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Research Article

Electronic Waste: A Growing Concern in Today's Environment

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Over the recent past, the global market of electrical and electronic equipment (EEE) has grown exponentially, while the lifespan of these products has become increasingly shorter. More of these products are ending up in rubbish dumps and recycling centers, posing a new challenge to policy makers. The purpose of this paper is to provide a review of the e-Waste problem and to put forward an estimation technique to calculate the growth of e-Waste.

1. Introduction

Over the past two decades, the global market of electrical and electronic equipment (EEE) continues to grow exponentially, while the lifespan of those products becomes shorter and shorter. Therefore, business as well as waste management officials are facing a new challenge, and e-Waste or waste electrical and electronic equipment (WEEE) is receiving considerable amount of attention from policy makers. Predictably, the number of electrical devices will continue to increase on the global scale, and microprocessors will be used in ever-increasing numbers in daily objects [1, 2].

(i) In the United States (US) market, less than 80 million communication devices were sold in 2003; the number was expected to exceed 152 million by 2008 [3], a growth of over 90 percent in 5 years. Meanwhile, in 2006, more than 34 million TVs have been exposed in the market, and roughly 24 million PCs and 139 million portable communication devices have been produced [4].

(ii) In the European Union (EU), the total units of electronic devices placed on the market in 2009 were more than 3.8 billion units, including 265 million computers, roughly 245 million in home consumer electronics, and 197 million consumer appliances (major), [5].

(iii) In China, approximately 20 million refrigerators and more than 48 million TVs were sold in 2001, and nearly 40 million PCs were sold in 2009 [6]. Furthermore, the growth rate is increasing every year [7].

Consequently, the volume of WEEE grows rapidly every year and is also believed to be one of the most critical waste disposal issues of the twenty-first century. To be precise, United Nation University estimates that 20 to 50 tons of e-Waste is being generated per year worldwide [8] and suggests that there is an urgent need to develop an estimation technique [3].

Compared to conventional municipal wastes, certain components of electronic products contain toxic substances, which can generate a threat to the environment as well as to human health [9, 10]. For instance, television and computer monitors normally contain hazardous materials such as lead, mercury, and cadmium, while nickel, beryllium, and zinc can often be found in circuit boards. Due to the presence of these substances, recycling and disposal of e-Waste becomes an important issue.

Most people are unaware of the potential negative impact of the rapidly increasing use of computers, monitors, and televisions. When these products are placed in landfills or incinerated, they pose health risks due to the hazardous materials they contain. The improper disposal of electronic products leads to the possibility of damaging the environment. As more e-Waste is placed in landfills, exposure to environmental toxins is likely to increase, resulting in elevated risks of cancer and developmental and neurological disorders.

A major driver of the growing e-Waste problem is the short lifespan of most electronic products—less than two years for computers and cell phones [11, 12]. In a 2006 report, the International Association of Electronics Recyclers projected that, with the current growth and obsolescence rates of the various categories of consumer electronics, somewhere in the neighborhood of 3 billion units would be scrapped by 2010 or an average of about 400 million units a year.

In this paper, we delineate the e-Waste problem and provide an estimation of the amount of e-Waste produced and recycled every year, our estimates lead us to believe that by the year 2015, over 500 million units will be disposed off and slightly over 113 million units will be recycled.

The paper is organized as follows: in Section 1 we introduce and define the concept of e-Waste; Section 2 enumerates the current challenges and regulations related to e-Waste; Section 3 provides an estimation technique to calculate the amount of e-Waste created and recycled; Section 4 outlines a case from the Swiss system of how to manage and recycle e-Waste; Section 5 provides the summary and limitations of this study.

2. Definition of e-Waste

As a popular and informal term, electronic waste (e-Waste) is loosely refers to any white goods, consumer and business electronics, and information technology hardware that is in the end of its useful life. Specifically, Puckett et al. [13] define e-waste as "a broad and growing range of electronic devices ranging from large household devices such as refrigerators, air conditions, cell phones, personal stereos, and consumer electronics to computers which have been discarded by their users". According to Sinha-Khetriwal [14], "e-Waste can be classified as any electrical powered appliance that has reached its end-of-life". As there does not seem to be a standard definition for e-Waste, we have for the purposes of this paper adopted the definition offered by Sinha-Khetriwal et al. [14]. Meanwhile, a list of prevalent definitions has been provided by Widmer et al. [15]. Widmer et al. [15] and Sinha-Khetriwal et al. [16] use the terms "WEEE" and "e-Waste" synonymously.

