Exploring E-Waste Resources Recovery in Household Solid Waste Recycling

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Keywords: waste recycling, waste management, waste composition of Karachi-Pakistan, household solid waste, metal recovery value, socio-economic benefits

Abstract:

The ecosystem of earth, the habitation of 7.53 billion people and more than 8.7 million species, is being imbalanced by anthropogenic activities. The ever-increasing human population and race of industrialization is an exacerbated threat to the ecosystem. At present, the global average waste generation per person is articulated as 494 kg/year, an enormous amount of household waste (HSW) that ultimately hits 3.71×1012 kg of waste in one year. The ultimate destination of HSW is a burning issue because open dumping and burning as the main waste treatment and final disposal systems create catastrophic environmental limitations. This paper strives to contribute to this issue of HSW management that matters to everyone's business, specifically to developing nations. The HSW management system of the world's 12th largest city and 24th most polluted city, Karachi, was studied with the aim of generating possible economic gains by recycling HSWs. In this regard, the authors surveyed dumping sites for sample collection. The sample was segregated physically to determine the content type (organic, metals, and many others). Afterward, chemical analysis on AAS (Atomic Absorption Spectrophotometry) of debris and soil from a landfill site was performed. HSW is classified and quantified into major classes of household materials. The concentrations of e-waste [Cu], industrial development indicator [Fe], and the main component of lead-acid storage batteries [Pb] are quantified as 199.5, 428.5, and 108.5 ppm, respectively. The annual generation of the aforementioned metals as waste recovery is articulated as 1.2 × 106, 2.6 × 106 and 6.5 × 105 kg, respectively. Significantly, this study concluded that a results-based metal recovery worth 6.1 million USD is discarded every year in HSW management practices.

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Abstract: The ecosystem of earth, the habitation of 7.53 billion people and more than 8.7 million species, is being imbalanced by anthropogenic activities. The ever-increasing human population and race of industrialization is an exacerbated threat to the ecosystem. At present, the global average waste generation per person is articulated as 494 kg/year, an enormous amount of household waste (HSW) that ultimately hits 3.71×10^{12} kg of waste in one year. The ultimate destination of HSW is a burning issue because open dumping and burning as the main waste treatment and final disposal systems create catastrophic environmental limitations. This paper strives to contribute to this issue of HSW management that matters to everyone's business, specifically to developing nations. The HSW management system of the world's 12th largest city and 24th most polluted city, Karachi, was studied with the aim of generating possible economic gains by recycling HSWs. In this regard, the authors surveyed dumping sites for sample collection. The sample was segregated physically to determine the content type (organic, metals, and many others). Afterward, chemical analysis on AAS (Atomic Absorption Spectrophotometry) of debris and soil from a landfill site was performed. HSW is classified and quantified into major classes of household materials. The concentrations of e-waste [Cu], industrial development indicator [Fe], and the main component of lead-acid storage batteries [Pb] are quantified as 199.5, 428.5, and 108.5 ppm, respectively. The annual generation of the aforementioned metals as waste recovery is articulated as 1.2×10^6, 2.6×10^6 and 6.5×10^5 kg, respectively. Significantly, this study concluded that a results-based metal recovery worth 6.1 million USD is discarded every year in HSW management practices.

Keywords: household solid waste; metal recovery value; socio-economic benefits; waste composition of Karachi-Pakistan; waste management; waste recycling

1. Introduction

Solid waste management is one of the most critical issues being faced by urban areas of the world [1]. The intensity of this issue is meager in developed countries because authenticated data of MSW (Municipal Solid Waste) is available and being collected and evaluated on a daily basis [2]. Contrarily, the developing countries, characterized by uncontrolled population growth with gravitation to industrialization accompanied by no substantial heed to environmental suitability, lacks the appropriate and authenticated data of MSW, making its management more critical and worse. This missing data is incredibly crucial to effectively and efficiently allot a sustainable destination to MSW. This data also defines the economic status of a nation [3].

Unfortunately, just like other developing countries, Pakistan is not an exception where adequate data is a nonentity. This gap of knowledge has been charging Pakistan by not only exacerbating the standard of urban life but also by refraining industries from its incineration for power acquisition purposes. The imperativeness of MSW converged the attention of researchers and substantial improvement has been observed in the last decade. Various urban regions of Pakistan such as Lahore [4–6], Gujranwala [7], Hyderabad [8], Faisalabad [9], and Karachi [1,10,11] has been evaluated on various bases and remarkable data has been acquired. This study contributes to filling the knowledge gap by providing experimentally calculated authenticated data of Karachi by focusing on improved collection systems, supported and organized recycling to develop state-of-the-art WMS. The main focus of previous studies of Karachi was on the concentration of combustible matter in MSW, its potential to generate energy and environmental impacts [11–13]. This paper reports detailed information about e-waste present in MSW of Karachi for the first time and also provides a significant evaluation of its annual economical worth.

