

Review

# E-Wastes: Bridging the Knowledge Gaps in Global Production Budgets, Composition, Recycling and Sustainability Implications

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Received: 31 July 2020; Accepted: 31 August 2020; Published: 9 September 2020



**Abstract:** Rapid urbanization, advancements in science and technology, and the increase in tech-savviness of consumers have led to an exponential production of a variety of electronic equipment. The global annual growth rate of e-waste volume exceeds the growth rate of the human population. Electronic waste has now become a point of concern globally (53.6 million metric tons, 2019). However, merely 17.4% of all global e-waste is properly collected and recycled. China is the largest contributor to the global production of e-waste (~19%), the second being the United States. Indeed, only 14 countries generated over 65% of global e-waste production in 2019. E-wastes contain a wide range of organic, and inorganic compounds including various metals. Emerging contaminants like plastics are amongst the fastest growing constituents of electronic waste. The current challenges include the lack of reliable data, inadequate identification and quantification of new emerging materials, limited effectiveness of current recycling technologies, need for cutting-edge detection and recycling technologies, and the lack of e-waste management policies and international collaboration. In this review, we strive to integrate the existing data on production rates at different spatial scales, composition, as well as health, economical, and environmental challenges, existing recycling technologies; explore tangible solutions; and encourage further sustainable technology and regulatory policies.

**Keywords:** electronic equipment; e-waste; WEEE; e-waste handling; recycling; zero net energy; nanoparticles; sustainability

## 1. Introduction

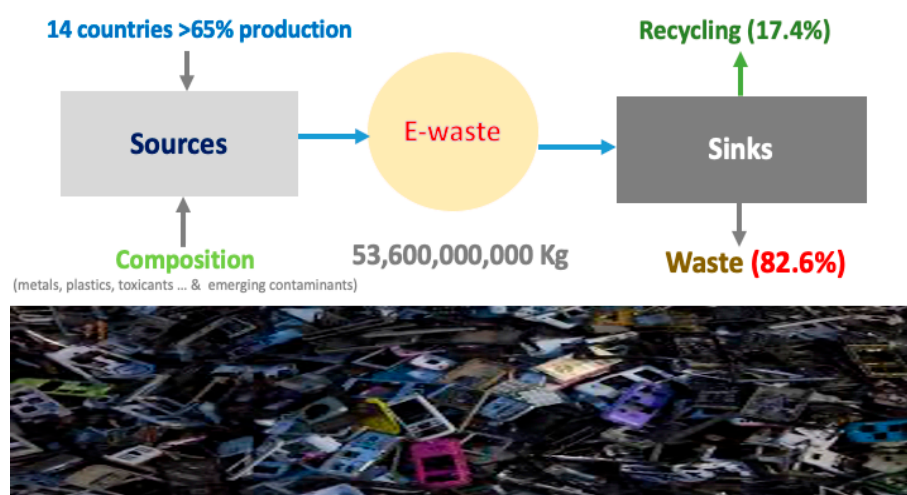
Electrical and electronic equipment (EEE) has become a backbone of modern human society. They are considered as a symbol of a modern lifestyle, comfort, efficiency, and even prosperity in developing countries. However, every EEEs become electronic waste at the end. As per the European Union (EU) WEEE Directive, e-waste is defined as “the waste from electrical and electronic equipment (WEEE) that includes all the components of electronic equipment, its subassemblies, and consumables which are the part of the product at the time it is discarded” [1]. E-waste thus includes outdated, damaged, or unwanted electronic materials.

E-waste is a fast-growing sector in the modern global economy. This acceleration is dependent on several factors such as rapid economic growth, urbanization, industrialization, and increased demand for consumer goods [2,3]. The Global E-waste Monitor 2020 reports the world generated 53.6 Mt of e-waste in 2019, up by 9.2 Mt since 2014 and is anticipated to surpass a staggering 74.7 Mt by 2030 [3].

In developing countries, the number of middle-class families with higher purchasing capacity is rapidly increasing. Therefore, people are spending more than ever before on electronic instruments. Many substances in e-waste are toxic (e.g., heavy metals such as lead, mercury, chromium, cadmium),

polychlorinated biphenyls (PCBs), brominated flame retardants (BFRs), etc. Open burning of circuit boards/wires or materials containing both chlorine and bromine can produce toxic byproducts such as multiple chlorinated and brominated dioxin compounds including mixed halogenated dibenzo-*p*-dioxins/dibenzofurans [4–6].

Developed countries such as Japan and in the European Union, and North America have the potential and infrastructure to recycle e-waste [7]; however, a significant amount of e-waste is legally or illegally transported to low-income countries having lax or no regulation for e-waste [8]. This shipment of the waste is motivated by strict e-waste policies and higher cost to recycle hazardous substances in developed countries than the cost to ship them to developing nations. The Global E-waste monitor 2020 reports that formally collected/recycled e-waste increased by 1.8 Mt since 2014 to reach ~17.4% in 2019. The whereabouts of the remaining waste is largely unaccounted for—apparently, this was illegally traded, incinerated, or dumped in landfills [3]. Figure 1 shows a schematic representation of generated, recycled, and undocumented e-waste recorded worldwide in 2019. Some developing countries such as India have recently started to impose e-waste rules, with tepid results. Although 71% of the global population is covered by the e-waste policies and legislation, their proper implementation is yet to be achieved [3] rendering informal sectors, mostly in developing countries, to handle e-waste with little or no safety precautions and knowledge and putting both the environment and public health at serious risk [9–11].



**Figure 1.** Simplified schematic of e-waste sources and sinks (2019 data), the waste deposit picture was obtained from the public domain.

E-waste is a burning topic of interest in sustainability as it touches on economy, energy, technology, culture and communication, waste management, human health, ecosystem health, international affairs, and policy. This multidisciplinary challenge is complex. However, there is an opportunity for sustainable growth. The value of raw materials in e-waste generated in 2019 is estimated to be worth nearly \$57 billion [3]. There is thus a great potential to change e-waste from a problem to a unique opportunity illustrated by the low documented collection and recycling of the waste. However, the opportunity jointly comes with challenges such as the heterogeneity of e-waste, cost of handling and treatment, toxic emissions, disposal of unwanted and hazardous remains, and lack of international collaboration.

In this review, we strive to integrate the current knowledge, analyze the challenges (economical, environmental, health, technological, governmental, policy and implementation, etc.), and explore sustainable solutions for better e-waste management. We also propose selected succinct recommendations for a more sustainable future for e-waste, which would require a progressive policy and circular economy.

## 2. Composition of E-Waste

E-waste comprises of a diverse range of substances depending upon age of e-waste, type, and categories of EEES [12,13]. A mobile phone can contain more than 40 reusable elements [14–16]. Some materials found in e-waste are precious metals (Au, Ag, Pd, Pt), base metals (Cu, Al, Ni, Sn, Zn, Fe, etc.), metals of concern (Hg, Be, In, Pb, Cd, As, Sb, etc.), halogens (bromine, fluorine, chlorine), and combustibles (plastics, organic fluids, etc.) [17]. Table 1 shows the contents of different materials in different EEES and E-wastes from different sources.

**Table 1.** Literature reported information on material composition in different types of electrical and electronic equipment (EEE) and e-waste.

EEE/E-Waste	Content (%w/w)						Content (ppm)			Ref		
	Fe	Cu	Al	Pb	Ni	Sn	Plastics	Glass	Ag		Au	Pd
TV boards	28	10	10	1.0	0.3	1.4	28	6	280	17	10	[17]
PC boards	7	20	5	1.5	1	2.9	23	18	1000	250	110	[17]
Cell phone	5	13	1	0.3	0.1	0.5	57	2	1340	350	210	[17]
Portable audio	23	21	1	0.14	0.03	0.1	47	-	150	10	4	[17]
DVD	62	5	2	0.3	0.05	0.2	24	-	115	15	4	[17]
Calculator	3	3	5	0.1	0.5	0.2	61	13	260	50	5	[17]
TV scrap	-	3.4	1.2	0.2	0.038	-	-	-	20	<10	<6	[18]
PC scrap	-	14.3	2.8	2.2	1.1	-	-	-	639	566	-	[19]
PCBs scrap	-	10	7	1.2	0.85	-	-	-	280	110	-	[20]

Note: “-” indicate data unavailable; PCB—printed circuit boards.

## 3. Diverse Materials in E-Waste: Sources and Implications

E-waste contains more than 1000 different materials many of which are valuable as well as hazardous [11,13]. Recycling through burning e-waste to separate plastic from metals [7] releases toxic substances to air, water, and soil contaminating the environment [21]. For instance, recent studies at the Abogbloshie e-waste site in Ghana showed high levels of Pb, Al, Zn, Cu, Cd, PAHs (polycyclic aromatic hydrocarbons), hydrochloric acid, and PBDEs (polybrominated diphenyl ethers) detected in soil, dust, and ash [8,22,23]. Significant levels of PCBs and PBDEs were also detected in the breast milk of local women working and/or living near the site [24].

A similar study at an e-waste dismantling site in Guiyu, China revealed that the concentrations of heavy metals in inhalable airborne particles (less than 2.5 micron diameter or PM<sub>2.5</sub>) were significantly higher [25]. Table 2 shows sources of typical toxicants of e-waste and their adverse effects on humans.