3. Global Significance of e-Waste

e-Waste has raised concerns because many components in these products are toxic and do not biodegrade easily if at all. Based on these concerns, many European countries banned e-Waste from landfills in the 1990s [17]. Ming Hong et al. [18] found alarming levels of dioxin compounds, linked to cancer, developmental defects, and other health problems; in samples of breast milk, placenta, and hair, these compounds are linked to improper disposal of electronic products. Furthermore, surveys have indicated that much exported US e-Waste is disposed of unsafely in developing countries, leaving an environmental and health problem in these regions [18]. The European Union has legislation requiring manufacturers to put in place e-Waste disposal mechanisms (Wanjiku, [19]). Due to the difficulty and cost of recycling used electronics, as well as, lackluster enforcement of legislation regarding e-Waste exports, large amounts of digital discards are transported internationally from various industrialized countries to certain destinations where lower environmental standards and working conditions make processing e-Waste more profitable [17]. Impacts from those countries, especially Asia, have already been reported. Meanwhile, recycling and disposal of e-Waste are also growing in regions beyond Asia, particularly in certain African countries.

Force of an international accord, known as the Basel Convention, has banned the export of hazardous waste to poorer countries since 1992, but the practice continues as pointed out by Chris Carroll (Woodell, [9, 10]). Commonly, the term "bridging the digital divide" is used when old WEEE are exported to developing countries. They are often labeled as "second-hand goods" since export of reusable goods is allowed. However, EU Commission estimates that anywhere between 25–75 percent of second-hand goods exported to Africa are broken and cannot be reused [20]. On the other hand, most WEEE that do work on arrival only have a short second life and/or are damaged during transportation. On the other hand, illegal disposal sometimes occurs in the name of charitable donation according to United Nations Environment Programme (UNEP). Recently, a report from Toxics Link reveals that 70 percent of WEEE disposed in New Delhi of India was imported from developed countries.

4. Current Challenges for e-Waste Elimination

In many cases, the cost of recycling e-Waste exceeds the revenue recovered from materials especially in countries with strict environment regulations. Therefore, e-Waste mostly ends up dumped in countries where environmental standards are low or nonexistent and working conditions are poor. Historically Asia has been a popular dumping ground, but as regulations have tightened in these countries, this trade has moved to other regions, particularly West Africa [22]. Most developing countries lack the waste removal infrastructure and technical capacities necessary to ensure the safe disposal of hazardous waste. And e-Waste has been linked to a variety of health problems in these countries, including cancer, neurological and respiratory disorders, and birth defects [23]. Therefore, the fight against illegal imports of WEEE has become one of the major challenges. From another perspective, some regulations, which have been established to handle e-Waste, are often limited since they exclude many hazardous substances that are used in electronics. Moreover, many regulations simply fail to address the management of e-Waste.

Osibanjo [24] states that in Africa, for example, there is a highly ineffective infrastructure for e-Waste management.

More precisely, there is no well-established system for separation, sorting, storage, collection, transportation, and disposal of e-Waste. Even worse, there is little or no effective enforcement of regulations related to e-Waste management and disposal. Under these circumstances, practical e-Waste management in Africa is unregulated, and rudimentary techniques are widely used. These techniques include manual disassembly of WEEE without concern of the hazardous chemicals, heating printed circuit boards (PCBs) to recover solder and chips, melting and extruding flame-retardant plastics, and burning plastics to isolate metals; generating an average of US $6 worth of material from each computer (Basel Action Network). This value is not much especially considering the environmental and health costs of burning plastic, sending dioxin and other toxic gases into the air and the large volumes of worthless parts dumped in nearby landfills, allowing the remaining heavy metals to contaminate the area and harm life.