1.1. Conceptual Basis

1.1.1. Global Household Solid Waste Generation

The destination of MSW is one of the most trending topics of discussion in this century. Its significance can be accessed from the ever-increasing attention of researchers towards it, as depicted in Figure 1. This paper is also a constituent of the same congregation.

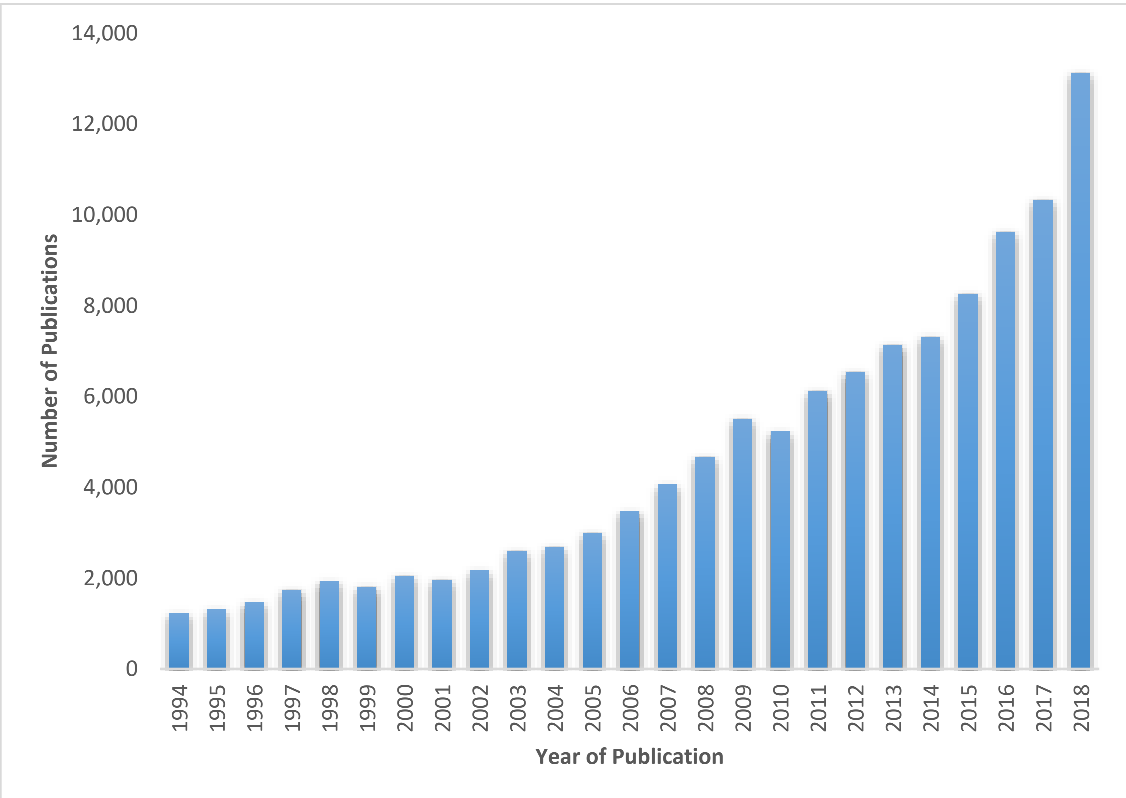

Figure 1. Ever-increasing attention of researchers towards environmental sustainability and destination of waste demonstrated by the number related publications per year (Web of Science).

The consequences of the rapid growth of the human population have remained a point of concern for environmentalists and economists. According to the UN, the human population across the globe is about 7.71 billion (Figure 2) and is increasing with an average growth rate of 1.1% per year. Since 1950, the population has almost tripled (Figure 2) and is on the rise, mainly due to better health facilities and low mortality rates. As people living on Earth are increasing in number, so is the household solid waste generated by them. The average generation of household solid waste is directly related to the population [14]. Every person does not generate the same amount of household solid waste, rather it depends upon lots of factors including the economic status and lifestyle of the individual. Per capita household solid waste generation values have been determined by researchers for selected regions; however, country-wise collection of data for per capita household solid waste generation is an enormous task and is beyond the scope of individual researchers or research consortiums. For country-wise data of household solid waste generation, available sources are mostly government organizations or international independent bodies. Existing data of household solid waste generation of different regions [15,16] have been analyzed to calculate the global average household solid waste generation per person per year. At present, the global average waste generation is 494 kg per person per year. As the population of the globe is 7 billion, thus 3.5×10^{11} kg of waste is estimated to be generated annually only from households.

