste associated PAHs in preschool-age children have been linked to high expression of NLRP3 and AhR; and cytokine storm [124]; low concentration of insulin-like growth factor 1 in the plasma [150], antioxidant alterations [126], cardiovascular endothelial inflammation [149], and alterations in platelets indices [151]. Herbstman et al. [152] reported an association between lowered levels of mental and physical development in children and mothers exposure to PBDEs during pregnancy. Lymphocytic DNA damage was reported to significantly differ in neonates of Guiyu when compared with the neighboring town, Chaonan, with a significant positive correlation to blood Cr concentration [145]. Decreased testis size and sperm concentration [153], reduced fecundability, attention problems and decrease fine manipulative abilities in school-age children [154], metabolic syndrome and diabetes [155], increased serum luteinizing hormone (LH) and cryptorchidism [156], decrease follicle-stimulating hormone, free androgen index, and LH with increase sex hormone-binding globulin (SHBG), free T_4 and inhibin B in men [157], increase estradiol, inhibin B and SHBG in infants [158], and decrease thyroid-stimulating hormone and subclinical hyperthyroidism in pregnant women [159] are all documented health effects in humans due to exposure to PBDEs in e-waste sites. Findings from two ecological data [116, 160] indicated a significant reduction in the indicators of physical growth especially body-mass index, height, and weight in children living in Guiyu. Association between children's health and exposure to air contaminants from e-waste showed that Guiyu's PM2.5 concentration was higher than what was recorded in Haojiang (control), resulting in a higher individual PM2.5 chronic daily intake (CDI). Concomitantly, saliva salivary agglutinin levels were lower in Guiyu children, and were negatively correlated with CDI. Additionally, peripheral counts of white blood cells, and the concentrations of interleukin-8 and tumor necrosis factor-alpha in Guiyu children were greater than in the control group, and were positively associated with CDI. Similar results were found for neutrophils and monocytes [127].

Table 5 Evidence from experimental and human studies, on mode(s) of action and main long term effects from chronic/repeated exposure to E-waste chemicals. Available safe dose (total daily, or weekly, dietary intake or upper level) are reported

Chemical	Mode(s) of action	Effects	Reference dose
PCDD/Fs	Significant bioaccumulation related to lipid solubility. Interaction with the AhR.	Reproductive and neurobehavioral development Immune development Carcinogenicity	TWI: 14 pg WHO-TEQ/kgbw
PBDEs	Significant bioaccumulation related to lipid solubility. Interaction with thyroid hormones. BFR may activate Pathways related to nuclear receptors, as shown by the Expression of the CYP isoforms CYP1A1, CYP2B and CYP3A, representing of, respectively. Aryl-Hydrocarbon (AhR, dioxin receptor), Constitutive-Androstane and Pregnane-X receptors	Reproductive development Neurobehavioral development Thyroid function, Hormonal effect levels in animals start from *ca* 1 mg/kgbw, but effects on spermatogenesis, suggesting hormonal causes have been observed at a low dose (60 μg/kgbw) of the PBDEs congener BDE-99	TDI: 0.15 μg/kgbw
PCBs	Significant bioaccumulation related to lipid solubility. Congeners with different modes of action: DL PCBs are similar to PCDD/Fs (interaction with AhR), though generally less potent; NDL PCBs show different properties concerning toxicity and persistence: interference with the metabolism of thyroid and estrogens, oxidative stress	Both NDL and DL PCBs may exert a variety of toxicological effects, including carcinogenicity on multiple targets such as liver, thyroid, immune function, reproduction and neurobehavioral development. DL PCB may act as tumor promoters in tissues such as liver; different congeners may alter different pathways, such as the induction of oxidative stress and/or inhibition of apoptosis	TWI (DL PCB): 14 pg WHO-TEQ/kgbw
PAHs (high molecular weight)	Genotoxic damage Oxidative stress Interaction with AhR	Carcinogenicity Mutagenicity Teratogenicity	
Al	Interaction with Ca cell-cell communication	Skeletal development and metabolism, Neurotoxicity Foetal toxicity	TWI: 1 mg/kgbw
As	Oxidative stress Interaction with glucorticoid receptor	Skin alterations. Decreased nerve conduction Increased risk of diabetes and cancer (skin and other tissues)	
Cd	Oxidative stress Interaction with essential elements as Ca and Se Agonist of ERα	Kidney damage, renal toxicity, bone disease (osteomalacia and osteoporosis). Possibly reproductive damage, and lung emphysema.	0.14–0.26 mg per day
Cu	Essential element[a], may be toxic at high dose levels	Liver damage	upper level: 5 mg per day
Cr(VI)	Cytotoxicity Oxidative DNA damage, mRNA expression of StAR, SF-1, 17β-HSD-1, 17β-HSD-2, FSHR, LHR ERα and ERβ Hypothalamic-pituitary-gonadal axis Oxidative stress	Carcinogenicity Reproductive functions Endocrine function Ovotoxicity	
Fe	Essential element[a], may be toxic at high dose levels	Liver damage	not established
Hg	Interaction with sulphur aminoacids Cell proliferation/differentiation/communication Interaction with Se, Methylmercury can bioaccumulate	Neurobehavioral development of children (especially methymercury) Anemia, kidney damage, chronic neurotoxicity	
Pb	Interaction with sulphur aminoacids Cell proliferation/differentiation/communication	Neurobehavioral development of children Anemia, kidney damage, chronic neurotoxicity	
Se	Essential element[a], may be toxic at supranormal dose levels. Interaction with sulphur aminoacids	Hair loss, Nail brittleness, cardiovascular, renal and neurological abnormalities	300 μg per day
Zn	Essential element[a], may be toxic at high dose levels. Impaired Cu metabolism	Increased risk of Cu deficiency (anemia, neurological abnormalities)	upper level: 25 mg per day