5. Regulations and Market Mechanism

So far, legislation on WEEE is mainly driven by certain European countries and the European Directive on WEEE. Most developing nations are lagging in the development of similar regulations and especially in their enforcement [25]. In most developed countries, legislations and policy guidelines have been developed and established in order to control the use of hazardous chemicals in those products, and the management of e-Waste after they are discarded. Among these, the most well known is European Union (EU) restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS) Directive [26], which currently addresses only limited amount of hazardous chemicals commonly used in WEEE, including heavy metals of cadmium, lead, hexavalent chromium (VI), and mercury and certain brominated flame retardants (BFRs). Furthermore, the EU WEEE Directive requires producers to set up systems for the treatment of WEEE. However, even with these regulations, all hazardous materials that are used in newly manufactured products cannot be fully controlled, and management of e-Waste within the supply chain cannot be fully addressed. According to one estimate, only 25 percent of the e-Waste in EU is properly collected [27]. And in the US this figure is even lower at only 20 percent [28]. e-Waste legislation in the US is primarily set at the state level with a few stalled efforts in the US Congress [17]. Normally, unaccounted e-Waste in both regions is exported to non-OECD countries. Although it is illegal in EU, such exports have been classified as legal recycling by US EPA [29].

Similar e-Waste legislation has been introduced in China and other countries as well. For instance, China has established administrative measures to control the pollution of WEEE [30]. Meanwhile, several multinational collaboration agreements are currently taking shape to prohibit or limit the shipment of hazardous waste, including e-Waste, from industrialized to developing counties. Those include the Stockholm Convention on Persistent Organic Pollutants (POPs), the Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade, and the Ban Amendment of the UN Basel Convention [25]. Despite the existence of those conventions, there is still a relatively high flow of WEEE from the US, Canada, Europe, Japan, and Korea to developing countries such as China, India, Pakistan, and several African countries [13, 29, 31], while some of those developing countries themselves are becoming the fastest growing markets for EEE and are currently generating large amount of WEEE [15]. Looking at South Africa as an example, there is no specific legislation currently to deal with e-Waste. However, the new National Environmental Management Waste Bill includes implications for e-Waste management, aiming to reform waste management legislation in South Africa in order to protect public health and the environment [32]. Furthermore, a national waste information system is envisaged as well.

In addition to these legislative- and convention-based initiatives, another policy option is to extend the WEEE producers' responsibility for their products over the entire lifecycle, of the product, from design—to use—to disposal. The concept of Extended Producer Responsibility (EPR) is defined as "the producer's responsibility for a product is extended to the postconsumer stage of a product's life cycle" [33]. EU is a good example of this. For instance, Switzerland has a decade-long experience of applying EPR to manage its e-Waste [16].

6. Current Approaches

When it comes to e-Waste, recycling faces a number of challenges, including dealing with hazardous materials such as CRT glass and finding markets for flame-retardant plastics. Furthermore, no technology currently exists for recycling certain EEE in an environmentally friendly manner.

In the US, the US EPA estimates that as much as three quarters of the computers sold are stockpiled in garages and closets. When thrown away, they either end up in landfills or incinerators or are exported to Asia. Table 1 enumerates a few places where e-waste ends up.

In 2005, more than 2 million tons of e-Waste were generated in the US alone (US EPA), but only 17 to 18 percent of that was collected for recycling. The rest, more than 80 percent, was disposed of, largely in local landfills. The hazardous materials in e-Waste can leach out of the landfills into groundwater and streams, and if the plastic components are burned, dioxins are emitted into the air [34]. Moreover, it is estimated that 50–80 percent of the e-Waste collected for recycling in the US is actually exported to developing countries, even though it is illegal for most of those countries to accept this toxic waste stream. Much of this illegally traded waste is going to the informal recycling sectors in many Asian and West African countries, where it is dismantled or disposed of using very primitive and toxic technologies [34].

On the other hand, cost is another big issue for e-Waste management. Cost of logistics and transportation is a challenge faced by most recyclers, preventing the flow of waste volumes in the country.

Table 1: Places where e-Waste ends up.

Landfill: According to the US EPA, more than 4.6 million tons of e-Waste ended up in landfills in 2009. Toxic chemicals in electronics products can leach into the land over time or be released into the atmosphere, impacting nearby communities and the environment.
Incineration: This process releases heavy metals such as lead, cadmium, and mercury into the atmosphere and which can bioaccumulate in the food chain, particularly in fish, which is the major source of exposure for the general public.
Reuse: This is a good way to increase a product's lifespan. Many old products are exported to developing counties. Although the benefits of reusing electronics in this way are clear, the practice is causing serious problems because the old products are dumped after a short period of use in areas that are unlikely to have hazardous waste facilities.
Recycle: Although recycling can be a good way to reuse the raw materials in a product, the hazardous chemicals in e-Waste mean that electronics can harm workers in the recycling yards, as well as their neighboring communities and the environment.
Export: E-Waste is routinely exported by developed countries, often in violation of the international law. Inspections of 18 European seaports in 2005 found that as much as 47 percent of waste destined for export, including e-Waste, was illegal. At least 23,000 metric tons of undeclared or "grey" market electronic waste was illegally shipped in 2003 to the Far East, India, Africa, and China. In the USA, it is estimated that 50–80 percent of the waste collected for recycling is being exported in this way. This practice is legal because the USA has not ratified the Basel Convention.

