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Household Hazardous Waste Management

Edited by Daniel Mmereki



HOUSEHOLD HAZARDOUS WASTE MANAGEMENT

Edited by **Daniel Mmereki**

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Contributors

Ali Karaduman, Johan Sohaili, Shantha Kumari Muniyandi, Trisia Farrelly, Joshua Edokpayi, John Odiyo, Olatunde Durowoju, Ahmed Adetoro, Daniel Mmerek

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Meet the editor



The editor, Dr. Daniel Mmereki, is a research associate of solid and hazardous waste management in the National Centre for International Research of Low-carbon and Green Buildings, Chongqing University, People's Republic of China. He was awarded PhD and postdoctoral degrees in Environmental Engineering from Chongqing University. He was also awarded an MSc degree in Environmental Science from the University of Botswana, Botswana. His research interests include innovative economic and environment-friendly techniques for management of solid and hazardous wastes. He has regularly published good-quality journals and conference proceedings and book chapters, and he is a book editor and reviewer of different journals related to valuable international publishers. He was honored with the Iraj Zandi Award for his contribution to the field of solid waste technology and management at The Thirty-First Conference on Solid Waste Technology, Philadelphia, PA, USA.

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Preface

The management of materials hazardous to the environment and public health has continued to be hot topics throughout the world, and the question of how to manage HHW has become a key environmental protection issue. If not well-managed, unpredictable negative outcomes of HHW can occur at its source (residential households), waste collection points, during transportation, and after deposit in landfills and/or incineration sites, with the potential to pose a serious threat to the environment and public health. Globally, it is widely recognized that it is critical to manage HHW properly to preserve the environment for the future generations. Furthermore, HHW should be given priority and governing legal frameworks need to be developed as well as to encourage the separation of HHW, such as batteries, oil paint, and light tubes prior to disposal. In recent decades, some researchers have observed that, to manage HHW effectively, local authorities need to create their own HHW database as quickly as possible. The emphasis has been on publishing articles that address the characteristics of HHW stream in various regions around the world, analyzing the relationships between HHW generation and parameters of income, consumption patterns, geographical location, dwelling type, and waste management policies. Through the introductory chapter, the book editor provides a background material on household hazardous waste management in the African context, including HHW generation, treatment, and disposal and governing legal framework. This book is a presentation by multiple authors and edited by experts in the field of solid and hazardous waste management meant for students, academics, researchers, hazardous waste managers, administrators, librarians, and practicing engineers interested in the field of hazardous waste management with particular emphasis on household hazardous waste management. Different authors who have contributed to this book have selected important topics on household hazardous waste management and identified problems of household hazardous waste management as well as exposure assessment to household hazardous waste. Most of the earlier books discuss the subject hazardous waste management, providing solutions to specific technology problems. More recently, a scientific approach to the basic treatment processes has been utilized. The five chapters within this book can be divided into two major parts covering some aspects of household hazardous waste management and dose and exposure assessment.

Clarity of presentation has been of fundamental concern. The text should be easily understood by graduate and undergraduate students, academics, and practicing engineers.

The book stems from various chapters submitted for a book on household hazardous waste management. Not only engineering students of diverse backgrounds but also practicing engineers from various fields would utilize this book at different times.

I am grateful to Almighty God for having given me the time to review the chapters of this book. I would like to thank all the qualified authors from around the globe for their time and valuable contributions that gave value to this book with a wide variety of studies for the scientific media. For the past 10 years of progress and continuous success, the role of InTech has been to publish detailed scientific, well-argued writing and applied scientific papers, which can be presented as original research papers and review articles on all aspects of the sciences. Particularly, I would like to sincerely acknowledge the Publishing Process Managers Ms. Maja Bozicevic and Ms. Dajana Pemac for their support, exceptional assistance, and marvelous cooperation and timely backing to the requests and inquiries I need assistance on. I wish to express my appreciation to Ms. Bontle Machola for the courage and support she gave me during the editing and reviewing of the chapters. I owe sincere thanks to Ms. Emily Lyon for her assistance in proofreading the introductory chapter and the correction of the page proofs.

Finally, I hope all success for this book to be a useful guide for the international and global research scientific community and audience.

