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Recent Developments in Management of Electrical and Electronic Waste with Focus on Developing Countries

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ABSTRACT

Technological innovations give improved performance at reduced costs for electrical and electronic equipments, generating waste. Combined with the profit driven production and marketing policies adopted globally by manufacturers, the world today is facing a huge challenge in sustainable management of the electrical and electronic waste. The dense population in the developing countries, along with dumping of the electronic wastes by the developed nations, aggravates the problem. Research brings out the various adverse effects of the incorrect and irresponsible disposal of electronic waste on the ecology, environment, and human lives. Research also brings forth innovative means such as bioleaching and polymer concrete, for the handling of the various hazardous elements present in such waste. Integrated waste management with strict enforcement of the environmental legislations and stipulations would be required for the world, especially for the developing countries. In this article, various such aspects of sustainable management of electrical and electronic waste are discussed.

Keywords: *Electrical Waste; Electronic Waste; Waste Management; Landfill; Sustainability; Developing Country;*

INTRODUCTION

World Commission on Environment & Development has defined sustainable development as 'the kind of development that meets the needs of the present generations without compromising the ability of future generations to meet their own needs' [1].

It is of utmost importance that the burden of management of the waste created by the present society should not be left for the coming generations. A very important and rapidly growing concern regarding sustainable behaviour of man is the production, use and disposal of the electrical and electronic items.

The market forces driving the industry compels it to bring out new and newer electronic products into the market, thereby making the older products obsolete and ready for disposal, even when they are yet to reach the end of their design life. Thus, huge amounts of electrical and electronic wastes are generated, which contain many hazardous materials along with some precious elements. The challenge is to process the electronic waste, extract the valuable elements, and prepare the hazardous materials for environment-friendly and sustainable disposal. However, neither the technology nor the governance are prepared to face this challenge.

The sense of social responsibility is on the decline and sheer craze to possess latest-in-market items at the cost of indiscriminate disposal of the functioning, but old, electrical and electronic appliances and gadgets is increasing alarmingly. The electronic products have increasingly shorter lifecycles and hazardous materials and processes are used in their manufacture, and these generate hazardous waste both during manufacture and at end of life / use. The manufacturers of electrical and electronic equipment are being targeted by environmental groups such as Greenpeace [2] for their lack of planning and efforts for adhering to the prevalent environmental legislations and standards during production or disposal.

With the latest breakthroughs in the technology, the improved performance at lower cost is coming on the market. The disposal of the old gadget is inevitable and thus it promotes unsustainable behavior. The electronic gadgets, especially the mobile phones, tablets, and laptops are often treated as the fashion statements and get disposed even before they perform for their short design life. Equally or more critical is the fact that the drive for ever-increasing sales has resulted in very short design lives of such products. The short service life, use of hazardous materials / processes for manufacture and generation of waste both at start of life and the end – all contribute to the growing menace that forms the electrical and electronic waste.

Another concern is negative publicity generated for manufacturers when their products are effectively dumped as electrical and electronic waste in Third World and Far Eastern countries, at end of their life [3]. Thus even today, many countries are unsuspectingly targeted as sink for the electrical and electronic waste generated by the so-called developed nations. For example, U.S. was reportedly exporting 80% of their e-waste to Asia, and Europe was also reported to export a large portion of e-waste to Asia [4]. The illegal e-waste import has been reported in literature as a significant issue in China [5]. This is principally irresponsible and dangerous behaviour of the nations advanced in technology and economy. And the third world countries might get unsuspectingly victimised by this conduct.

There has been concerted efforts towards achieving a sustainable work plan for use of resources and the reduction of such wastes dumped in landfills.

Further, at the end of design life / service life, the electrical and electronic items may be, to the extent possible, earmarked for re-use, recycle and recovery. The energy consumption and hazardous material use during manufacture and waste management have to be critically evaluated and stringent monitoring policy should be implemented.