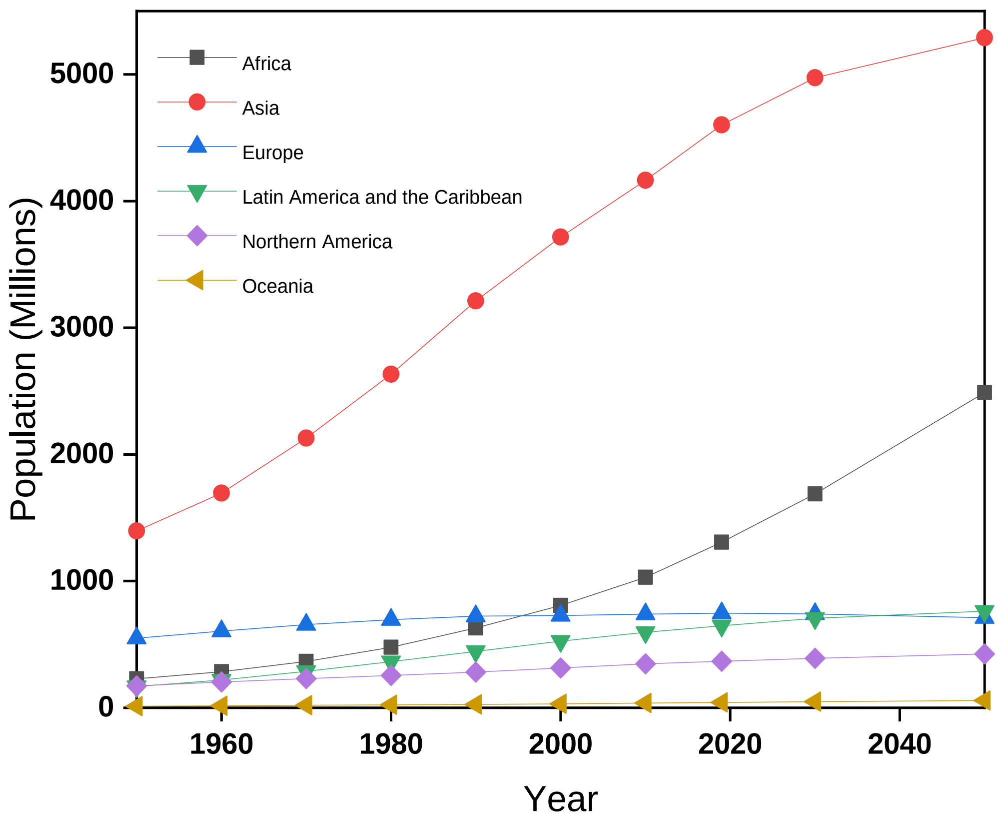

Figure 2. World population, both sexes combined (Million) [17].

1.1.2. Relationship between Socio-Economic Conditions and HSW Generation

The generation of household solid waste per capita has a multi-variant dependency. Among the most influential variables, affecting the quantity and composition of household solid waste, are the socio-economic conditions of the inhabitants of the area under consideration. Data mentioned in Figure 3 shows the relationship between GDP (Gross Domestic Product) per capita and household solid waste generation of countries of interest. It shows that Brunei Darussalam, France, and Germany have high GDP values, and their per capita household solid waste generation is also high. Economically more stable and high-income societies have high availability of resources to utilize for maintaining better living standards [18]. As a result, the amount of household waste generated is also higher in quantity and comprises more synthetic and metallic articles compared to low-income areas where the composition of household solid waste comprises more kitchen and organic waste. In addition to socio-economic conditions, education, and awareness about environmental concerns also have a significant effect on household solid waste generation [19,20].