**Table 2.** Selected e-waste organic and inorganic components and their health implications.

Components	Typical Sources	Effects on Humans	Ref.
Mercury	Thermostats, sensors, monitors, printed circuit boards, cathode ray tubes, fluorescent lamps, etc.	Causes chronic brain damage.	[26,27]
Lead	Printed circuit boards, Cathode ray tubes, light bulbs, and batteries.	Harms nervous system, blood system, and kidneys; affects brain development of children.	[26,27]
Cadmium	Switches, springs, connectors, printed circuit boards, semiconductor chips, photocopy machines, cathode ray tubes, mobile phones, etc.	Respiratory irritation, chronic lung disease, toxicity to kidneys, etc.	[26,28]
Chromium	Anticorrosion coatings, data tapes, etc.	Strong allergic reactions such as asthmatic bronchitis, can cause DNA damage.	[26,27]

Table 2. Cont.

Components	Typical Sources	Effects on Humans	Ref.
Barium	Cathode ray tubes and florescent lamps	Causes brain swelling, muscle weakness, damage to heart, liver, and spleen	[26,27]
Beryllium	Power supply boxes, computers, X-ray machines, ceramic parts of electronics, etc.	May cause lung cancer and skin diseases	[26,27]
Arsenic	Doping agents in transistors and printed wiring boards	Skin ailment as well as decrease nerve conduction velocity, and lung cancer.	[27]
Brominated flame retardants (BFRs) Polybrominated diphenyl ethers (PBDEs)	Fire retardants for electronic equipment	Affects growth hormones, sexual development, immune systems, and brain development in animals	[26,29]
Polychlorinated biphenyls (PCBs)	Dielectric fluids, lubricants, coolants in generators, capacitors, and transformers, fluorescent lights, ceiling fan, dishwashers, and electric motors	Affects immune hormone, nervous, and enzyme systems. Probable carcinogens for humans.	[26,27]
Polychlorinated dibenzo-dioxins (PCDDs) Polychlorinated dibenzofurans (PCDFs)	Released as byproducts in open combustion.	Induces chloracne, increases cholesterol levels, decreases testosterone levels, increases the chances of diabetes.	[26,30]
Polycyclic aromatic hydrocarbons (PAHs)	Released as combustion byproducts	increases risk of skin, lung, and bladder cancer	[26,31]

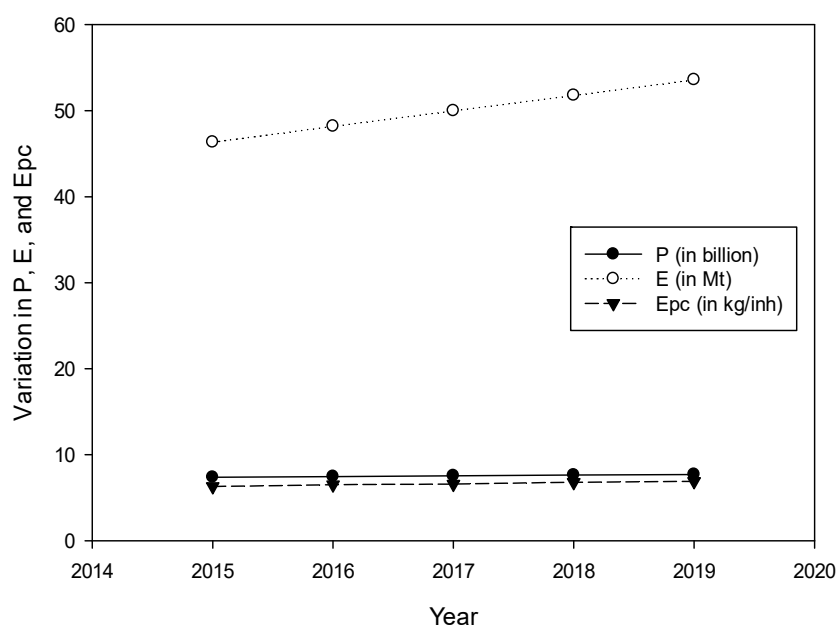
#### 4. Global, Continental, and Regional Budgets of E-Waste

##### 4.1. Global Overview

Figure 2 illustrates the changing trends of the global population, e-waste production, and e-waste per capita between 2015 and 2019. E-waste per capita has been calculated using population data from the United Nations' World Population Prospects 2019 [32]. These are listed in Table S1 of Supplementary Materials. Global e-waste generation increased from ~46.4 Mt in 2015 to ~53.6 Mt in 2019 [33]. The corresponding e-waste per capita in 2015 and 2019 were 6.3 kg/inh and 6.9 kg/inh respectively, where inh denotes inhabitant. The global e-waste generation is expected to reach a whopping ~74.7 Mt by 2030 [3]. If we consider the minimum global e-waste generated in 2005 as ~20 Mt [34] as the reference, the global e-waste production increased by ~168% between 2005 and 2019 whereas the global population increased by ~17.9% within the same period.

The compound annual growth rates of global population and electronic waste between 2015 and 2019 were calculated to be ~0.9% and ~2.9%, respectively. This suggests that global e-waste generation is growing at a faster rate than the global population. The amount of e-waste formally collected/recycled in 2019 was 9.3 Mt (~17.4%) growing by 1.8 Mt since 2014 [3]. The remaining waste and its impacts are largely unaccounted and differ in high- and middle-/low-income countries—the former is estimated to incinerate or dump ~8% of the waste which comes from discarding e-waste in waste bins, some discarded items are repaired and shipped while a significant volume of the e-waste generated (~7% to 20%) is expected to make illegal transboundary movements while in the latter case, informal sectors are responsible in handling most of the e-waste [3].

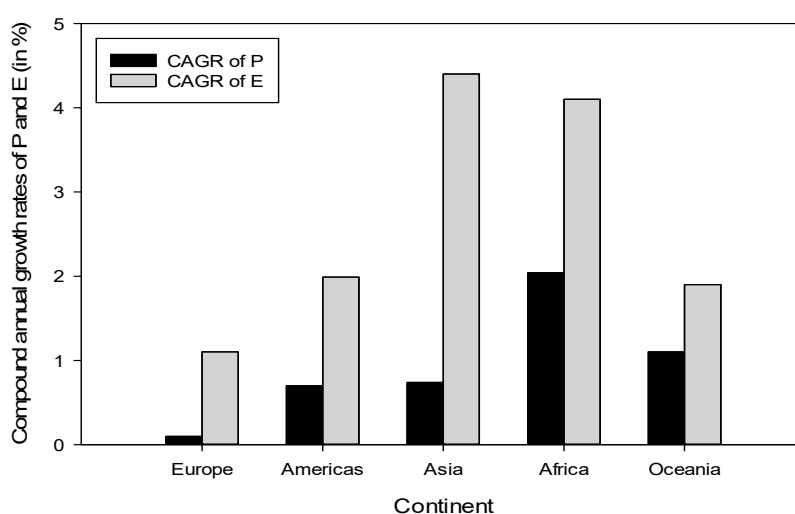
The global population covered by national legislation and policies of e-waste has increased over the years. For instance, in 2014 it was ~44% from 61 countries which increased to ~66% from 67 countries in 2017 and reached ~71% from 78 countries in 2019 [3]. An increase in the coverage of the global population by e-waste policies and legislation does not necessarily translate into the successful implementation of the policies [9].



**Figure 2.** Variation of the global population, e-waste generation, and e-waste per capita between 2015 and 2019. P, E, and Epc denote population, e-waste, and e-waste generated per capita. Source of P [32]. Global e-waste for a particular year is obtained by adding e-wastes of all the continents for the very year taken from the source [33]. Note that the error bars are not included, as the exact estimates were not presented systematically for all data. However, we raise the caveat that the minor variation can be within the margin of errors.

#### 4.2. Continental Overview

Figure 3 shows compound annual growth rates of different continents calculated between 2015 and 2019. It illustrates that the compound growth rate of e-waste is higher than the growth rate of the population indicating that e-waste is increasing rapidly in all the continents. Asia shows the highest annual growth rate of e-waste of  $\sim 4.4\%$  during this period. The e-waste annual growth rate of the remaining continents in the decreasing order are Africa ( $\sim 4.1\%$ ), Americas ( $\sim 2\%$ ), Oceania ( $\sim 1.9\%$ ), and Europe ( $\sim 1.1\%$ ), respectively. Similarly, Africa shows the highest population growth rate ( $\sim 2\%$ ) whereas Europe has the lowest ( $\sim 0.1\%$ ).



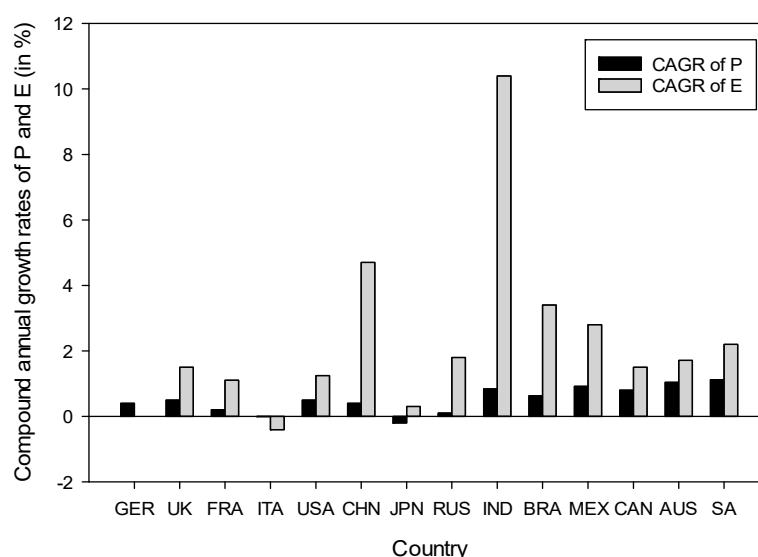
**Figure 3.** Compound annual growth rates of population and e-waste generation of five continents from 2015 to 2019. Sources of E and P [32,33].