The policy of 'producer responsibility' basically implies adoption of the 'polluter pays' principle by placing the responsibility for end-of-life waste disposal on the original manufacturer [6]. This would be complex to implement, when the ownerships of the producing companies undergo switchover at frequent intervals.

This is especially difficult in third world countries, where legislation formulation, government ratification and implementation of such laws would face steep challenges. The display of political will for formulating or implementing any policy or reform, which might adversely affect the large business conglomerates, is largely conspicuous by its absence.

The sustainable principles of electrical and electronic goods production would be achieved by adopting the following [6]:

- Minimize consumption of energy during manufacture;
- Eliminate or at least reduce use of hazardous materials in manufacture;
- Use of greater amounts of recycled parts / components;
- Minimize waste during production, use and disposal;
- Improve the re-usability of the products;
- Use of materials which pose less problems for disposal;

These technological tools have to be used in tandem with the administrative policies and implementation framework. The infrastructure for collection, recycle and reuse of the electrical and electronic wastes have to be established by the local government. Additionally, public education regarding this exponentially building problem area would be extremely useful. Sustainable and responsible social behavior have to be inculcated in the populace.

In this direction there have been several legislations and directives across the world. Two prominent ones are the Waste Electrical and Electronic Equipment (WEEE) Directive and the Restriction of the use of certain Hazardous Substances in electrical and electronic equipment (RoHS) Directive. These are discussed briefly below:

WEEE Directive [7, 8] aims to control the disposal of electrical and electronic products at the end of their lives along with the percentage going to landfill. Further, it sets targets for the percentages of an item that would compulsorily be recovered and recycled in some form. The basic aims identified are as follows:

- Separation of WEEE during garbage collection;
- Adhering to stipulated standards for treatment;
- Target achievement for recovery and recycling;
- Option of collection at retailers for end-of-use items;
- Voluntary and free return of old items by consumer;
- Original producer pays from collection till final disposal;

- Business users may exercise the choice to pay some or all of costs;

Thus, WEEE Directive adopts a holistic approach towards production, use and disposal of electrical and electronic equipment and aims to improve the environmental performance of all involved in the lifecycle of the equipment such as producers, retailers, customers and recyclers.

RoHS Directive, which was originally included in the WEEE Directive, has been subsequently formulated as a stand-alone and complementary Directive to the WEEE Directive. The objective of this legislation is to protect the human and environment from the uses of hazardous materials such as lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls and certain polybrominated diphenyl ethers [9, 10]. Thus, it has a strong impact on producers, distributors, retailers, and recyclers of electrical and electronic items. If a product is found to contain any of the materials, implementation of RoHS would force the manufacturer to withdraw them from the market. The RoHS Directive covers all types of products enumerated in WEEE Directive. This specifies that a hazardous material should not be present above a stipulated percentage weight. This stipulated weight is set as 0.1% by weight for each of the proscribed materials, except cadmium for which the level is ten times lower at 0.01% [9, 10].

It is evident that a comprehensive plan needs to be in place for handling this alarmingly growing problem before it blows into a deep crisis. The obstructions and barriers in the paths of sustainable electrical and electronic waste management would have to be removed through research and development, legislations and implementation, and consumer education and participation.

Cecera and Martinelli [11] evaluated the role of three major drivers of knowledge creation in this area: innovation induced by the high price of precious materials; technological advances; and regulatory stringency. Their study brought out the patterns of growing diversification of research areas and highlighted the effects of regulation and raw material price on development of new technologies.

Technology and market demand play different roles in different phases. While technology is important at the beginning of technological development, the market forces control the innovation diffusion phase and transition from laboratory technology to viable real-life application [12]. In the present article, author discusses pertinent decision points and highlights a few recent research findings for management of end-of-life / end-of-use electrical and electronic equipment.