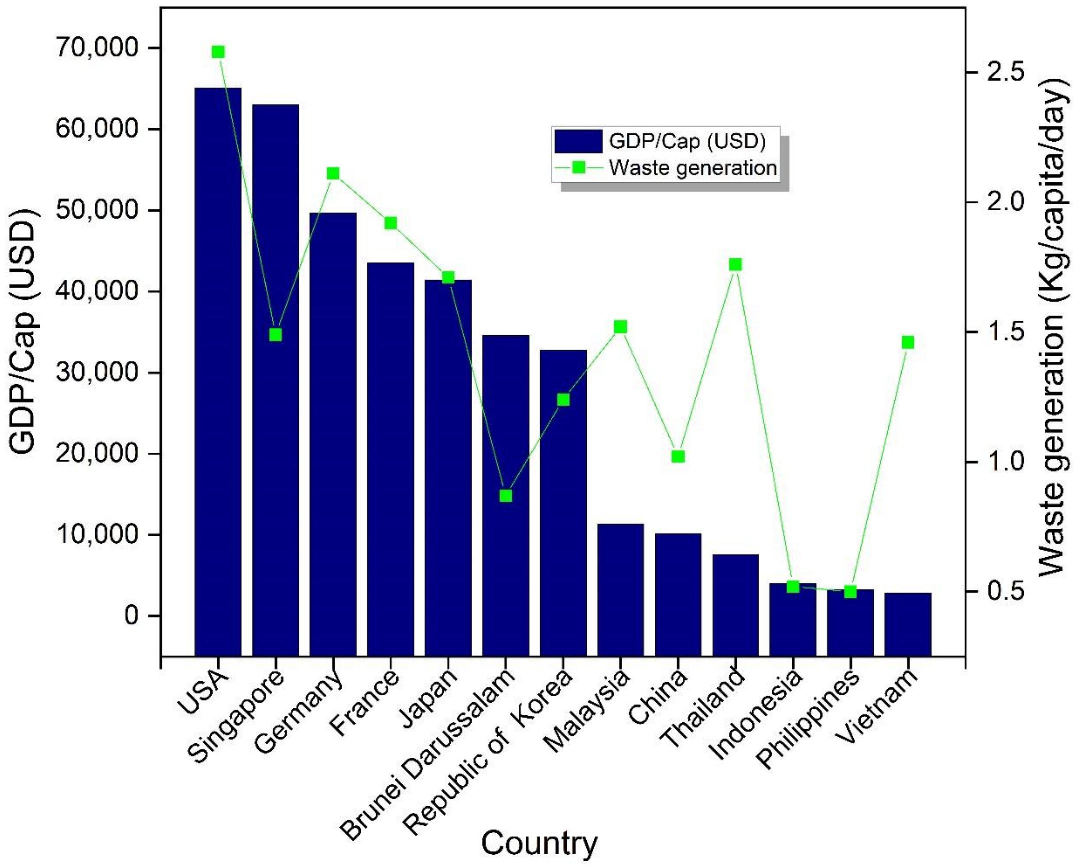

Figure 3. Relationship between GDP per capita and HSW (Household Solid Waste) generation [16,21].

1.1.3. HSW Generation by Developed and Developing Countries

Technologically advanced countries have better resources and therefore accentuate on recycling of waste into other reusable items. The percentage of recycled materials out of total HSW generated in the USA is 45%, and 44% in the UK, whereas the percentage of recycling HSW in developing countries is very low due to the unavailability of resources and limited realization of environmentally-friendly waste management. The population in developing regions of the world is increasing faster as compared to the population of developed regions, as depicted in Figure 2. Population growth leads to increment in utilities' demand in order to meet basic needs. Ultimately, developing countries will increase the rate of industrialization, paying no heed to HSW management, mainly due to low budget. Hence, the total amount of household solid waste generation is expected to rise with population growth and economic development. Statistics show that in 2016, 2.01 billion tons of MSW were generated globally and projections evaluated this quantity to be 3.40 billion tons by 2050. Developing countries are forecasted to triple their waste by 2020 [22].

Thus, a time will come when developing regions will join developed regions in GDP, and their per capita household solid waste generation is also expected to increase. According to the above facts, household solid waste generation is expected to increase in the future. Due to the unavailability of complete data, determination of percentage of HSW recycling with accuracy is not possible, however close estimates based on published data lead to recycling percentages of Malaysia = 5%, Pakistan = 5% and Thailand = 11%. The point of concern is comparatively increased in the population of developing regions as compared to the developed regions.