Source: Greenpeace International.

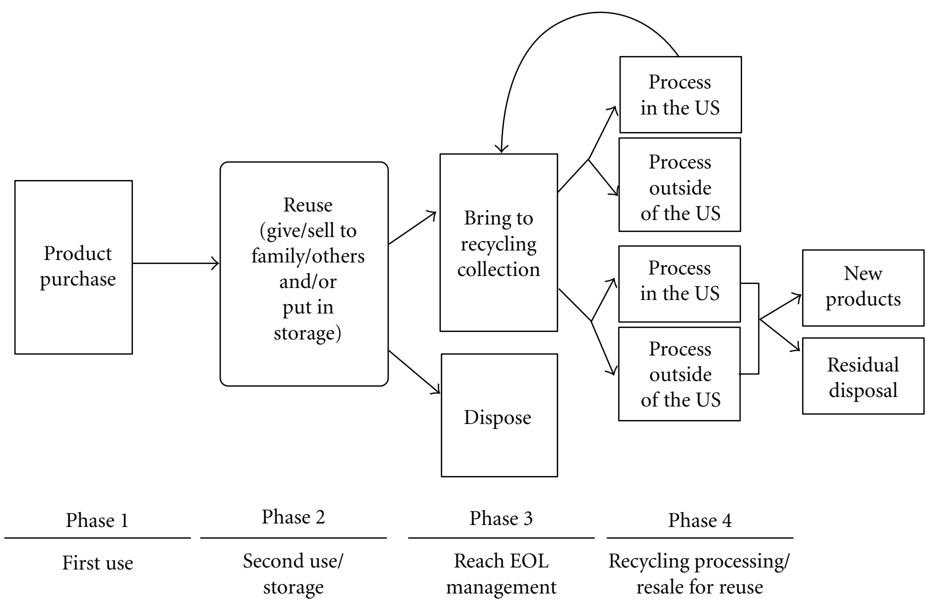

Figure 1: Framework for modeling the product lifecycle, source [21].

7. e-Waste Estimation Techniques

In order to predict the number of units and the tons of e-Waste for the targeted years, Microsoft Excel was used to apply linear regression technique. Framework for modeling the product lifecycle is illustrated in Figure 1. For Phase 1, we assembled product sales data, as well as data on the average weight of products by year. The model considered product sales from 1980 through 2007 and predicted the annual quantity needing end-of-life (EOL) management through 2007 [35].

7.1. Estimating the Quantity of EOL Products Generated That Are Recycled versus Disposed. The modeling effort resulted in estimates of the quantity of products that are generated annually for EOL management. EOL management consists of recycling or disposal. This corresponds to the two options in Phase 3 of Figure 1: "Dispose" or "Bring to Recycling Collection." Disposal was estimated as the difference between what was generated for EOL management and what was recycled [35].

7.2. Estimating the Portion of EOL Electronics Recycled. Recycling of consumer electronics includes the recovery of products by municipal and other collection programs for materials separation and recovery, as well as reuse in both domestic and foreign end markets. It also includes businesses and institutions contracting directly with electronic recyclers for recycling services of their EOL equipment. Donation organizations also collect EOL electronic equipment for reuse or recycling. The term "reuse" in the EOL management stage refers to products entering the recycling materials management system that are in working order and can be