Table S2 in Supplementary Materials shows annual population and e-waste generation data of different continents between 2015 and 2019. Asia is the largest e-waste generator in the world. It generated ~20.1 Mt and ~24.9 Mt of e-waste in 2015 and 2019 respectively [33]. Its contribution to the global production was ~43.3% in 2015 and reached ~46.5% in 2019. The huge contribution of Asia may be mainly due to the significant contributions from China and India owing to their booming economies. It can be anticipated that Asia will leave other continents far behind in the future considering the huge population and increase in per capita income of China, India, and other emerging countries.

In 2019, continents trailing behind Asia were the Americas (~13.1 Mt), Europe (~12 Mt), Africa (~2.9 Mt), and Oceania (~0.7 Mt), respectively [33]. Even if Africa generates a small volume of e-waste per annum, it is significant since much of its e-waste burden is due to the imports of new and used electronic equipment from developed countries while only a small fraction of it is due to the production of electrical equipment from a few local assembly plants [9].

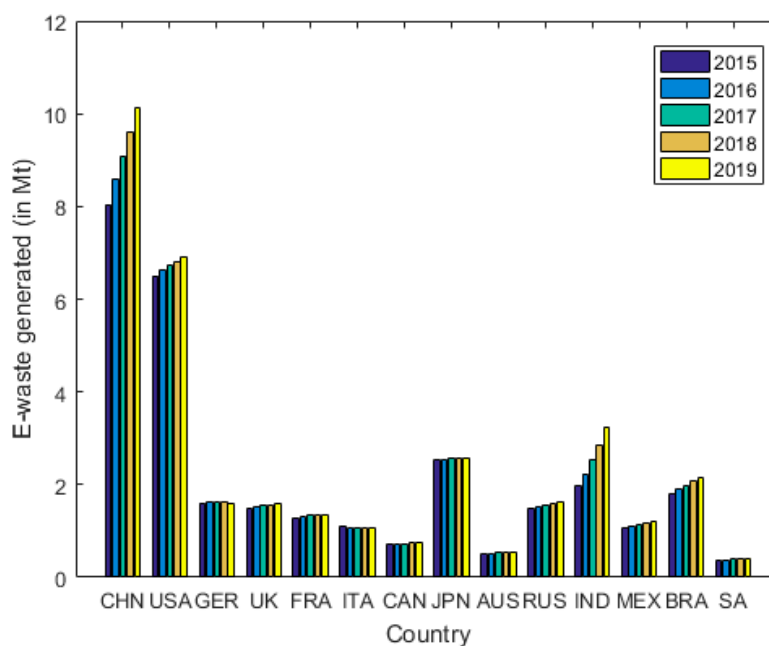
Data shows that Europe is in the forefront of collecting and recycling its e-waste. In 2017, Europe collected ~5.1 Mt of e-waste [33] which was ~43.6% of its e-waste generated in the same year. Similarly, Asia and America collected and recycled ~2.9 Mt (~13.6%) and ~1.23 Mt (~10.1%) of their respective e-wastes in 2016 [33]. In the Americas where countries such as the United States, Brazil, Mexico, and Canada generate significant volumes of e-waste per year, the collection/recycling of the waste is found to be quite inhomogeneous within the continent. North America reportedly collected ~15% of its e-waste in 2019 whereas collection and recycling of other regions of the continent were between 1% and 3% [3]. The United States and Canada are found to have similar collection/recycling rates, however, the overall waste management scope is much wider in many provinces of Canada than in the United States [3]. Oceania collected/recycled ~59 kt in 2018 [33] which represents ~9% of its e-waste generated in the same year. Meanwhile, Africa lies at the bottom with ~26 kt collected and recycled through formal channels in 2016 [33]. This merely represents ~1% of its e-waste generated in the same year.

Notwithstanding the fact that all data have been obtained from the international resources, the error bars associated with these numbers are not included in Figures 2–5. There are clearly uncertainties associated with all estimations, however, we were not able to obtain systematically the uncertainties. However, we raise the caveat that the minor variations in production over the years may fall within margins of error, which have not been evaluated.



**Figure 4.** Compound annual growth rates of population and e-waste of different countries between 2015 and 2019. Sources of E and P [32,33].





**Figure 5.** E-waste generated by different countries from 2015 to 2019. Source [33]. E-waste in China and India are rapidly growing, whereas countries such as Germany, Japan and Italy have managed to plateau their growth.

In brief, several factors such as population, socio-economic development, awareness of the general public towards e-waste, as well as government policies and regulations, play key roles in the magnitude of e-waste that a country/continent generates.

#### 4.3. Regional Overview

A couple of decades ago, developed countries, mainly Organization for Economic Cooperation and Development (OECD) countries, were responsible for generating a substantial amount of e-waste [11]. However, emerging countries are rapidly changing this global picture which can be noted from the United Nations University (UNU) reports of 2014, 2017, and 2020 [3,9,35]. China and India have seen phenomenal economic growths in recent times and have established themselves as leading economic powerhouses. A recent article from the British Broadcasting Corporation (BBC) reports that by 2050, China and India will become the top two economic giants displacing the US to the third position while other countries such as Indonesia, Brazil, Russia, Mexico, and Nigeria will also make significant economic strides [36].

In view of the emerging countries' potential impacts on the global economy and e-waste, it is meaningful to discuss the changing trend of e-waste generation of some developing countries along with the already existing economic and/or e-waste giants. The selected countries are the United States, China, Germany, United Kingdom, France, Italy, Canada, Japan, Australia, India, Russia, Mexico, Brazil, and South Africa. These countries are chosen because they contribute a significant burden to global e-waste and for representing each habitable continent.

These fourteen nations share more than 65% of the global e-waste production each year. Their percentage contributions on global generation each year from 2015 to 2019 are nearly constant (~65.7%, ~65.7%, ~65.7%, ~65.6% and ~65.7%). Population and e-waste generation data of the selected countries in the five-year period between 2015 and 2019 is shown in Table S3 of Supplementary Materials. Figure 4 shows compound annual growth rates of e-waste and population of these countries calculated in the five-year period. India shows the highest annual growth rate of e-waste more than double than the closest growth rate of China. Except for Germany and Italy, all other countries demonstrate that the growth rate of e-waste exceeds the growth rate of the population. The e-waste growth rate of Germany

is ~0% and that of Italy is negative. European countries are far ahead in the collection/recycling of e-waste while Brazil, India, and South Africa lie at the bottom. The above-mentioned EU countries have been suggested to lag far behind some other European counterparts such as Croatia (~78%), Estonia (~76%), Norway (~72%), Iceland (~71%), Sweden (~70%), Switzerland (~63%), Poland (~60%), etc. [33]. In fact, Sweden, Switzerland, Norway, Denmark, and Netherlands had developed their WEEE legislation and management systems that played important models for developing the EU's WEEE management in subsequent years [37]. Countries such as China and India lack formal and/or advanced collection/recycling facilities—a significant volume of the e-waste is expected to be managed via informal sectors with dubious knowledge and expertise in sustainable e-waste management.

#### 4.3.1. China

China is the world's most populous country with strong EEE manufacturing, exports, consumption, as well as a vast market for re-use, refurbishment, and recycling of materials [9,38]. The variation of China's e-waste from 2015 to 2019 is shown in Figure 5. Its e-waste generation rose from 8045 kt in 2015 to 10,129 kt in 2019 [33]. China's e-waste generation in 2005 was 1.8 Mt [39] and population data [32] reveal that from 2005 to 2019, China's population and volume of e-waste generation have increased by ~7.7% and ~463%. It shows the severity of growing e-waste in China which is much larger than the population growth rate.

China has been the largest generator of e-waste by recently displacing the United States to second place. China's global share of e-waste is also significant with ~17.4% in 2015 and ~18.9% in 2019. It collected 1546 kt in 2018 [33] representing ~16.1% of the electronic waste generated in the same year. Thus, contrary to China's significant rise in e-waste generation its formal collection and recycling rate is low. However, its collection rate is still higher in comparison to India and comparable to developed countries such as the United States and Canada. China has banned the imports of used EEEs [40], while it has seen a significant increase in domestic and foreign investments in recycling sector [41]. Although, China has implemented national legislation to manage e-waste collection and treatment for a range of electronic equipment, the informal sector is still dominant in the collection/recycling sectors, which makes likely unsafe e-waste handling from both health and environmental perspectives [9].