Daniel Mmereki, PhD, Postdoctor

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Introductory Chapter: Overview of Household Hazardous Waste Management in the African Context

Daniel Mmereki, Baizhan Li, Liu Hong and
Andrew Baldwin

Additional information is available at the end of the chapter

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1. Introduction

Today, the management of household hazardous waste (HHW) is continuing to be a hot topic throughout the world due to the hazards or risks posed into the environment and public health. Scientific research has confirmed that in the recent decades, rapid global urbanization and increases in living standards, buying power and easier access to products that are convenient but not always safe have led to changes in the HHW characteristics [1]. It has been observed that people are, therefore, exposed to a greater amount of diversified hazardous materials and/or potentially hazardous materials, such as phthalates [2], antibacterial agents [3] and monosodium glutamate [4]. Improper management of HHW poses unpredictable negative impacts at the source of generation, at the waste collection points, during transportation and after disposal in landfills and/or incineration sites, with significant negative impacts to the environment and public health [5–7]. Other harmful effects of HHW include air pollution, which may be caused by the release of mercury, lead, cadmium and nickel into the atmosphere from burning batteries [1]. In most of the African countries, inadequacies of the policy frameworks include lack of capacity and governance [8]; fewer resources available to deal with environmental health issues arising, limited expertise and knowledge on HHW management technologies, inappropriate HHW classification and characterization and municipalities have not created their own HHW database. On the other hand, developed countries have dedicated substantial economic resources to regulate the production, treatment and disposal of HHW [9].

In the African context, the management of household hazardous waste (HHW) is becoming a major cause of concern in the twenty-first century. Currently, there is no segregation of household hazardous wastes and a consistent policy framework specifically dealing with

HHW regulation and a significant proportion of these waste are generated from residential daily life. However, there are uncertainties in the generation of household hazardous waste due to a lack of a consistent and efficient waste management system. As innovative processes such as phytoremediation, recycling and reuse are still nascent and/or nonexistent, most of the waste generated is indiscriminately disposed of or through conventional landfilling. This introductory chapter gives an overview of household hazardous waste disposal in African countries and provides recommendations for due adjustments and improvement of the current situation.

2. Materials and methods

The introductory chapter applied the survey of relevant published literature and electronic sources of information, news articles, reports and issues by international organizations such as the World Bank, the World Health Organization (WHO), the African Union (AU), the South African Development Community (SADC), the Economic Community of West African States (ECOWAS) and knowledgeable and well-informed individuals to provide an overview of HHW management in the African continent.

3. Overview of HHW in the African context

3.1. Sources of HHW

Household hazardous wastes are produced from residential daily life. This is related to lifestyle and public convenience in using products categorized as household hazardous waste. These include home cleaning products such as drain openers and all-purpose cleaners, medicines and personal cares, home maintenance and batteries, automotive maintenance, amusement and educational products.

3.2. Definition and HHW classification

Household hazardous waste (HHW) has been defined as “hazardous waste entering the municipal solid waste stream, representing a variety of waste types classified together based on the possession of hazardous properties (e.g., flammability, corrosivity, reactivity, caustic and toxicity)” [10, 11]. It has been shown that HHW cannot only include such products as batteries, pharmaceuticals, discarded light bulbs and mercury thermometers but also used motor oil, pesticides and solvent and paint residues in used bottles and cans (also known as “packaging and containers,” PC) [11]. It has, however, been noted that there is no universally defined classification of HHW, even within a country; different regulatory frameworks classify HHW differently [12]. Different classes of waste are governed by different regulations and are subject to different forms of treatment [1]. Furthermore, the definition of HHW may change over time in any given country.

3.3. HHW generation and composition

In developing countries in the African region, it is difficult to compare the quantities of HHW produced because of the differences in the way they are defined due to inappropriate policy frameworks. In most cases, however, these countries have no national databases on HHW production.

3.4. Collection and disposal

Generally, most people in the African countries mix all the components of household wastes, including household hazardous waste. Efforts to manage and process hazardous waste also focus on industrial hazardous waste processing without covering all the aspects of HHW. Domestic hazardous do not receive adequate attention. Researchers have shown that there have been no continuing efforts which are done to process household hazardous waste.