Hurdles for Recycling of Electrical and Electronic Wastes

The primary hurdle is the physical distance between the original manufacturer and the consumer in the global business regime. Thus, this involves a collection and transportation problem and expenses for the manufacturer. Though retailers and distributers may service a reverse flow for the waste electrical and electronic equipment, their reluctance arises from the additional burden of storage, collection and transport – which would have cost, health, safety and security implications. On consumer level, there exists public apathy and unwillingness to participate in any effort to separate their electrical and electronic waste from regular municipal waste. On the face of this, even the well-intentioned and coordinated efforts of the government / non-government organizations fail to bring positive results in achieving the desired sustainability objectives. And such efforts are generally rare, especially in the developing countries where the electrical and electronic consumption and waste production are very high. Concerted efforts for creation of large drop-off facilities for the recycling of the electrical and electronic wastes would be required along with extensive public education for appreciation of the collective problem and individual responsibility for solution.

Recycling Hierarchy

The materials in the electrical and electronic wastes include plastics, polymers, glass, and metals such as copper, tin, silver, gold, palladium, and steel, among others. From the considerations of the sustainable practices and the recovery value, hierarchy may be defined for treating these wastes for recycling. A broad step-by-step guideline can be found in literature [6]:

- Refurbish and re-use: to repair and make the equipment good for further use;
- Repurpose: use the equipment for a different purpose than for which it was primarily manufactured;
- Recover and re-use functional modules: various functional modules may be used as parts in new assemblies;
- Recover and re-use components: different components may be recovered from the equipment and used for repair / new assemblies;
- Recover materials: materials of construction may be extracted and used in production lines;
- Produce raw material feed-stocks: feed stock may be generated from the recovered materials;
- Recover energy

Lifecycle assessment (LCA) studies have found that one of the most significant impacts of a mobile phone on the environment is the energy used to manufacture the phone's components [6]. This is just an example to emphasise that the recycling and re-use option will have to be adopted immediately for attaining sustainable practices within the next few decades. Handling of the items at the time of consumer disposal will be important as a clean component / module would be much more valuable than a dirty one.

Recent Concerns over Electrical and Electronic Wastes

Health

In their study on presence of bromine in plastic consumer products, Turner and Filella [13] reported presence of bromine in about 42% of 267 analyses performed on electrical and electronic samples and 18% of 789 analyses performed on non-electronic samples. Amongst electronic items, highest concentration of bromine was found in appliances such as boiler thermostat, smoke detector, various rechargers, light bulb collars and printed circuit boards, especially the pre-2005 ones. The non-electronic items such as jewellery, coffee stirrer, child's puzzle, picture frame, various clothes hangers, Christmas decorations and thermos cup lids were reported as highest bromine-containing. Mostly the causal factor was use of brominated flame retardant in the commodities. Coupled with the presence of bromine at below flame-retardancy concentrations in many more electronic and non-electronic items, these findings indicate the widespread recycling of electronic plastic waste as the possible cause. The presence of bromine in such innocuous items could evade the attention of the end-user and recycler resulting in their disposal along with conventional municipal wastes. This would result in entry of brominated flame retardant into the environment and, when present in food-contact items, exposure to humans.

Recycling of electrical and electronic wastes remain a major source of livelihood for many urban poor in developing countries. This economy provides a valuable economic lifeline to scavengers and rag pickers, who roam the city collecting waste items intended for sale and effectively beautify the city while reducing government expenditures on waste segregation and transportation. Amankwaa et al. [14] performed a study on the health impact of the personnel involved in the informal processing of the electrical and electronic waste. They evaluated the lead levels in the blood for a representative populace from Ghana. The blood lead levels were significantly higher in the persons involved in such activities as compared to those not involved. They inferred that the health risk posed due to informal processing of these wastes were not limited to the direct workers but also spread among the traders, visitors, and residents of the immediate vicinity through different environmental vectors.