#### 4.3.2. United States

Changing trend of e-waste generated by the United States from 2015 to 2019 is shown in Figure 5. Data shows that the United States is the second largest e-waste generator in the world. Its e-waste volume increased from 6502 kt in 2015 to 6918 kt in 2019 [33]. Its e-waste volume is increasing at a compound annual growth rate of ~1.2%. Although e-waste volume in the United States is increasing annually, the contribution to global generation, however, shows a decreasing trend with ~14% in 2015 to ~12.9% in 2019. It formally collected and recycled ~15.2% (1020 kt) of electronic waste in 2017 [33]. The United States has implemented general measures to curb e-waste and its effects. For instance, hazardous electronics must be managed according to the Resource Conservation and Recovery Act (RCRA) and handling cathode ray tubes (CRTs) also have specific management rules [9].

#### 4.3.3. Germany

Germany's trend of e-waste growth from 2015 to 2019 is shown in Figure 5. The country has maintained a near-constant volume of e-waste generation with 1607 kt, 1612 kt, and 1607 kt in 2015, 2017, and 2019 respectively [33]. The compound annual growth rates of population and e-waste of Germany in the same period are calculated to be ~0.4% and ~0% respectively suggesting that Germany's e-waste generation per year has nearly plateaued. Germany's e-waste collection/recycling sector works in accordance with the management regulated by the EU's WEEE Directive. According to Eurostat [42], it collected 837 kt of e-waste in 2017 equivalent to ~51.9% of the total e-waste that it generated in the same year.



#### 4.3.4. United Kingdom

The variation in annual e-waste production of the United Kingdom from 2015 to 2019 is shown in Figure 5. The UK showed a slight and gradual increase of e-waste volume from 1483 kt in 2015 to reach 1598 kt in 2019 [33]. The compound annual growth rates of population and the e-waste generated in the same period are calculated to be ~0.5% and ~1.5%, respectively. The e-waste growth rate is smaller in comparison to the Asian, American, and African countries; however, it is still higher than many EU countries considered in the study which can be observed in Figure 4. The collection/recycling of e-waste in the UK works in accordance with the EU's WEEE Directive. Eurostat [42] shows that United Kingdom collected/recycled 871 kt of e-waste in 2017 which represents ~56.6% of its total e-waste generated in the same year. In fact, the collection/recycling rate of the UK is the highest among the list of countries herein presented.

#### 4.3.5. France

France's trend of e-waste generation per year is shown in Figure 5. The figure shows that its e-waste production increased almost steadily from 1292 kt in 2015 to 1362 kt in 2019 [33]. France, like the other EU countries mentioned above, shows smaller annual growth rates in both population (~0.2%) and e-waste generation (~1.1%) for the five-year period. E-waste policies in France comply with the EU's WEEE Directive. Eurostat [42] shows that France formally collected and recycled 742 kt of e-waste in 2017 corresponding to 55.6% of the total weight of electronic waste that it generated in the same year.

#### 4.3.6. Italy

E-waste generated by Italy between 2015 and 2019 is shown in Figure 5. Unlike the other EU countries, Italy showed a negative growth rate of both population and e-waste and the declining rate of e-waste is higher than that of the population. Its e-waste volume gradually decreased from 1085 kt in 2015 to 1077 kt in 2017 and reaching 1063 kt in 2019 [33]. Like other EU nations, the e-waste collection/recycling sector of Italy works in accordance with the management regulated under EU's WEEE Directive. Italy collected 369 kt of e-waste in 2016 equivalent to ~34.1% of the total e-waste that it generated in the same year [33].

#### 4.3.7. Canada

Canada's trend of e-waste generated between 2015 and 2019 is shown in Figure 5. There is a gradual increase of e-waste volume from 703 kt in 2015 to 732 kt in 2017 reaching 757 kt in 2019 [33]. Canada managed to collect 101 kt of e-waste in 2016 [33] which represents ~14.1% of its total electronic waste generated in the same year. Except for Nunavut, which is the least populated region, 12 provinces and territories of Canada have implemented different forms of e-waste regulations [3].

#### 4.3.8. Japan

Figure 5 illustrates the trend in e-waste generated by Japan in the period between 2015 and 2019. The figure shows that Japan's e-waste is growing, yet at a much smaller rate in comparison to other Asian countries such as China and India. It generated e-waste volume of 2532 kt in 2015, 2560 kt in 2017, and reached 2569 kt in 2019 [33]. Figures 4 and 5 shows that Japan's e-waste growth rate is smaller than other Asian, American, and African countries and its population is declining annually. The negative growth rate of the population of Japan suggests that it will somehow affect its EEE consumption thereby annual changing e-waste generation and e-waste per capita in the long term. Like EU, Japan has strong e-waste management legislations and collects/recycles most of UNU's categories of electronic scraps [9]. It collected 570 kt of e-waste in 2017 [33] representing ~22.3% of its electronic waste generated in the same year. The collection rate is smaller than the EU countries but still higher than the American and Asian counterparts.

#### 4.3.9. Australia

Annual variation of electronic waste generated by Australia between 2015 and 2019 is depicted in Figure 5. In 2015, Australia produced 509 kt of electronic waste that reached 534 kt in 2017 and 554 kt in 2019 [33]. The compound annual growth rates of population and e-waste calculated within the same time interval is shown in Figure 4. In 2010, Australia generated 410 kt of e-waste [43] suggesting that between 2010 and 2019 its e-waste volume increased by ~35.1%. In the entire Oceania region, only Australia has implemented a national scheme to manage electronic waste through the National Television and Computer Recycling Scheme (since 2011) [9]. Australia collected 58 kt of e-waste in 2018 [33], which represented ~10.7% of its total weight of electronic waste produced in the same year.

#### 4.3.10. India

India's annual e-waste generation in the period 2015–2019 is depicted in Figure 5. Its e-waste generation increased sharply from 1973 kt in 2015 to 2529 kt in 2017 reaching 3230 kt in 2019. The compound annual growth rates of population and e-waste generated are calculated to be ~0.8% and ~10.4%. As shown in Figure 4, this is the highest growth rate of e-waste among all the countries taken into consideration. Furthermore, the growth rate of e-waste far exceeds the growth rate of the population.

India generated 134.7 kt of e-waste in 2005 [44]. Thus, between 2005 and 2019, India's e-waste volume grew by ~2298%. In the same period, China's e-waste volume increased by ~463%. The aforementioned figures, however, do not ascertain that India's annual e-waste generation would exceed China's generation in the near future. China's per capita income and population are still higher—both of which directly influence EEE consumption and hence e-waste generation.

Unlike developed countries, both India and China are unsaturated markets from the perspective of EEE consumption. The higher consumption in EEE may result in more generation of e-waste in the upcoming years in these countries. However, India is still far behind the major e-waste generators such as China and the United States. India's contribution to the global e-waste volume in 2019 was ~6%. India imposed its e-waste rules in 2011 and amended it further in 2015 [9]. However, its e-waste collection rate is significantly lower than the European and American nations. Several studies including [45] suggest that India manages to collect only about 5% of its annually generated e-waste through formal channels. However, a recent report [33] suggests that India formally collected only 30 kt of e-waste in 2016 which covers only ~1.3% of its electronic waste volume generated in the same year. The fate of the remaining e-waste is undocumented; but it is estimated that a large number of people, over 1 million according to [9], are relying on the collection of solid waste through informal channels. The unsafe delegation of that magnitude of e-waste without any safety precautions might be a serious concern since it directly affects both their health and the environment.

#### 4.3.11. Russia

Figure 5 shows the trend of electronic waste generated by Russia from 2015 to 2019 and Figure 4 shows the annual growth rates of population and e-waste in the same time period. E-waste generated increased from 1494 kt in 2015 to reach 1631 kt in 2019 [33]. Russia contributed ~3% of electronic waste burden to the global generation in 2019. It produced 1.2 Mt of electronic waste in 2014 [35] and collected only 90 kt (~7.5%) of the waste in the same year [33]. This shows that unlike its European counterparts, Russia is far behind in collecting and recycling e-waste. Russia has no national legislation to manage electronic waste; however, there are few organizations to collect and manage but their low capacity is unable them to handle a large amount of e-waste that it generates annually [3].

#### 4.3.12. Mexico

Mexico has emerged as a key player in the e-waste arena from Latin America. The variation of e-waste generated by Mexico from 2015 to 2019 is shown in Figure 5. E-waste generated by Mexico

increased from 1065 kt in 2015 to reach 1220 kt in 2019 [33]. Mexico generated 230 kt of e-waste in 2005 [46] revealing that between 2005 and 2019 its e-waste volume increased by ~430%. Of the 1 Mt of electronic waste generated in 2014 [35], it managed to formally collect only 36 kt (3.6%) in the same year [33]. Mexico is one of the few Latin American countries to implement e-waste policies on a national level [3]. However, the low collection rate indicates that Mexico still has to work for a good implementation of the e-waste policies. To increase collection, Mexico is planning to review its existing e-waste legislation by redefining stakeholders' responsibilities, e-waste categories, and collection targets [3].

#### 4.3.13. Brazil

Annual e-waste generation trend of Brazil between 2015 and 2019 is shown in Figure 5. Brazil is the second largest generator of e-waste in Americas [9]. Electronic waste generated by Brazil increased from 1813 kt in 2015 to 1993 kt in 2017 and reached 2143 kt in 2019 [33]. It generated 351.1 kt of electronic waste in 2005 [47] which shows that its e-waste volume increased by ~510% between 2005 and 2019. Brazil has not implemented e-waste policies at a national level [3]. However, it has enacted National Solid Waste Management Policy in 2010 with an aim to expand the treatment of e-waste through state and municipal levels [47].