1.1.4. A New Class of Waste, the E-waste

Electronic waste is a relatively new environmental problem. Its disposal procedures and recycling techniques are inviting researchers and investors towards new scientific and business opportunities. The unprecedented ingress of electronic and IoT components in daily life are giving rise to an emerging problem, which demands early solution. E-waste contains 60% valuable materials like iron, copper, aluminum, gold and other metals, whereas it comprises 2.70% pollutants and hazardous materials [23], especially Pb, Sb, Hg, Cd, Ni, polybrominated diphenyl ethers (PBDEs), and polychlorinated biphenyls (PCBs). A study carried out in 2008 concluded that the quantity of rare and noble metals in e-waste is more than in typical metal mines [24]. The rapid development in software pushes manufacturers to develop new technologies and tempt consumers to upgrade hardware at a continuously increasing rate. In 1994, the average life of a personal computer was 4–5 years and it was estimated that approximately 20 million PCs (about 7 million tons) became obsolete in that year. By 2004, average PC life decreased to 2 years and in that year approximately 100 million PCs (about 35 million tons) became obsolete. As an estimate, 100 million PCs contain approximately 574,400 tons of plastics, 143,600 tons of lead, 273 tons of cadmium and 57 tons of mercury [25]. Since 2005, the use of handheld electronic devices like mobile phones and tablets have gained popularity, and the average life before getting obsolete for mobile phones has become less than two years. Nevertheless, the quantity of WEEE (Waste from Electrical and Electronic Equipment) generated constitutes one of the fastest-growing waste fractions, accounting for 8% of all municipal waste [26]. Exposure of the general public to these e-wastes is a routine matter, but the severity of this exposure, either direct or indirect, is high. Untreated e-waste dumped at landfill sites has all the means to come into indirect contact through soil, water, air, animal and plant sources. People can come into contact with e-waste materials, and associated pollutants, through contact with contaminated soil, dust, air, water, and through food sources, including meat [27–39]. Multi Criteria Analysis (MCA) of e-waste management and Applications of Life Cycle Assessment (ALCA) have recommended recycling as the best course of action for e-waste disposal [40–42]. The task of e-waste disposal and recycling is enormous and requires the intervention of governments in the form of legislation, direct investment and subsidiaries to small recycling enterprises. Apart from the government's responsibility for protecting the environment from pollution by e-waste recycling, manufacturers should also be made accountable for reducing environmental hazards from their products. The principle of Extended Producer Responsibility (EPR), which obliges producers to cover the cost of collection, recycling, and disposal, should be effectively and sufficiently implemented [42–48].

1.1.5. General Concept about HSW Recycling

The Earth has a limited supply of resources available for humans to explore and utilize. Our future generations depend on these resources. For future survival of the human race, a reduction in the consumption of new resources and recycling of available resources is imminent. On the other hand, poor solid waste management will keep on adding to the pollutants, and leave Earth as an inhabitable planet. In both cases, recycling is unavoidable for the survival of the human race, until some other habitable planet is discovered at a reachable distance in the universe. Notwithstanding the above arguments, today's profit-oriented system is more focused on the gains of today than the fortunes of tomorrow. In order to determine whether the recycling of household solid waste was economically worth performing, Karachi city was selected as subject location. The fieldwork research was carried out and the results depicted that it would be significantly expensive.

2. Materials and Methods

2.1. Demography of Karachi

To evaluate the possible economic benefits obtainable from recycling, the HSW management system of the world's 12th largest city Karachi was selected for the study. Karachi is a 3527 km^2 metropolitan area and its population is estimated at over 14.91 million as of 2017. The average population density is about 6300 people/km^2. It is situated 129 km due west of the present Indus River delta. The boundary of the city lies between the geographical co-ordinates 24°45′ N to 25°38′ N and 66°40′ E to 67°34′ E. For the city, six officially designated landfill sites are available, whereas a number of unofficially used sites for landfill are in use.

2.2. Survey and Site Selection

Among the six officially designated landfill facilities, the largest in terms of area and load dumped per day is the Deh Jam Chakro landfill facility. Household solid waste from 14 out of 18 towns of Karachi is dumped at this site. The site is located at 25°01′ N and 67°01′ E, surrounded by the thickly populated areas of New Karachi, Orangi Town and Surjani town. For this study, the authors performed the survey in the first week of every month from April 2017 to March 2018. Household solid waste was collected from 54 different sites of Karachi. These sites were carefully selected to give equal representation of all types of socio-income groups.

Sample Collection for Chemical Analysis

Samples were collected from a zone of 0.3048 m (12 inches) from the surface of the soil ash mixture residue, leftover after the burning of household solid waste. To ensure that the sample was a true representative sample, a systematic distribution approach was adopted for sample collection. For this purpose, 3 replicates of samples were collected from each corner of the 20.9032 sq meter grid of square geometry. In this way the total area of 209 sq meter area of the Jam Chakro landfill facility was covered during sample collection. This resulted in 30 samples collected from 10 sites at the landfill facility. Three replicates of samples were collected from each of the 10 sites. Collected samples were sealed in airtight containers and transported to the laboratory for analysis. All the equipment used in the process of sample collection was non-metallic in nature and mostly made up of plastic.