Asamoah et al. [15] assessed the breast milk collected from mothers residing / working in an electronic dumping hot-spot located in Ghana for incidence of Polychlorinated Biphenyls (PCB). PCB is often found in the environment though its natural occurrence in the ecosystem is not documented. In addition to being carcinogenic to humans, PCBs are associated with immune system disorders, behavioural alterations, birth and reproduction defects. A total of seven indicators of PCB-s could be identified in the breast milk samples. Breast milk from donor mothers from the hot-spot (105 numbers) had high levels of PCB-s compared to that from mothers residing in non-hot-spot area (23 numbers). The hazard quotient was evaluated using Health Canada's guidelines (with a threshold limit of 1 µg/kg bw/day) and this indicated that there was no potential health risk to babies. However, considering minimum tolerable value of 0.03 µg/kg bw/day defined by the Agency for Toxic Substances and Disease Registry (ATSDR), the PCB levels of some mothers were very close to the threshold values for health risk, which may get reflected in their babies. The authors recommended continuous monitoring of the PCB levels in humans in the Ghanaian population. The same would be advisable for other electronic waste disposal hot-spots in other developing countries too.

Environment

Printed circuit boards (PCB) form the backbone of all electronic gadgets. PCB-s contain significant amounts of hazardous / toxic constituents in addition to a variety of metals, ceramics and polymers. The prevalent e-waste recycling methods were identified as manual dismantling, open burning, chipping, melting, burning wires to recover copper, acid & cyanide salt leaching, and other inadequate metallurgical treatments, Dwivedy and Mittal [16] reported. The possible toxic elements include zinc, copper, nickel, cadmium, lead, mercury, chromium, molybdenum, and arsenic. These materials may accumulate, persist and contaminate soils and environment thereby posing a challenge to plant, animal and human health [17].

Saini et al. [18] presented a novel approach for capturing some potentially toxic elements, other particulates and emissions during the heat treatment of electrical and electronic waste. Using alumina adsorbents, they could capture, up to 17% of the weight of the absorbent, the gaseous emissions from heat treatment (~ 600 °C) of the waste PCB-s of mobile phones. Different carrier gases like air, nitrogen and argon were examined and it was concluded that the highest absorption occurred for nitrogen atmosphere and small particle size alumina. The absorption improved with the higher contact time of the gases and the absorbent. Copper, lead, tin, manganese and carbon were among the elements absorbed in the alumina filter. The procedure was advocated for informal sector and developing countries for reduction of the emissions from treatment of electronic waste. This would help management of the emissions within the prescribed environmentally safe limits, reduction of its impact on the flora and fauna, and foster sustainable practices.

Innovations in Processing and Recycling of Electrical and Electronic Wastes

The difficulties for recycling the valuable metals from electrical and electronic wastes are induced by the high complexity of such waste. Sun et al. [19] demonstrated a new approach of selective separation of copper from industrially processed information and communication technology waste with high complexity. For this purpose, they employed an ammonia-based leaching process wherein the copper present in the wastes was first leached into solution, and then recovered from the solution with up to 95% efficiency - with ammonium carbonate as the leaching salt. Further, by controlling the electro-deposition conditions, they reported improvement of efficiency by 80–90%, depending on the ammonia salts and high purity copper (99.9 wt.%). The study paved a new path for improving the recyclability and efficiency of copper recovery from such electronic waste.

Valuable elements such as gold, palladium, silver, copper, nickel, and other rare earth elements are often present in the electrical and electronic wastes. The research aimed at proper and improved treatment of electronic waste is not only an environmental and ecological need, but also presents scope of recovery and recycle of valuable metals and critical materials. Diaz et al. [20] explored the efficient recovery of value and critical materials from scrap mobile electronics. They proposed an electrochemical process for the selective recovery of base metals leaving precious metals for separate extraction, and this reduced the chemical demand of the extraction process. The recovery of rare earth oxides from the ferromagnetic fraction was performed by an anaerobic extraction in acid media. A comprehensive flow sheet was developed for extraction of valuable elements from the electronic wastes.