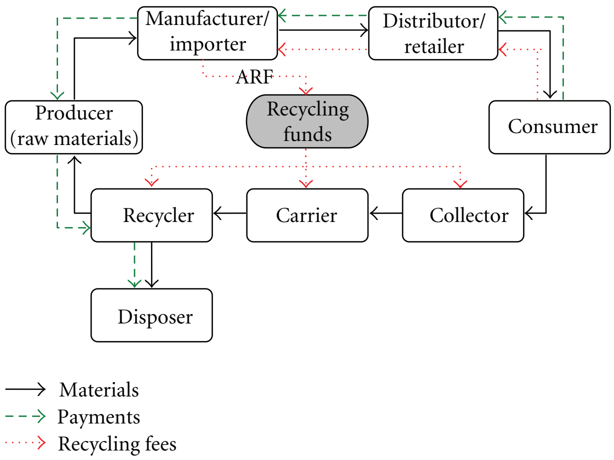

Figure 2: Flow of materials and finances in the Swiss e-Waste management system, source [16].

resold "as is" or refurbished for resale by electronics recyclers and dismantlers. The reuse of consumer electronics before they enter the management system (i.e., products that pass between individual users) is assumed to occur prior to EOL management [35].

7.3. Estimating the Portion of EOL Electronics Disposed. To estimate the portion of the estimated EOL electronics generated every year that is disposed, we subtracted the amount estimated to be recycled from the estimated amount generated for EOL management. Table 2 includes the disposal estimates for 1999 through 2007.

According to this analysis, 18.4 percent, by weight, of the EOL electronics generated in 2007 were collected for recycling. During the time period 1999 through 2005, even though the amount of material being recycled increased, the amount of EOL products generated kept pace such that the percentage of material being recycled remained relatively constant. A larger gain in the recycling rate has been estimated for 2006 and 2007. Implementation of state electronics recovery and disposal regulations has provided a boost to the electronics recycling industry. The majority of EOL material that is not being recycled is probably mostly going into landfills [35].

Table 3 shows the prediction of EOL through 2015. As can be seen, EOL grows from a meager 159 million units in 1999 to a 615.2 million units in 2015,emphasizing the need to seriously tackle this issue.

8. e-Waste Management in Industry

For e-Waste management systems, some of the most successful examples can be found in countries such as Switzerland and the Netherlands [16]. Experience of the Swiss e-Waste management system is shown as an example in this paper. Generally, the Swiss e-Waste management system can be viewed as an ERP-based system, where each stakeholder has their own clear definition of role and responsibilities as shown in Table 4.

As shown in Figure 2, the solid black line indicates the material flow in the e-Waste management system. In order to optimize the closed loop of material flow, raw materials are first converted into EEE products by manufacturers, then end-of-life products after going through retail and consumption are collected and recycled to produce new goods. Besides recycling, other materials which cannot be recycled go to incineration for energy recovery, and a small portion goes to landfill, approximately 2%. Payments as well as recycling fees, shown as green and red lines, respectively, indicate financial flow of the system. Producer responsibility Organizations (PROs), such as SWICO and SENS, collect advanced recycling fees (ARF) from producers on their sale or import of an appliance. Then, ARF are passed down to retailers or distributors who invoice consumers for their purchase of new appliance. This ARF is used to pay for the whole e-Waste recycling system, including collection, distribution, dismantling, sorting, decontamination, and recycling of the disposed EEE products [16].

According to a study by Hewlett-Packard (HP), the Global Digital Solidarity Fund (DSF), and the Swiss Federal Laboratories for Materials Testing and Research (Empa), most countries in Africa lack legislative mechanisms to tackle the problem of e-Waste and have not yet recognized it as a hazardous waste stream. However, several pilot projects have been initiated in Africa to show that recycling can provide both employment opportunities for local communities and act as a step towards a sustainable solution for tackling e-Waste (Wanjiku, [19]) . For instance, a pilot project in Cape Town initiated by HP processed 60 metric tons of electronic equipment in 10 months in 2008, generating an income of about $14,000 and creating direct employment for 19 people. This project also tried to incorporate informal processing activities that proved highly effective in dealing with waste. This team is expected to launch the second phase of this project, to engage corporate and government partners to further extend e-Waste management programs to other countries and to tackle the problem in the entire continent (Wanjiku, [19]).

Gregory et al. [37] proposed an e-Waste take-back system, whose main functions are collection, processing, system management, and financing scheme. Meanwhile, several examples of current system models have been presented including California, Maine, and Minnesota in the US, and Belgium, France, and Germany, in the EU. Even though some successful stories of e-Waste take-back system currently exist, but several challenges still remain including

(i) how to balance the harmonization between manufacturers and recyclers with respect to finance, operations, technologies, and so forth,

(ii) how to deal with different business models of stakeholders from various industries,

(iii) how to determine the amount of policy in law, leaving others to be industrial standards,

(iv) how to ensure that obligations are met by the stakeholders.