[a] Essentiality or toxicity of chemical elements depends on chemical form, oxidation state and solubility

Source: Frazzoli et al. [142]

E-waste potential to reduce placental telomere length has been associated with an increased level of placental Cd [161]. The shortening of the fetus and newborn's telomere was associated with an increase in the cases of leukemia in children in the study location. E-waste recycling facility workers were reported to have blurred vision, rash/itching, hand-and-feet numbness, headaches [162], hypertension [163], reduce gonadal hormones [164], symptoms associated with respiratory tract and chest, discomfort in the stomach [165], nausea, allergies, aches, migraine, and cancer [166]. Exposure to e-waste has also been shown to have the potential of inducing prostate cancer in human males. Igharo et al. [167] reported that mean alpha-fetoprotein and prostate-specific antigen levels in the e-waste exposed group were significantly higher compared with non-exposed participants. Dust PBDEs in Nigeria have been linked with abnormal reproductive and thyroid functions in both adults and children [168].

Pregnancy outcomes have been studied in people exposed to e-wastes. Many studies have shown that despite differences in the toxicants assessed and exposure settings, consistent exposure effects exist with an increase rate of reduced birth weights, premature births [169–171], birth lengths [169], stillbirths [170, 171] and spontaneous abortions [166, 169]. A link has been established between adverse birth outcomes and exposure to increased concentrations of PAH [171] and POPs, including PBDEs, perfluroalkyls [169], and PCBs [171]. Similarly, close associations between e-waste recycling activities and alterations in children's temperaments have been noted in Guiyu [172].

The ability of e-waste to damage the DNA has been documented. Workers at e-waste recycling villages in the Junhai County have recently been shown to have chromosome aberrations which were 20-fold higher than the control villagers [173]. Significantly higher levels of micronucleated binucleated cells compared to the control group were observed in 49 e-waste workers [174]. The subjects with a history of working with e-wastes had a 28-fold increased risk of micronucleated binucleated cells compared with the subjects without such history. The workers also showed an elevated level of thyroid hormone which was associated with the elevated level of PBDE in the blood of the e-waste workers. Similarly, studies [175, 176] reported that e-wastes induced an increase in MN rate in people living close to the e-waste recycling site when compared with the control group. Furthermore, it was found that there were more genetic aberrations in men than in women, suggesting that men may be more susceptible to e-waste pollution-related health defects. An increase in the frequency of peripheral blood micronucleated binucleated cells of e-waste exposed individuals have been reported [177–179].

Report by Alabi et al. [141] also observed significantly high MN in the buccal cells of e-waste teenage scavengers at informal dumpsites in Alaba International market, Nigeria, where POPs were associated with a significantly higher level of CA in the populations from the e-waste disposing region. Increased MDA (5-fold higher) [173] and ROS (2-fold higher) [180] were also observed in the blood sample of exposed individuals. Eight mPAEs in urine samples of e-waste exposed workers had significantly positive associations with the urinary concentration of a DNA oxidative stress marker, 8-hydroxy-2′-deoxyguanosine [127]. In a study on perceived health issues experienced by residents and workers of major electronic markets in Lagos, Nigeria, Alabi and Bakare [166] showed positive correlations between exposure to e-waste by living in the vicinity or working at electronic markets and close to e-waste dumpsites; and significantly higher perceived public health problems.