2.3. Quantification and Characterization Technique

As per the recommendations from the industrial peers of the case study area, industrial level extraction of the metals needs to focus on the physical segregation of metals. Hence the first step of experiment was the physical segregation of HSW; afterwards, chemical analysis was also performed. For segregation purposes, the collected household solid waste was mixed to obtain a representative sample of the whole city. Constituents of the sample were then separated as per the defined categories and weighed, as discussed in the results. Segregation of HSW was followed by grinding of segregated content, digestion in acidic medium, dilution and, finally, analysis with AAS.

In order to determine the metal content of HSW at the Jam Chakro landfill facility, open air burning of HSW was carried out. During this process, most of the combustible substances were burnt and non-combustible materials including metal were left behind in the ash–soil mixture. Heavy metals were selected to analyze in the ash–soil mixture collected from the Jam Chakro landfill facility. The purpose was to estimate the amount of metals that can be extracted from the site and recycled. Due to limited resources, the study was restricted to detailed estimations of Cu, Fe and Pb only and generation of these metals as waste in kg/yr was determined. The following sections provide deep insight into the experimentation section.

2.3.1. Sample Pretreatment

All the collected samples were mixed in laboratory with a plastic trowel. A testing sample, weighing 0.02 kg, was withdrawn. To pass a selected sample through the mesh of a 0.841 mm grid opening, it was finely grounded. A total of 5.0 g of the sieved sample was transferred into an Erlenmeyer flask.

2.3.2. Blank Preparation

In order to analyze the sample on Atomic Absorption Spectrometry (ASS), separate blanks were made ready form soil, dust, plant and water analysis. The preparation methodology for the blanks was quite similar to that of sample pretreatment, but the respective samples were not added.

2.3.3. Chemical Analysis of Samples

All chemicals used during the analysis were AnalR grade. An aqua regia solution was prepared for digestion of sample by mixing equal volumes of 0.05 N HCl and 0.025 N H_2SO_4. A total of 20 mL of Aqua regia was added to the Erlenmeyer flask, the mixture was stirred for 20 min using a magnetic stirrer and filtered through a Whatman® No 42-filter paper into a 50 mL volumetric flask and made up to the mark with aqua regia solution. The analytical reagent blanks containing only acids (Aqua Regia) were prepared for baseline calibration and for AAS cleaning between the sample runs. The concentration of heavy Cu was determined by Flame Atomic Absorption Spectrometer (Perkins Elmer model 2380) [23].

Atomic absorption spectroscopy was used to analyze the samples of debris and soil from the landfill site. The set of parameters used during analysis are tabulated in Table 1.

Table 1. AAS (Atomic Absorption Spectroscopy) parameters used for analysis.

Element	Cu	Fe	Pb
Wavelength (nm)	324.8	248.3	283.3
Slit (nm)	0.7	0.2	0.7
Mode	AA	AA	AA
Flame	Air-Ac	Air-Ac	Air-Ac
Burner Head	10 cm	10 cm	10 cm
Lamp	HCL (Hollow Cathode Lamp)	HCL	HCL
Spiked conc. (mg/L)	2.5	2.5	2.5
Read Time (seconds)	3	3	3
Replicates	3	3	3
Air Flow (L/min)	17	17	17
Acetylene flow (L/min)	1.5	1.5	1.5

3. Results

Contents of the sample of HSW generated in Karachi have been separated and classified (Section 2.3 refers) into major classes of substances present in it. Figure 4 depicts the percentage-wise distribution of different substances present in this sample. It is observed that the percentage of organic material is highest followed by metal content. Out of 11% metal content, further separation of different metals is performed and 51% of the total metal waste is determined to be iron, which has considerable recycling worth. Table 2 shows the weight of per day generated waste of selected materials in the household solid waste of Karachi.