#### 4.3.14. South Africa

The trend of e-waste generated by South Africa from 2015 to 2019 is shown in Figure 5. Its e-waste generated increased from 373 kt in 2015 to reach 416 kt in 2019 [33]. According to [48], South Africa generated 59.65 kt of e-waste in 2007 which shows that between 2007 and 2019, its electronic waste production increased by ~597%. South Africa reportedly collected 18 kt of e-waste in 2015 [33], which represents ~4.8% of its e-waste generated in the very year. It has implemented a national policy on e-waste, but enforcing the policy is still very challenging [3].

## 5. Initiatives in Tackling the E-Waste Problem

E-waste is increasing at a significant rate at both regional and global levels. To address this problem, several initiatives have been adopted around the world. Notable initiatives associated with e-waste and/or the hazardous substances are discussed below.

### 5.1. The Basel Convention

The Basel convention is one of the important initiatives to control the transboundary movement of hazardous wastes and their disposal [49]. It was adopted in March 1989, entered into force in 1992 and includes 188 parties (nations) from around the world [50]. The main objectives of the Basel convention are to (i) protect human health and environment from hazardous wastes by containing hazardous wastes within a country capable of handling it; (ii) ban the export of hazardous waste to developing nations except when "written" prior informed consent; (iii) reduce hazardous waste generation and promoting their environmental sound management [49,50].

### 5.2. The European Union (EU) Waste from Electrical and Electronic Equipment (WEEE) Directive

The EU WEEE Directive (Directive 2002/96/EC) paved the way for collection, reuse, recycle, and disposal of WEEE throughout the member states of the European Union. Later, the revised Directive (Directive 2012/19/EU) was adopted to address the rapid growth of electronic waste [51]. The main objectives of the WEEE Directive are to (i) increase re-use of EEEs and/or recycling of WEEE and reduce the disposal of waste to ensure the safety of human health and the environment; (ii) encourage producers to integrate recycled materials and/or their assemblies of WEEEs into new equipment; (iii) make consumers aware that they are able to return their WEEE free of charge by assuring them that producers finance the collection, treatment, recovery, and disposal of WEEE either

by themselves or by joining collective schemes through take-back systems; (iv) inform consumers not to dispose their WEEEs into municipal waste but to collect them separately; (v) keep information about the weight or numbers of products put on market, collection rates, reuse, recovery/recycling and export of WEEE collected in accordance with the Directive; and (vi) set targets for WEEE generation and also for the rate of reuse, recovery, and recycling according to different categories [51–53]. In order to achieve these goals, WEEE in the EU is collected according to 10 categories of EEE namely: large household appliances, small household appliances, information technology and telecommunications equipment, consumer equipment, lighting equipment, electrical and electronic tools, toys, leisure, and sports equipment, medical devices, Monitoring and control instruments, and automatic dispensers [53]. Thanks to the WEEE Directive, the EU region has now established a vast network of formal collection sites through municipalities, retailers, reuse centers, and scrap dealers [54].

### 5.3. Restriction of Hazardous Substances (RoHS)

The EU adopted “Restriction of Hazardous Substances” or RoHS as a sister legislation of the WEEE Directive [49]. It initiated with the first Directive (2002/95/EC) and later adopted the revised RoHS recast Directive (2011/65/EU) [51]. RoHS was enacted mainly to (i) aim at the design phase of products to limit the percent weight of hazardous materials namely lead, mercury, cadmium, hexavalent chromium, and flame retardants such PBBs, and PBDEs; (ii) eventually substitute the above substances with safe and safer materials; (iii) ensure the safety of human health and the environment; (iv) encourage reuse, refurbishment, and recycle of WEEE; and (v) increase the possibility of economic profitability of recycling by prohibiting the hazardous substances in EEEs [51,55]. Both the EU WEEE Directive and RoHS have become influential in establishing similar legislation in many countries including the United States, Canada, Australia, Korea, and Japan [49].

### 5.4. Solving the E-Waste Problem (StEP)

“Solving the E-waste Problem” or StEP is a UN-led initiative launched in 2007 to enhance and coordinate different efforts around the globe in the arena of reverse supply chain [49]. This initiative includes 35 members worldwide including businesses, international organizations, governments, non-governmental organizations (NGOs), and academic institutions [56]. Its main focuses are to (i) promote reuse of the recycled materials; (ii) facilitate research, analysis, and dialogue among the concerned parties; (iii) incorporate a comprehensive view of social, environmental, and economic aspects of the design, production, usage, and final disposal of EEE; and (iv) support cooperation between industrializing and industrialized/post-industrialized countries for global solutions [49,56]. StEP contributions are mainly guided by five principles namely: policy, redesign, reuse, recycling, and capacity building. Its idea of redesign with disposal in mind has had a growing impact [49].

### 5.5. Global E-Waste Statistics Partnership (GESP)

The GESP (The Global E-waste Statistics Partnership) is a collaboration of the International Telecommunication Union (ITU), the United Nations University (UNU), and the International Solid Waste Association (ISWA) established with collective goals to (i) improve and collect worldwide statistics on WEEE; (ii) promote the understanding and importance of the global e-waste data; (iii) deliver capacity building trainings on e-waste; and (iv) raise awareness in public, policy makers, industries, and other relevant stakeholders [57]. In 2019, the GESP launched an open web portal [globalwaste.org](http://globalwaste.org) that displays e-waste statistics in regional, continental, and global level [57].

### 5.6. Basel Action Network, Silicon Valley Toxics Coalition, and Electronics TakeBack Coalition

The Basel Action Network (BAN), the Silicon Valley Toxics Coalition (SVTC), and the Electronics TakeBack Coalition (ETBC) are three US-based non-governmental organizations that work together on e-waste issues such as: (i) raising concerns of e-waste relevant to the well-being of consumers, workers, communities, and the environment; (ii) promoting “Basel Ban” which is a stricter amendment of

Basel Convention; (iii) promoting domestic collection and recycling; and (iv) performing investigative research [49].

Recently, big companies like Apple, Microsoft, Samsung, LG, Acer, Dell, Hewlett-Packard, Best Buy, Canon, Epson, Lenovo, etc. have initiated different forms of take back and/or recycling schemes [49,58]. In 2016, Apple launched “Liam” a system of robots capable of disassembling an iPhone 6 in eight discrete components in just 11 seconds. One line of Liam systems could disassemble 1.2 million sets of iPhone 6 per year [59]. More recently, Apple’s newest disassembly robot “Daisy” was launched which is capable of disassembling 200 iPhones per hour [60].

## 6. Opportunities and Challenges of Secondary Mining

EEEs contain up to 69 elements from precious metals (gold, silver, copper, platinum, palladium, ruthenium, rhodium, iridium, and osmium), to critical raw materials (cobalt, palladium, indium, germanium, bismuth, and antimony), and non-critical metals (aluminum and iron) [3]. Table 3 shows that e-waste in 2019 contained ~25 Mt of selected metals having a potential worth of ~57 billion USD. Despite low weight share, precious metals such as copper, gold, and palladium contribute significant worth to the total metal content. Moreover, as shown in Table 1, printed circuit boards contain a much higher concentration of these metals. The collective demand of iron, aluminum, and copper was ~39 Mt for EEE production in 2019 while in an ideal case the secondary recovery of these metals could supply ~25 Mt from electronic waste [3]. The staggering volume of e-waste generation, its low documented collection, together with the aforementioned facts suggest that electronic scrap can be a good source of secondary mining and can pave the way for urban mining. Despite this, only 10 billion USD worth of materials could be recovered in 2019 [3].

**Table 3.** Selected metals in e-waste and their potential values in 2019.

Material	Amount in E-Waste (in kt)	Potential Value (in Million USD)
Iron/steel	20,466	24,645
Copper	1808	10,960
Aluminum	3046	6062
Gold	0.2	9481
Silver	1.2	579
Palladium	0.1	3532
Antimony	76	644
Cobalt	13	1036
Total	25,410	56,939

Source: Reference [3].

The high cost of recycling and/or heterogenous nature of e-waste often pose difficulty in efficient and economical recycling of e-scrap. Most formal sectors are legally compliant for collecting, treating, and disposing e-waste according to health, environmental, and safety standards—the case may not true for informal sectors [3]. Consequently, recycling through non-compliant sectors become much cheaper in comparison to legitimate recyclers applying the best available technology with full compliance [61]. Unlike other facets of e-waste, the economical implications of recycling electronic scrap is rarely fully analyzed [62,63]. Different studies have shown profitability of recycling materials from e-waste [64–66]. Together with the economical, there are other aspects of recycling that need further consideration. Primary production of metals, especially precious and special metals, is challenging because of their low concentration in the ores and has other disadvantages such as the large land mass used for mining, waste-water, significant energy consumption, and emissions of sulfur dioxide and carbon dioxide gases [48]. Compared to raw materials, recycled materials also lead to other advantages such as reduction in air pollution, mining of raw materials, waste generation, and saving significant energy. Recycling one million laptops is equivalent to saving electricity consumed by 3657 homes



in a year [67]. According to the Global E-waste Monitor 2020, it is estimated that ~71 kt of plastic containing BFRs and ~50 t of mercury arose worldwide from the unaccounted flows of e-waste in 2019. Similarly, inferior recycling of undocumented refrigerators and air conditioners released ~98 Mt of carbon dioxide equivalents in the atmosphere [3]. Recycling iron, aluminum, and copper helped save ~15 Mt of carbon dioxide equivalent emission in 2019 [3]. Moreover, ozone-depleting chemicals such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), which also have high global warming potential, are present in cooling and freezing devices [48], their emission can be prevented by applying effective recycling techniques [68].