Bulut and Sahin [21] proposed a novel recycling option of the plastic waste from discarded electrical and electronic equipment. Using the plastics as one of the raw materials for polymer concrete, the issue of meeting the ever-increasing demands of ingredients for concrete production would also be addressed. Along with quartz sand and gravel, plastic from electrical and electronic waste was used as filler materials in various percentages such as 0%, 5%, 15%, and 25%. Along with the plastics being used as fillers, unsaturated polyester resin material was taken as the polymer material and used as binder in polymer concrete production. From the results, it was observed that the compressive, flexural and splitting tensile strength values decreased with increase in the plastic filler percentage while at the same time, the ductility improved. The ideal percentages for resin and the plastic were identified as 15% and 5%

respectively. The use of electronic waste in concrete in the prescribed percentages will not cause technical problems but will provide benefits such as getting rid of waste landfill/storage costs, making energy savings and protecting the environment from the effects of possible pollution.

Rozas et al. [22] discussed a bioleaching method of separation of metals from discarded electrical and electronic wastes by bacteria isolated from marine sponge Hymeniacidon heliophila (Porifera). The authors set up experiments to investigate the bioleaching capabilities of the most active strain, Hyhel-1, identified as Bacillus sp., under two different temperatures, 30◦C and 40◦C. There was crust formation when the bacteria was present with the typical electronic waste.

The experiment started at neutral pH (8) and ended with a pH of around 5.3. It was confirmed from measurements that the composition of the bacterial net surface was mostly of iron (16.1% w/w), and a higher concentration of copper was observed in the supernatant (1.7% w/w) and in the precipitated (49.8% w/w).

The study demonstrated that there is promise in employing bacteria such as Hyhel-1 as a copper recovery tool from electronic waste. The Hihel-1 strain offered a new cost effective alternative to recover metals from electronic wastes when compared to solvent extraction or acidification.

Integrated Electrical and Electronic Waste Management: Holistic Approach

The handling of electrical and electronic waste poses additional issues for developing countries, where methods such as open burning, open dumping, unsanitary landfill are practiced. There is acute lack of knowledge about environmental impacts and lack of awareness of toxicity of the discarded electrical and electronic waste. Complex composition of the electronic wastes with different environmental impacts for the various components make segregation, re-use and recycling very challenging.

The economic costs for the proposed methods and infrastructure requirements would have to be in-built in the long term planning. Added to this is the dumping of the electrical and electronic wastes by the developed countries, which make the task of management extremely difficult in developing countries.There have been a few studies in the recent years, which advocated holistic solution for this problem.

Pathak et al [23] evaluated the legislation and practices in India for management of electrical and electronic wastes. India, the fifth largest generator of such wastes in the world, is facing the daunting task of their sustainable management. Towards this purpose, Government of India has been trying to establish a proper institutional and legislative framework. The e-waste legislation draft of 2016 was among those studied. The generation, management policies and recycling practices in India were systematically evaluated with special attention to the future initiatives, environmental and health hazards. The potential recovery of valuable metals / elements from the recycling was emphasized. The authors formulated a mathematical model of generation of electrical and electronic waste in India and identified the various influences of recycling in sustainable management. Such studies form the foundation upon which the sustainable management practices may be implemented for the electrical and electronic wastes in other developing countries as well.

Today's world is riddled with electronic items in possessions of consumers even in remote locations on the face of the earth. For such remote locations, the consumer voluntarily takes the responsibility of purchase and transport of the electronic item from city / town with their personal benefits in mind. However when the time comes for disposal, such consumer often casually and irresponsibly dumps the electronic item in the wilderness or with the municipal waste. Even for towns and cities, one of the main concerns regarding recycling and scientific disposal of electrical and electronic waste is the collection, storage and transportation from the consumers to the recycling plants.

A novel approach to address this problem was presented by Innocenzi et al. [24]. They described a mobile demonstration unit, which could recover metals from waste of electrical and electronic equipment and other waste such as spent batteries and exhausted industrial catalysts, according to the standards set by the prevalent environmental regulations and norms. The concept of mobile treatment-cum-recovery plant offered an effective solution to the problem of collection of the electronic waste, reduced the environmental impact of their incorrect disposal, and enabled recovery of critical materials as rare earths and precious elements. The consumer of the electronic goods is physically separated from the place of production of the item, often in a different country. When implemented, the mobile treatment-cum-recovery van would yield economic and environmental benefits, without moving hazardous wastes between countries.