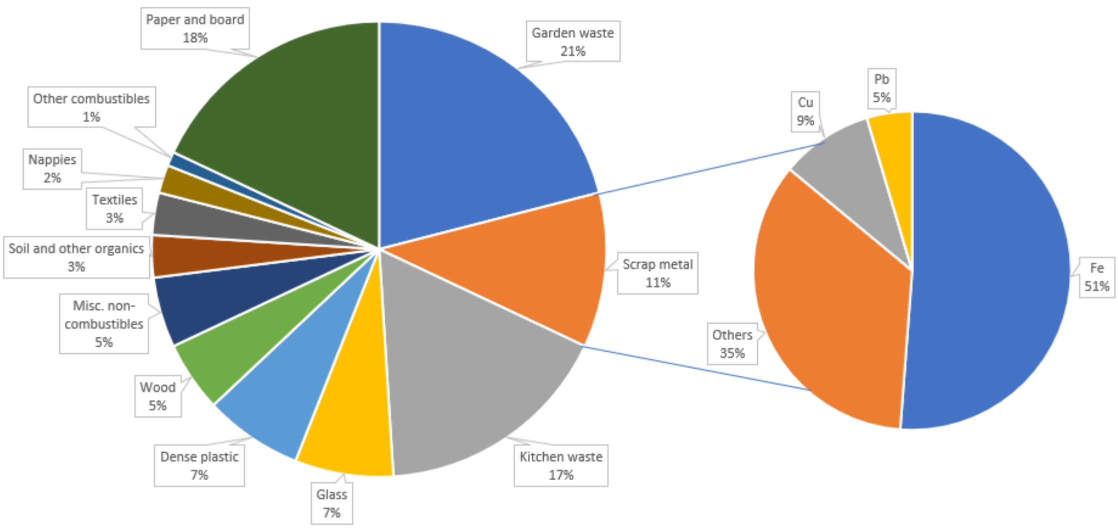

Figure 4. Classification of HSW generated in Karachi.

Table 2. Classification of HSW generated in Karachi.

Class of Material	Composition in HSW kg/Day	Metals	Composition in HSW kg/Day
Garden waste	18,480		
Paper and board	15,840		
Kitchen waste	14,960		
Metal	9680		
		Sub Classification of Metals	Composition in HSW kg/day
		Cu	906
		Fe	4958
		Pb	447
		Others	3369
Glass	6160		
Dense plastic	6160		
Textiles, Cotton, Nappies	4400		
Wood	4420		
Misc. non-combustibles	4390		
Soil and other organics	2640		
Other combustibles	880		

The estimated weight of household solid waste generated in Karachi city is 88,000 kg per day and the amount of copper in this household solid waste is 906 kg/day, the amount of Iron is 4958 kg/day, the amount of lead is 447 kg/day, and other metallic contents are 3369 kg/day.

The major constituents of E-waste i.e., [Cu] were determined to be 199.5 ppm, industrial development indicator i.e., [Fe] were determined to be 428.5 ppm, and the main components of lead-acid storage batteries i.e., [Pb] were determined to be 108.5 ppm, as detailed in Table 3.

Table 3. Concentration of metals in the soil of the Jam-Chakro landfill facility.

Metal	Number of Samples Run (n)	Sample Average Concentration ppm	Standard Deviation within Batch	Standard Error of the Mean	Confidence Interval	95% Confidence Interval Min	95% Confidence Interval Max
Cu	10	199.5	3.140534	0.993124	2.246446433	196.4257	202.5743
Fe	10	428.5	2.64928	0.837776	1.895049162	425.2	431.8
Pb	10	108.5	2.736506	0.865359	1.957442291	105.946	111.054

The amount of metal present in total household solid waste is 11%. The amount of recyclable metals estimated in Table 2 is a considerable amount, such as about 5000 kg/day of iron, about 900 kg/day of lead, 450 kg/day of copper and 3400 kg/day of other metals. These amounts have been converted into their worth per annum and results are very much promising to encourage the industry to take up the recycling of metals from household solid waste as a profitable business (Table 4).

Table 4. Annual worth estimation of Cu, Fe and Pb.

Metal	Per Day Metal Weight kg	Annual Metal Weight kg	Worth of Metal USD per kg	Annual Worth of Metal USD
Cu	906	330,849	6.38	2,109,802.20
Fe	4957	1,809,540	1.21	2,189,700.70
Pb	447	163,257	1.95	318,152.25
Total annual worth of 65.2% HSW metals generated in Karachi				4,617,655.15

The soil of Deh Jam Chakro landfill facility was analyzed, to determine concatenation of heavy metals (Cu, Fe, Pb) and the concentrations were found to be higher than unpolluted soil values, as detailed in Table 4. These metals will not be confined to the limits of soil, but will transfer to underground aquifers through leaching and will find a way to the food chain.