Table 2: Distribution of used and EOL products.

	Total EOL products		Total recycled			Total disposed		
Year	Units (mill)	Tons(000)	Units (mill)	Tons (000)	Ton (%)	Units (mill)	Tons (000)	Ton (%)
1999	159	1,056	23.6	157	14.9	135.4	899.2	85
2000	161.6	1282	24	190	14.8	137.7	1092	85
2001	193.6	1447.6	28.1	210	14.5	165.5	1237.6	85
2001	225.2	1634	34.6	250	15.3	190.7	1384	85
2003	273.8	1944.7	40.8	290	14.9	232.9	1654.7	85
2004	310.7	2043.5	48.6	320	15.7	262	1723.5	84
2005	342.1	2172.6	54.3	345	15.9	287.8	1827.6	84
2006	342.9	2107.8	61.3	377	17.9	281.5	1730.8	82
2007	372.7	2251.7	68.5	414	18.4	304.2	1837.7	82

Source [36].

Table 3: Prediction of EOL using forecast function.

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2001	225.2	1634	34.6	250	15.3	190.7	1384	85
2003	273.8	1944.7	40.8	290	14.9	232.9	1654.7	85
2004	310.7	2043.5	48.6	320	15.7	262	1723.5	84
2005	342.1	2172.6	54.3	345	15.9	287.8	1827.6	84
2006	342.9	2107.8	61.3	377	17.9	281.5	1730.8	82
2007	372.7	2251.7	68.5	414	18.4	304.2	1837.7	82
2008	412.6	2527.1	72.4	441.2	18	340.1	2088	83
2009	441.5	2674.7	78.2	471.9	18.4	363.2	2205.4	82
2010	470.5	2822.9	84	502.6	18.8	386.3	2322.8	82
2011	499.4	2970.5	89.8	533.3	19.2	409.4	2440.3	82
2012	528.4	3118.7	95.6	564	19.1	432.5	2557.7	82
2013	557.3	3266.3	101.5	595.3	19.9	455.6	2675.1	81
2014	586.3	3414.5	107.3	626	20.3	478.7	2792.5	81
2015	615.2	3562.1	113.1	656.7	20.7	501.8	2909.9	81

Table 4: Stakeholders and their role in Swiss e-Waste management system.

Stakeholders	Roles and responsibilities
Federal government	The federal government oversees the whole process and initiates basic guidelines and regulations.
Manufacturers/importers	Manufacturers have the physical responsibilities of managing daily operation of the system.
Distributors/retailers	Retailers are also part of the physical responsibility of the EEE products besides manufactures.
Consumers	Consumers are responsible for returning discarded EEE to retailers or collectors.
Collector (collection points)	Collection locations collect all kinds of WEEE free of charge, and are responsible for the safety of the disposed products to prevent illegal exports.
Recyclers	Administration from government is required to operate a recycling facility. Recyclers must follow minimum standards on emissions and concern employee' health.

Source [16].

9. Summary

According to the electronics waste management of the EOL, no more than 19 percent by weight of the EOL electronics generated in 2007 were collected for recycling, and at least 81 percent goes to the landfill [11, 35]. Recycling is the key to reduce the e-Waste. Recycling has environmental benefits at every stage in the life cycle of a computer product—from the raw material from which it is made to its final method of disposal. Aside from reducing greenhouse gas emissions, which contribute to global warming, recycling also reduces air and water pollution associated with making new products from raw materials. By utilizing used, unwanted, or obsolete materials as industrial feedstock or for new materials or products, we can do our part to make recycling work.

One more aggressive but challenging approach to minimizing illegal dumping of electronics is to impose tougher laws. Some States in the US govern e-Waste to ensure a much greater enforcement. Strictly enforcing these laws is strongly suggested as a way to prevent those who make a certain kind of "donations" to developing countries. Future efforts to minimize illegal dumping will undoubtedly include a combination of aggressive legislation, new technological solutions, and increased public awareness through more education on e-Waste. Present laws should be evaluated and modified periodically to allow proper progression.

Educating people about how to recycle, reuse, and dispose electronics at all levels will teach them and their communities how to behave more responsibly towards the environment. Indeed, electronic waste is a global problem requiring a global solution.