Understanding the core of e-waste development cycle involves the necessity to assess collection, treatment, and the related environmental, economic, and social impacts of the waste [69]. Recycling processes can be made more profitable by significantly increasing e-waste collection so that the recycling industries can obtain better incentives to invest in innovation of more efficient recycling technologies [70]. The decreasing market lifespan of EEEs and increasing demand for latest electronic products of EEEs will eventually increase their supply risk and the importance of recycling [71]. Furthermore, recycling materials from e-waste is more than metal supply and their economic aspects when linked closely to their relevant environmental issues, the development of sustainable technologies worldwide have, therefore, become necessary [72]. With effective recycling of e-waste, their metal/material contents can be recovered over and over again, thereby conserving primary metals and energy for future generations.

## 7. Current Practices of E-Waste Handling

Electronic waste can be profitable if we repair and/or reuse it or recycle the usable materials that it contains. On the other hand, it can be equally challenging to manage given that it contains a significant number of toxic substances. The basic principle of e-waste management thus includes collection, transportation, recycle, and disposal of the remaining waste with least negative implications on the health, environment, and aesthetics of the location. There are several methods to manage e-waste and these techniques vary in developed and developing countries. For instance, the EU has a vast network formal collection centers as well as its superior recycling technologies can recover many metals with high efficiency whereas informal sectors still dominate China's e-waste collection and its recycling industries still face challenges to process PCBs and handle the toxic substances in the waste [54]. The crude recycling methods in developing countries manage to process easily recoverable materials such as copper and small amount of gold; however, rare metals such as indium, ruthenium, and palladium are still lost with their low-tech methods [49].

Some of the widely used methods of e-waste handling are discussed below. The techniques are described and classified according to their ease, efficiency, and shortcomings.

### 7.1. Direct Treatments

#### 7.1.1. Disposal to Landfill

Landfilling is one of the most widely used methods for the disposal of e-waste because of its ease of operation. In this method, either the waste is openly dumped or mining voids/borrow pits can be used to bury e-waste. However, this method can cause leachate formation in landfill sites as well as changes the site into wasteland unable to be exploited anytime soon in the future [73]. Different studies have shown that e-waste can release toxic metals and polyhalogenated organics including PBDEs that can seriously harm health and the environment [13,74–76]. Among other pollutants, metals are regarded as the most dangerous since they do not disintegrate via physical processes and hence remain for a long time [77], affect biogeochemical cycles, accumulate within organisms including humans through the food chain and cause harm to our vital organs or even death [78]. A study of leachates and groundwater collected from landfill sites in Australia showed the presence of PBDEs and significantly higher concentrations of Pb, Al, As, Fe, and Ni [79]. Moreover, landfills with e-waste contain a higher concentration of toxicity than landfills without e-waste [76,80]. These pollutants may transport via



soils and groundwater in and around dumping sites [77]. Summarizing the above points, landfilling is considered as an inappropriate method of e-waste disposal.

### 7.1.2. Incineration (Pyrolysis)

Incineration involves burning a combustible fraction of e-waste in order to obtain non-combustible fractions such as metals. The main advantages of incineration are: faster reaction rates, easy to separate and recycle metals, and the gases and liquids formed as a result of material burning may provide enough energy to self-sustain the process thus serving as energy or chemical source [29,81,82]. However, at low temperature (600–800 °C), copper can act as a catalyst and releases highly toxic polybrominated dibenzo-dioxins (PBDDs), polybrominated dibenzo-furans (PBDFs), polychlorinated dibenzo-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs), fly ash, carbon oxides, hydrogen bromide, methane, ethylene, benzene, toluene, phenol, benzofuran, styrene, PAHs, bromophenols, etc. [67,83–86] while landfilling the non-metallic fractions can result in secondary pollution caused by heavy metals and BFRs leaching the groundwater [87]. In contrary, combustion at high temperature, above 1200 °C, is found to reduce CO formation and removes maximum PBDD/Fs in the forms of HBr or Br<sub>2</sub> which have significantly lower toxicity [88]. However, such high temperatures favor NO<sub>x</sub> formation above the standard emission level of 500 mg/Nm<sup>3</sup> [73]. Furthermore, HBr and Br<sub>2</sub>, despite being less toxic, need additional treatment such as adsorption before releasing to the environment [73]. Two-stage pyrolysis method that involves dehalogenation and then pyrolyzing shows promising results for chlorinated plastics of e-waste but it will in turn increase the recycling cost [89]. Moreover, solid residues of incineration remnants called “bottom ash” have significantly higher levels of heavy metals such as Cu, Pb, and Cd that brings a further challenge for their safe disposal [90]. Studies suggest that pollutants such as mercury (Hg<sub>(g)</sub>), benzene, toluene, ethylbenzene, and xylenes can be removed via iron oxide nanoparticles adsorbents [91,92] but their inclusion in pyrolysis and other recycling processes is yet to be seen.

Summing up the above facts, it can be concluded that incineration is a tedious, costly, and not environmentally friendly process of e-waste management.

### 7.2. Reuse/Repair

Repairing/reusing instruments can be a good measure for sustainable waste management because it lowers the manufacturing volume of EEEs thereby reducing the amount of e-waste. A large volume of EEEs such as mobile phones has also created an opportunity to repair and reuse, but is not realized well in many countries [93]. However, changes in product designs, technology, and wireless services often pose difficulties to upgrade or repair instruments [94].

### 7.3. Recycling

Recycling is an important method of e-waste handling because it helps re-extract materials from e-waste, reduces carbon emission, and restricts many usable and/or hazardous substances to end up in landfills. Only a small fraction (~17.4%) of the total e-waste generated in 2019 was documented to be collected and formally recycled [3]. Average composition of an EEE includes 38% of ferrous and 28% of non-ferrous materials, 19% of plastics, 4% of glass, 1% of wood, and 10% of other materials [95]. On the other hand, printed circuit boards, which are essential parts of most EEEs, are rich in metal contents—an estimation is that a ton of circuit boards contains 40 to 800 times more gold and 30 to 40 times more copper than a metric ton of natural ore [96]. These facts suggest that e-waste can be a good source of recycled metals and can supplement the use of virgin materials for EEE production.

E-waste is non-homogeneous, and very complex. Similarly, PCBs, the key components of most electrical equipment, are heterogenous mixture of metals, non-metals (polymers and ceramics), and some hazardous substances [51,67,97]. In addition, their composition changes over time. These variations create difficulty in liberation and separation of each fraction and make the recovery process more complex [67]. Proposing an effective recycling technique for e-waste, therefore, requires

a complete characterization of the waste in terms of its materials, composition, hazardous substances they contain, physical properties (magnetic, density, electric conductivity, volume resistivity, specific gravity, shape, size, liberation properties, etc.) and chemical properties [95,98]. Table 1 shows material composition of selected EEE/E-waste reported in different literatures. Detailed characterization of e-waste are discussed in several works of literature [67,95,98–100]. Techniques such as gamma activation analysis have shown promising results for analyzing both valuable and hazardous materials present in bulk heterogeneous samples in few minutes with excellent sensitivity for elements (gold, silver, copper, tin, bromine, lead, etc.) important from monetary and environmental perspectives [101].

A typical recycling process includes dismantling, processing, and end-processing. Dismantling can be either manual or mechanical and involves the separation of hazardous and valuable components. Europe, where labor cost is high, has preferred mainly mechanical processing in which either a smasher is used to slowly break e-waste or a cross flow shredder is used to cut the scrap. This is followed by sorting out hazardous and valuable materials. Further crushing and separation are performed using a variety of techniques such as hammer mills, magnetic separation, sieves, eddy current separators, etc. These techniques produce metal concentrates that go to metal mills, and plastics [54]. The end-processing step may take place at varying destinations depending upon the output content. For instance, ferrous fractions are diverted to steel plants to recover iron, aluminum fractions are sent to aluminum smelters, while copper/lead fractions, circuit boards, and other fractions containing precious metals are sent to integrated metal smelters [102] whereas the hazardous and non-recyclable substances are sent for disposal [54]. Recycling plastics is difficult because e-waste consists of more than 15 different polymers contains BFRs including PBBs/PBDEs [98].

Selected recycling processes with their positive and negative aspects are discussed below.

### 7.3.1. Pyrometallurgical (Smelting) Processing

Pyrometallurgy has emerged as an easy, promising, and efficient method [103] mainly used to recover non-ferrous materials such as copper and precious metals from e-waste [99,104]. It can be used to recover pure metals with high efficiency by combining with hydrometallurgical and/or electrometallurgical methods [103]. It involves a number of recycling routes such as smelting, combustion, pyrolysis, molten salt, and pyrochemical techniques of which smelting is widely used to recover metals [103]. The working process of a typical pyrometallurgical plant such as Noranda Smelting processing in Quebec, Canada, is explained by [104]. At first, e-wastes are crushed and fed to a molten bath at 1250 °C that removes plastics. The mixture is churned in a supercharged air (up to 39% oxygen). Similar to pyrolysis, plastics and other flammable materials act as the energy source on heating. Ozone formed at this high temperature converts impurities such as iron, zinc, lead, etc. into their oxides to form a silicate solution called slag. This slag is cooled and further mined to recover more metals before disposal. The molten copper called matte containing precious metals is removed and transferred to converters. Then the liquid blister copper is electro-refined in anode furnaces and collected with 99.1% purity. The remaining metals such as gold, platinum, silver, palladium, tellurium, selenium, and nickel settle can be recovered through further electrorefining of the anodes.