4. Discussion

A major problem being faced by the major cities of the world is municipal solid waste management. There exists a direct relationship between human population size and household solid waste generation. In the case of Karachi, limited resources and inadequate budget allocation make HSW management a strenuous issue. Moreover, ignorance about environmental problems and a lack of civic sense among the masses make HSW management a challenging task. Here, the household waste is collected by the garbage collectors, working on a public–private sharing basis. Due to limited resources, the Karachi Metropolitan Corporation is incapable of collecting household waste from all the houses. In this situation, vacant plots, underneath bridges and similar areas are illegally used as garbage dumping points from where garbage is collected and transported to landfill sites. Due to resource limitations, only 70% of household solid waste is transported to landfill sites, where it is combusted in the open air. Point source segregation of the household solid waste is a very convenient and inexpensive segregation technique, which is further helpful in recycling and the proper management of waste. In the city of the case study, materials worth direct sale value or recycle value are collected by scavengers, however a proper system of segregation of household solid waste does not exist.

The classification of household solid waste according to its composition, revealed that a major component of the waste is organic in nature with a considerable amount of kitchen and garden waste. These materials, if segregated at source, will be saved from hazardous chemical contamination thereby caused after mixing with other substances of chemically or physiologically harmful properties. Thus, they may be re-used at cattle farms (as cattle feed) without any major process involved. Paper and board can be recycled to regenerate paper products and packaging material. Plastics can be recycled to make new plastic products at very low cost.

The scope of the study was restricted to a detailed estimation of only Cu, Fe and Pb in household solid waste. Subsequently, the generation of Cu, Fe and Pb as waste in kg/yr is determined to be 3.3×10^5, 1.8×10^6 and 1.6×10^5 respectively. Detailed results of the analysis are tabulated in Table 2. In August 2020, the market price of copper in the international market is 6.38 USD/kg (United States dollar per kilogram), iron is 1.21 USD/kg and lead is 1.95 USD/kg. Thus, it is estimated that the annual worth of three metals in the household solid waste of Karachi is USD 4.6 M. It is pertinent to mention that these three metals comprise only 65.2% of total metal present in household solid waste generated in Karachi; therefore, segregation and recycling of the remaining 34.8% of metals present in the HSW will increase the worth of recyclable material present in the household solid waste.

During the study of the transportation cycle of HSW in Karachi, observations show that the task of HSW segregation is being performed to some extent by scavengers. These scavengers collect HSW of resale value and can be classified as informal agents of recycling. The results of the study also conclude that the formal and planned establishment of industries for recycling of reusable material present in household solid waste will be profitable in economic terms and will make development sustainable in environmental terms.

Apart from the capital worth of recyclable materials in household solid waste, another very important aspect is sustainable development. As the resources are limited, the development must be futuristically sustainable. This is only possible if the available energy and material resources are recycled and reused, in various applications such as CMOS (Complementary Metal Oxide Semiconductor) technologies [23–25]. These recycled materials will be a crucial base for electronic and thermo-photovoltaic applications [26,27]. If recycling is not given due importance, the available resources will deplete, thus pushing environmental pollution to increase over the years. The rise in population accompanied by increasing waste generation is a threat to the sustainability of life on Earth.

5. Conclusions

Metal resources for extraction, throughout the globe, are limited, but in the form of waste, they are persistent in nature for considerably long periods of time and their recycling is economically worth processing. In this regard, the recycling of household solid waste, in the mentioned case study area, is proven to be profitable when used along with point source segregation system. In this study, the amount of metals determined to be present in waste when translated in terms of worth of recovered metal will be more than USD 4.7 Million per annum. Based on the HSW segregation and classification results, it is estimated that the total annual worth of all the metals discarded in HSW will be around USD 27 Million per year. In developing countries, budget constraints faced by governments restrain investment in environmental protection and recycling projects. This study indicates the presence of a significant opportunity for profitable investment while protecting the environment from global pollution of HSW.

Household solid waste is not given much importance when sources of pollution are considered, but, as proven here, despite being less in volume, HSW is a constant source of pollution and, on an annual scale, the amount of waste produced is massive. A misconception among the masses is that HSW does not cause much harm to the environment due to the domestic nature of its origin. The factual figure is otherwise, as HSW contains several toxic components and elements like lead, which are non-degradable and have the ability to leach into underground water streams, making their way to the human food chain, through animal or plant sources.

Electronic-waste generation is on the rise, and the positive side is that most components in e-waste are recyclable. E-waste is hazardous for animal and plant life; it is sourced from depleting natural resources and can have a disastrous impact if not recycled. There is evidence that e-waste-associated contaminants may be present in some agricultural or manufactured products for export.

In general, the household waste generated is expected to increase with population, and so will the need for efficient recycling, as astronomers and astrophysicists have not yet been able to find any habitable planet in outer space.

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