E-waste has also been shown to upregulate or downregulate the expression of certain genes in exposed individuals. Report of He et al. [180] showed the activation of a series of DNA damage response genes in both males and females of the e-waste exposed group with dysregulation of many important DNA repair pathways. Additionally, Li et al. [176] reported that the α-hemoglobin stabilizing protein gene was down-regulated in the exposed population and exclusively down-regulated in women with intensity increasing with proximity to e-waste sites. They, therefore, concluded that the observed gender-preferential aberration might profoundly affect the genotoxicity and overall metabolism in e-waste exposed individuals. Another report by Xu et al. [181] showed the effect of exposure to e-wastes on the expression of insulin growth factor (IGF) in the placental of exposed neonates. The data revealed an upregulation of IGF-1 and IGFBP-3 genes which were shown to correlate positively with the concentrations of PAH and PBDE in the umbilical cord blood of the exposed neonates. A positive correlation was reported between changes in the expression profiles of spermatozoa's miRNA and e-waste exposure. Also, 182 miRNAs were expressed differentially when comparing unexposed and exposed individuals, with a possible correlation between exposure to e-waste, sperm count, and sperm quality [182]. Increased expression of neonates' placental metallothionein [183], downregulation of S100P proteins, increased placental Cd concentration, and metallothionein expression in mothers [184] were reported in Guiyu. In northern China, Wang et al. [185] reported associations between blood PCBs (28 congeners) and increased level of spermatozoa and lymphocytes' DNA damage of e-waste exposed men. Also, concentration of MDA in the blood serum was significantly increased while 13 genes were down-regulated.

Conclusions and recommendations

E-waste has provoked the generation and release of different types of hazardous substances especially heavy metals and POPs. This review has shown that e-waste contains constituents capable of causing environmental and human deleterious effects. However, there is an enormous data gap between exposure quantification and possible health effects. In environments with

indiscriminate disposal of e-waste and informal recycling activities, important information for epidemiological investigations, informed plans for intervention, and environmental policymaking are provided by exposure biomonitoring, most especially in vulnerable young children and pregnant women. To understand fully the effects of exposure to e-waste toxicants, there is a need for systematic studies on assessment of exposure and its associated health effects. Collaborative research by scientists from various fields (environmental scientists, engineers, toxicologists, and other professionals) is required in other to reduce or eliminate e-waste toxicants exposure. There is also a huge research gap in the reported heavy metals from environmental and biological samples after exposure to e-wastes. More data is needed especially from developing countries where informal recycling is highly practiced, hence environmental and public health are more endangered. A systematic study of the environment and exposed individuals from these areas will help to get a holistic overview of the detrimental effects of improper management of e-wastes. An important step in the prevention of this toxicant exposure will be by placing a ban on the use of hazardous chemicals in EEE manufacturing. Modernized and appropriate technologies for recycling should be mandated and utilized for e-waste. Elimination or reduction to the barest minimum of primitive and informal e-waste recycling practices is important. The households and communities should minimize the exposure of children to toxicants in e-wastes. Legislation and strict enforcement of environmental regulations on e-waste management are very necessary for the prevention of exposure to excessive toxicants. A joint effort between the developing and developed countries is necessary to regulate the manufacturing of electronic devices and e-waste's transboundary movement. Countries with the problem of primitive e-waste recycling and its associated public health effects, especially children's health should be motivated to enact regulations aimed at the proper management of recycling activities.

The following are recommendations to safeguard environmental and public health from e-waste contamination and adverse effects:

1. Governments of different countries should implement a well-coordinated management strategy to check indiscriminate disposal of e-waste into the environment. This will reduce if not eliminate the dumping and open burning of e-waste.
2. There is need for remediation of contaminated water and soil in areas involved with e-waste activities and other similar areas so as to prevent both workers and residents from further exposure to the e-waste contaminants.
3. There is need to separate residential area from e-waste recycling sites in other to prevent exposure of residents to e-waste contaminants.
4. Governments of countries where e-waste recycling is taken place must ensure that the workers wear protective gears and the process of recycling meets state-of-the-art so as to reduce or eliminate environmental contamination.
5. There is a need for public enlightenment on the hazards of e-waste exposure. This is necessary for both the workers and residents of e-wastes activity areas. The citizens also have to be educated not to dispose of their e-waste with municipal solid wastes or to store them in their attics or backyards.
6. Have measures that will encourage the use and importation of EEE manufactured with chemicals that are not toxic or hazardous, but recyclable in accordance with the EU RoHS Directive.
7. There is a need to implement Extended Producer Responsibility which mandates producers and importers/retailers to be responsible for collection, disposal, and recycling of EoL EEE.
8. Citizen's responsibility: The success of EPR depends on the full cooperation of the citizenry. Each citizen should be responsible for the type of EEE they purchase, whether it contains toxic substances or it is toxic-free, and subsequent release of such items after usage, to foster recycling by the appropriate bodies.

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