Despite being widely used, the pyrometallurgical method has some disadvantages. The drawbacks include its inability to recover iron, aluminum, organics, and glass components, high energy consumption, emission of toxic byproducts such as dioxins and halogen compounds, and its main use in processing only high-grade PCBs containing high gold concentrations [99,103]. The release of toxic substances requires further emission controls. Ceramics and glass in e-waste increases slag causing an increased loss of precious and base metals from the waste [104]. Furthermore, effective recovery of pure metals from base metals through pyrometallurgy requires its subsequent combination with hydrometallurgy and/or electrochemical treatment.

### 7.3.2. Hydrometallurgical Processing

Hydrometallurgical processes use alkaline or acidic solvents to leach metals from e-waste. It is superior to pyrometallurgical techniques because of its higher accuracy, predictability, controllability, low operating cost, reduced environmental impacts, and higher metal recovery efficiency [105,106]. It consists of a series of steps such as mechanical processing, leaching, separation-purification, and recovery of metals [107]. Mechanical processing involves converting e-waste into granular form. In leaching, solvents such as acids or caustic leaches are used to extract a soluble portion of the waste. Some commonly used leaching agents include cyanide, halide, thiourea, and thiosulfate—acids considered the most effective of all because they can leach both base and precious metals [104,107,108]. Some selected leaching agents and metals include nitric acid for base metals, sulfuric acid, or aqua regia for copper, thiourea or cyanide for gold and silver, and hydrochloric acid or sodium chlorate for palladium [109]. The details of different leaching processes are explained in [104,110]. The solution then follows the separation and purification process and finally precious metals from the leachate can be recovered by electrorefining, chemical reduction, or a crystallization process [109]. Some processes to recover precious metals are explained in literatures [111–114].

Despite the superiority of hydrometallurgy over the pyrometallurgical method, it has also some disadvantages. While cyanide is most effective in gold extraction from ores, its lethal toxicity, high consumption of chemicals, and accidents causing severe contamination of rivers and groundwaters have brought serious concerns [110,115]. Cyanide can be treated before disposal but this will make it costlier than other leaching agents at the end [109]. Some non-cyanide alternatives have been suggested such as thiosulfate, thiourea, and halides (chlorine/chloride, iodine/iodide) [104,116–118]. Thiosulfate poses less environmental impacts, can recover gold efficiently, and is cheaper than cyanide [118,119]. However, the slow process and higher consumption of solvent are the main drawbacks of thiosulfate leaching [104,118]. Thiourea offers lower environmental impacts than cyanide and has faster reaction rate and higher recovery efficiency (99%) in acidic conditions but it is plagued by low leaching extent (75%), high consumption of the solvent, higher costs than cyanide [104,118]. The process needs further development as it is still in its infancy. Among halides, chlorine/chloride leaching has been widely used in an industrial scale [117]. Aqua regia, a 3:1 mixture of concentrated HCl and HNO<sub>3</sub>, is used as to dissolve gold (and platinum group metals) [120]. Using chlorine/chloride as a leaching agent can have some disadvantages such as the higher toxicity of chlorine gas and strong corrosivity of the chlorine solution [104]. Iodine/iodide leaching can be an alternative to cyanidation as it is environmentally less dangerous but the cost of the solvent is high [116].

### 7.3.3. Biometallurgical Processing

Conventional recycling techniques need large sums to be invested in building infrastructures and that too comes at a cost of secondary emissions of hazardous substances risking both the human health and the environment. Biometallurgy has emerged as a promising sustainable recycling process over the last decade and has gained interest from major industries. This process involves microorganisms (both eukaryotic or prokaryotic) to use metal species for their structural and/or catalytic functions i.e., by binding the metal ions to the cell surface or transferring them inside the cell for different intracellular functions [104]. The interactions include sorption, reduction, oxidation, and sulfide precipitation [109]. Some commonly studied microbes are cyanogenic bacteria (*Chromobacterium violaceum*, *Pseudomonas fluorescens*, *P. aeruginosa*), mesophilic chemolithotrophic bacteria (*Acidithiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans*), thermophilic bacteria, acidophilic bacteria, and fungi (*A. niger*, *P. simplicissimum*) etc. [67,121–123].

Both hydrometallurgy and biometallurgy involve leaching processes, the only difference being unlike in hydrometallurgy which uses chemical leaching agents biometallurgy uses chemicals produced by the microbe itself. Leaching helps metal ions to form complexes or precipitates whereby they are separated from the culture broth for direct use or further refining [73]. Electro-winning is performed

for the final processing of the metal [29]. Biometallurgical processing can be sub-divided into two categories: bioleaching and biosorption.

Bioleaching is a bacteria-assisted process to recover metals from their sulfide ores which are rich sources of base and precious metals [124]. It involves microbial oxidation of sulfide to water-soluble form (sulfate) that contains the metal of interest [125]. Microbial leaching has two potential mechanisms: direct and indirect—the former involves direct oxidation of minerals and solubilize metals whereas the latter involves microbes converting ferrous to ferric ion and the ferric ion then acting as an oxidizing agent for minerals. The reaction mechanisms of both are detailed by [104]. Bioleaching has already been used to obtain copper and gold from their ores in industrial scale [125]. In addition, metals such as Co, Mo, Ni, Pb, Ag, and Zn can be technically leached from their sulfide ores. Several studies have shown the feasibility of bioleaching to extract metals from e-waste [126–129].

Some disadvantages of bioleaching include its slow process, difficult to control secondary reactions, and precipitation of lead, tin, and some other metals [122,130,131].

Biosorption is a passive mode of metal sorption mechanism that uses dead biomasses of microorganisms called biosorbents [132]. Biosorbents are prepared from biomass of algae, fungi, or bacteria that features high metal uptake [104,133]. Biosorption process can either be metabolism-independent involving physical or chemical sorption onto cell wall or it can be related to cell metabolism [134]. One of the important features of this process is the fact that the biosorbents can bind and accumulate metallic species even when there is no cell metabolism (dead microbes). Both base and precious metals can be sorbed using biosorption techniques but they require different biosorbents [135]. Several researchers have studied biosorption process of metal recovery [136–139] and many hybrid methods have also been developed with promising results [140,141]. Eco-friendly, low operating costs, reduced volume of chemical and/or biological sludge, and high efficiency in detoxifying effluents are some advantages of a biosorption process [104]. However, the time-consuming recovery process and the fact that it is less developed to recycle more complex metallic e-waste are two of its known disadvantages [29,142]. It is a new recycling method and its feasibility for wide applications is currently undergoing extensive research.

Recent promising results from mineral processing have given hope to apply the techniques in biometallurgy; however, this can have some limitations to apply on e-waste treatment given the size of the particles and material contents vary significantly in the two processes [104]. Despite this, studies have suggested that biometallurgy can offer promising recycling technique of electronic waste. Further studies are recommended to evaluate the effectiveness of this technology.

#### 7.4. Other Sustainable Technologies to Reduce E-Waste

It has now been over a decade when several initiatives of sustainability have been undertaken to address various recycling of electronic wastes pollution in air, water and soil. In this section, we will discuss a few ongoing research projects using natural nanomaterials including airborne particles as well as natural minerals, with zero net energy usage. We also review the concept of hybrid technology, namely bioreactors and natural nanotechnology, for recycling e-waste toxic components. We will encourage a wide range of sustainable research and technology development projects, to decrease electronic waste in various environmental matrices and upscaling laboratory achievement to larger-scale recycling solutions.

##### 7.4.1. Use of Airborne Nanoparticle for Effective and Efficient Recycling of E-Waste

A large range of airborne natural particles including airborne particles which is rich in natural minerals have been used as interfaces to remove airborne pollutants, including many of which that are produced from e-waste deposits as well as during the e-waste industrial processes [92,143–148]. Since airborne nanoparticles and microparticles are quite diverse, several studies have focused on those that uptake airborne pollutants through physisorption processes which require much less energy (~10–15 kcal/mol) for their recycling-recovery processes, in comparison to chemisorption procedures

(>15 kcal/mol). For instance, various iron oxides were used as interface to remove a variety of organic compounds (e.g., BETX), as well as trace metals such as mercury, which is commonly used in several e-waste products such as energetically efficient fluorescent lamps. Interestingly, the usage of magnetism of particles (e.g., magnetite,  $\text{Fe}_3\text{O}_4$ ) allowed researchers to transport particles without much energy, while removing very effectively and efficiently the pollutants emitted from e-waste materials [92,146–148]. Furthermore, various different natural coatings such as cellulose products which are known natural waste (e.g., carboxymethyl cellulose) to selectively remove gas-phase pollutants [148], or to increase their uptake at various humidity levels [144] or control competitive adsorption in presence of several co-pollutants [146,147]. There have been additional efforts to combine natural nanoparticle physisorption processes for e-waste material, with solar-run operated salt-based electrochemistry [92,145] to remove both organic and metal contaminants. This approach was shown to be not only energetically neutral but indeed highly efficient (>95%) within minutes time scales [145].