Ikhlayel [25] discussed integrated approach for e-waste management with particular attention to the factors of the developing countries. The suggested approach was to optimise the scenarios in which the municipal solid waste (MSW) and electrical and electronic waste (e-waste) get mixed, utilise the established channels of MSW collection and processing for both wastes, and aim at economic and environmental benefits. Evaluation of the existing e-waste practices would help identify the requirements for legislations, education or augmentation of the infrastructure.

It was advocated that a planning, evaluation and monitoring system be implemented. The overall cost function would include the environmental and social impacts due to improper e-waste management and the additional cost that would be incurred for improving the system. The technical feasibility would have to be supported with economic viability, cultural norms, political and industrial priorities and planning.

Future Directions for Electrical and Electronic Waste Management

The electrical and electronic industry would have to grow up to face the challenges coming in near and far future. Some of the possible solution guidelines are [6]:

- Restrictions and stricter limitations on the materials used in electronics, such as brominated flame retardants and heavy metals;
- Stringent legislations for end-of-life recovery, re-use and recycling;
- Improvement in the energy efficiency of products for all phases;
- Holistic approaches covering all aspects of the product lifecycle from design stage till the end of life;
- Adoption of more sustainable business practices;
- Avoid commoditisation of electronic products and move towards product service system-type approaches.

Few vital areas where extensive work needs to be done are identified as follows:

- Public education (from child to adult till aged population) regarding the environmental impacts of the electronic wastes and their incorrect disposal.
- Policy formulation and implementation roadmaps for making manufacturer responsible for the wastes generated during production, use and disposal of their products. Particularly, when the ownership changes, this responsibility should get transferred to the new owner notwithstanding any condition of the sale contract.
- Policy formulation and implementation roadmaps for the refurbish and upgradation regime of electronic gadgets like mobile phones and laptops for reduction of generated waste. The policy of incremental upgradation for aggressive marketing adopted by the manufacturers should be curtailed, possibly by limiting the number of new models allowed to be launched in a year. Priority should be given for the consumer to refurbish (hardware) and upgrade (software) their working gadgets within a time frame from the purchase of the product, say five years. Particularly, when the ownership changes, this responsibility should get transferred to the new owner notwithstanding any condition of the sale contract.
- Collection, storage, transport and reprocessing methodologies for the electrical and electronic wastes with special attention to the socio-economic, political and legal scenarios of the particular country.
- Innovations in sustainable recycling and reuse options for the electrical and electronic wastes.

Summary

The disposal of electrical and electronic waste, and their sustainable management is an increasingly growing menace to present society and in case of developing nations this issue is further complicated by addition of imported e-waste to the indigenously produced e-waste. The various aspects of this problem had been discussed in the paper along with the international legislation and directives applicable for handling of e-waste. Formulating an effective mangement policy for the e-waste would be required, especially for the developing countries like China, African nations and India. A few important considerations for formulation of the management policy were mentioned. The common hurdles often encountered in management of electronic waste and the desirable recycling hierarchy for sustainable management were included. Recent research in this area, which addressed the various aspects of this particular problem, were highlighted. While there are wide-spread concerns about the health and environmental impacts of incorrect disposal of these wastes, innovations such as bioleaching and polymer concrete would be extremely effective when made viable in real life applications. Research towards improvement in chemical processes for segregation and extraction of the various elements in the wastes were discussed. The latest concepts like mobile collection-cum-recovery vans and holistic approach towards integrated waste management programs were elucidated. The future directions which would be appropriate for effective and sustainable managemnet of e-waste were discussed. The various aspects needing further research and development for application of the concept of reduce-reuse-recycle as applied to the sustainable management of electronic wastes were identified.

Conflict of Interest

The author declares that there is no conflict of interest for the review presented in this article.

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