One of the limitations of this work is that it is limited to looking at the e-waste issues and we have not considered the persistent organic pollution (POPs) issues. POPs negatively impact human and wildlife [38, 39]. Other significant research on airborne as well as water-/ground based contamination exists. Researchers (e.g.: [11, 40–42] have focused on various contaminants such as Polybrominated Diphenyl Ethers, Polychlorinated Biphenyls, and Organochlorine Pesticides.

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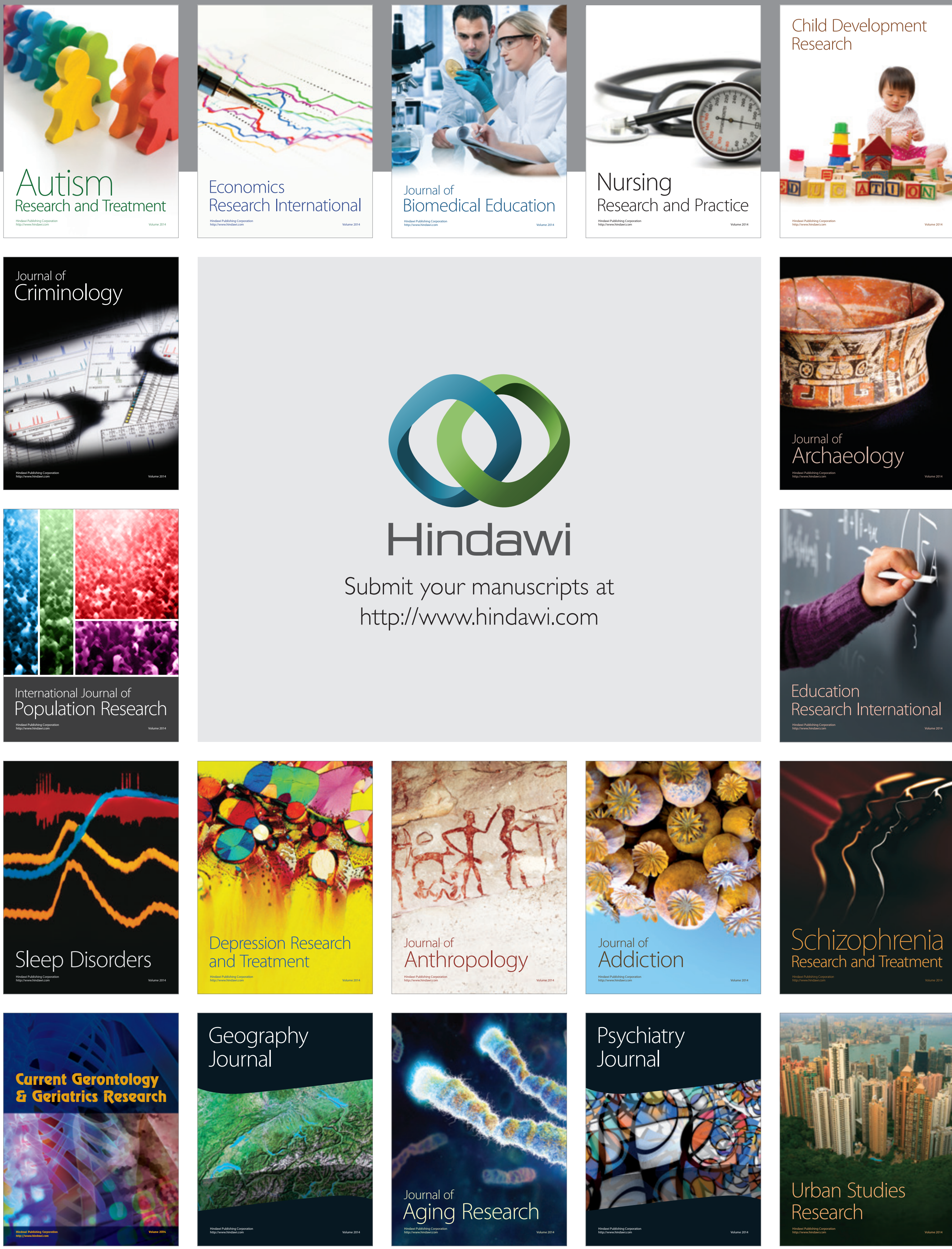
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