#### 7.4.2. Clay Minerals and Kaolin Nano and Microtraps to Remove and Recycle E-Waste Components

Another method that has been explored during the last decade has been the use of natural minerals such as clay mineral and montmorillonite nano and micro-traps to remove and recycle the pollutants including toxic compounds produces in e-waste [143,149]. Furthermore, material science niche allowed the development of sustainable technology with the highest effectiveness capacity [149], leading to the construction of an efficient ( $\sim 1.9 \text{ gg}^{-1}$ ) nano-trap, made of montmorillonite-Fe-iron oxides, to instantaneously remove mercury (II) ions from water with no additional energy which was shown to be inexpensive and competitive and can remove mercury in a few seconds. Another advancement was the use of kaolin, which is a natural and inexpensive clay mineral, is ubiquitous in soil, dirt, and airborne particles. Kaolin has a layered structure, is the most efficient natural gaseous adsorbent for gaseous trace metals (e.g., Hg, Langmuir maximum adsorption capacity  $Q_m = 574.08 \text{ } \mu\text{gg}^{-1}$ ). Hg physisorption on kaolin occurs in the dark, yet the adsorption rate is enhanced upon irradiation. The physisorption with kaolin was shown to switch from chemisorption to chemisorption upon the addition of  $\text{CuCl}_2$  to kaolin and this process was completely reversible. In short, without any energy or even electrochemistry, these processes could proceed within timescales of seconds.

#### 7.4.3. Combination of Bioreactors and Nanotechnology for Removal and Recycling E-Waste

Many E-waste treatment processes use fossil fuel combustion that generate gaseous emissions that contain a number of toxic organic pollutants and carbon dioxide ( $\text{CO}_2$ ) that lead to climate change and atmospheric pollution. There are new development of hybrid technologies, for instance integrated bioreactor combined with recyclable iron oxide nano/micro-particle adsorption interfaces, to remove  $\text{CO}_2$ , and undesired organic air pollutants using natural particles [150]. Such hybrid technologies allow keeping the existing technology with novel features, to remove the toxicants while allowing the efficiency and effectiveness of the processes, which should be considered in e-waste management.

## 8. Concluding Remarks

Global e-waste generation is growing rapidly at a faster rate than the global population growth.

Electronic wastes include a wide range of chemical components, and several of them are known toxicants for human health and ecosystem.

A wide range of emerging contaminants including plastic materials are emitted from e-waste and this requires further attention, in light of potential biogeochemistry in aquatic systems.

The growing trend of e-waste is gradually shifting from developed to developing countries. Evidently, e-waste growth rate and contributions from countries such as China, India, Brazil, and Mexico are significant.

China has highest production of e-waste of more than 1/5 of the global production. The US is the second major generator. 14 countries produced  $\sim 66\%$  of total e-waste in 2019.



The EEA countries and Switzerland, Japan, the US, Canada, and China recycle higher percentage of e-waste generated than any other countries considered. As such EEA and Switzerland have the highest collection/recycling rate per continent, while Africa has the lowest with merely ~1% collection/recycling rate.

Growing e-waste and low collection and recycling rates have also brought us with opportunities or mining materials from the waste. However, there are issues related to the toxicity and hazards of some of the materials in e-waste.

Pyrometallurgy is an easy and efficient process to recycle e-waste. However, it cannot be used to recover iron, organics, and glass components. It also produces hazardous byproducts such as dioxins and halogen compounds that require further treatments before emission. Thus, the overall cost including treatment becomes expensive at the end.

Hydrometallurgy has some advantages over pyrometallurgy, but it is not without major shortcomings. However, cyanide is the most cost-effective leaching reagent although its highest toxicity is a major concern. Cyanide can be treated before disposal; however, it will increase the cost at the end. Aqua regia, thiourea, thiosulfate, and halides can be used as alternative lesser toxic reagents, but challenges with their use have not yet been resolved.

Biometallurgical processes are more environmentally friendly than conventional methods. However, these are slow processes and still need further research to recycle more complex e-wastes. Extensive ongoing researches in biometallurgy is expected to improve its shortcomings in the future.

Natural airborne particle interfaces are shown to be among the most efficient interfaces for volatile organic compounds and trace metals. The costs are not as cheap as kaolin, but they are shown to be recyclable using salt-based electrolysis operated by solar energy. Further research is recommended to optimize such technologies for large scale operations.

Surface soil components, namely kaolin and montmorillonite, have been shown to be active interfaces, particularly when they are doped with other natural compounds. Since these technologies are both effective (>95%) and efficient (second time scale), and they operate on net zero energy, and are recyclable, they should be considered as viable options. Further research is required to optimize for targeted pollutants.

Hybrid systems are amongst the recent sustainable technology that can combine techniques such as bioreactors with nanotechnology to recycle waste while producing sources of energy.

Since a few countries have a disproportionate impact on the global emission of e-waste, there is now an opportunity to further place regulatory measures and specific implementation policy at the United Nations level for those major polluters to slow rapid growth on the planet.

Further upscaling of several effective and efficient sustainable technologies at laboratory scales for large-scale e-waste recycling is recommended.

## 9. Future Directions

*Need for reliable data:* there is a lack of accurate data e-waste generation, imports, collection, recycling, and disposal. Moreover, such data for the long term are needed to make more accurate and valid conclusions and develop suitable models to address the issues of e-waste.

*Multidisciplinary approach:* as e-waste is a multidisciplinary problem, it requires integration of chemical, mechanical, and physical research approaches with strong international collaboration such as helping developing countries with technology transfer for e-waste handling and so forth.

*Advancing sustainable technology for recycling and recovery, and detection of emerging contaminants:* there is a need for sustainability on two fronts. First there is a need to improve the existing processes in terms of energy, up-scaling promising sustainable technologies for recycling, and perform further research to assure the lack of adverse environmental and health effects, and secondly, new processes and/or improvements in the recycling technology as well as the detection of emerging contaminants are required.



*Addressing the emerging problems of today and tomorrow:* there is a very limited number of studies on the emerging contaminants constituents of e-waste. These include (but are not limited to) some airborne nanoparticles, and airborne particles containing selected toxic metals, soot, organic compounds, and plastic materials (including micro-plastics and nano-plastics). This is notwithstanding the fact that some studies have already suggested significant increase in air pollution in or near landfill/dumping sites.

*Recommendation on international collaboration and sustainable policy:* there is an absolute need for international regulation, which can only be achieved through good-fate collaborations among different countries around the world, specifically 14 countries which generate the majority of e-waste globally.

*Human and ecosystem health:* it is noteworthy that a significant fraction of e-waste is currently composed of known toxicants for human beings as well as pollutants in the Earth ecosystem. The lack of international collaboration and regulatory measures is pivotal to avoiding adverse impacts, notably in several developing countries which are now used as e-waste garbage disposal sites by the polluters.

**Supplementary Materials:** The following are available online at <http://www.mdpi.com/2673-4079/1/2/12/s1>, Table S1: Global population and e-waste generation during the period of 2015 to 2019, Table S2: Continental population and e-waste generation in different years, Table S3: Annual population and e-waste generation of different countries in the period between 2015 and 2019.

**Author Contributions:** Conceptualization, H.G. and P.A.A.; writing—original draft preparation, H.G.; writing—review and editing, P.A.A.; supervision, P.A.A. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the support from the National Science Engineering Research Council of Canada, Environment and Climate Change Canada and PRIMA Quebec.

**Acknowledgments:** We acknowledge the Natural Science and Engineering Research Council of Canada (NSERC), the Environment and Climate Change Canada (ECCC) and PRIMA Quebec for financial support. This paper is based upon some case studies and peer-reviewed literatures. We are thankful to the authors of all the literature that has been studied and also express our deep gratitude towards laboratory colleagues for directly/indirectly sharing their valuable knowledge on the subject.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Abbreviations

Ag	Silver
Al	Aluminum
As	Arsenic
Au	Gold
Ba	Barium
Be	Beryllium
Br	Bromine
Cd	Cadmium
Co	Cobalt
Cr	Chromium
Cu	Copper
Fe	Iron
Hg	Mercury
In	Indium
Li	Lithium
Mn	Manganese
Ni	Nickel
Pb	Lead
Pd	Palladium
Pt	Platinum
Sb	Antimony
Se	Selenium

Sn	Tin
Zn	Zinc
BFRs	Brominated flame retardants
EAA	European Economic Area
CFCs	Chlorofluorocarbons
CRT	Cathode Ray Tube
EEE	Electrical and electronic equipment
HBr	Hydrogen bromide
HCs	Hydrocarbons
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
LCD	Liquid Crystal Display
OECD	Organization for Economic Co-operation and Development
PAHs	Polycyclic aromatic hydrocarbons
PBBs	Polybrominated biphenyls
PBDDs	Polybrominated dibenzo-dioxins
PBDFs	Polybrominated dibenzo-furans
PBDEs	Polybrominated diphenyl ethers
PCBs	Polychlorinated biphenyls
PCDDs	Polychlorinated dibenzo-dioxins
PCDFs	Polychlorinated dibenzofurans
PHAHs	Polyhalogenated aromatic hydrocarbons
WEEE	Waste Electrical and Electronic Equipment
BTEX	Benzene, toluene, ethylbenzene and toluene

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