In most African countries, landfilling is the most common means of HHW disposal because it is the least expensive option and has low technical operating requirements, although sub-quantities of HHWs are incinerated and recycled in some countries. Moreover, landfilling may consist of open dumps or burying the wastes in unlined, excavated pits, or dumped in open spaces or water bodies. The wastes dumped in water bodies are likely to contaminate groundwater and surface water sources. Although most of the countries have ratified the Basel Convention, there has been a relatively lower interest and progress to minimize the generation of HHW. If the efforts to reduce HHW cannot be implemented, then significant environmental health impacts are realized. Fewer government programs encourage the recycling of consumer products such as batteries and electrical and electronic equipment, ending up in landfills. Although some of the HHWs such as solvents can be reused in other capacities like combining with other fuels and use in industrial burners, these wastes are disposed of in landfills. However, solvents with toxic properties are best destroyed by incineration. There is lack of data and information of quantities of HHWs dispersed throughout the region and no one knows what is disposed of, what was disposed of some decades ago and how it was disposed of. Safe methods of treatment and disposal are therefore required.

In much of the African continent, waste disposal facilities are unregulated or uncontrolled. Although no figures have been provided in countries like Botswana, it has been observed that a significant proportion of HHW disposal occurs with inadequate control or treatment [8]. It is a common practice to dispose of HHW wastes in unregulated landfills, conventional landfilling.

Furthermore, landfilling is likely to continue to be the primary means of HHW waste disposal. It has been observed that the construction of high-technology landfills with multiple synthetic liners, extensive monitoring devices and gas collection systems may be beyond the resources of many developing countries, particularly in the African context. The implementation of low-technology and low-cost approaches can increase the capacity and safety of landfills. Such approaches and techniques might include the separation of HHW from nonhazardous waste to reduce the amount of HHW going into landfills and installing leachate collection systems to reduce off-site migration of contamination. Another method of HHW disposal is incinera-

tion [13]. Although incineration is regarded as the safe and effective method for destroying hazardous wastes, in most of the African countries, incineration operates under less stringent regulations; countries have not enacted stricter regulations to minimize emissions of dioxins. Many of the incinerators installed in most of the African countries to treat HHWs are operating without adequate emission controls.

3.5. Comparison among countries

In the African context, a comparison of HHW production between countries is problematic, because of varying definitions or nonexistent of definition on what constitute household hazardous wastes. Also, the registration of wastes is not complete in some countries. This also makes the tracking of waste generation in these countries difficult because of lack of definition of HHW. This makes it difficult to devise methods and tools to update HHW data and trends, sources and fate of HHW as well as serious threats to the natural environment and public health.

3.6. Environmental health impacts

Meanwhile, the problem of HHW in some African countries is magnified by the importation of HHW from developed countries. These countries are unable to treat or dispose of the waste efficiently due to potentially higher treatment cost and remediation measures for environmental health impacts arising. For instance, workers' safety and health is relatively low in African countries receiving these wastes; not adequately trained to handle and manage HHW or does not have access to adequate protective equipment (PE).

3.7. Regulatory framework

There is no consistent and established approach to HHW regulation and standardized operational procedure on the characteristics and properties of waste, including the quantities of HHW generated, composition, content, and sources and fate of HHW. Most of HHW is currently codisposed with municipal solid waste. Due to inadequacies in policy frameworks in most of the African countries, some undefined proportion of HHW is shipped legally or illegally to African countries such as Nigeria, Ghana and Somalia from developed countries. These African countries accept HHW even though they lack administrative and technical resources to deal with them. In some countries such as Somalia, with inadequate policy framework or with no clear national government, waste trafficking from developed countries is becoming problematic.

3.8. HHW management

African countries lack technical and operational norms; so the household hazardous waste management system in society is individually interpreted as their habits. It can be concluded that there are no standardized operational norms about the management of household hazardous waste. Although most countries in the African continent have acquired more industrial growth and rapid economic growth, environmental health concerns related to HHW

have not attracted increased attention from both the private and public sector agencies. In addition, there is a relatively lower advocacy and attention on environmental health issues from the public sector, the press and national advocacy groups. Furthermore, public programs that deal with the impacts of HHW on public health and the environment are rudimentary.

3.9. Recommendations

To improve HHW management efficiency in developing countries in the African region, it is critical to implement efficient and well-functioning approaches, including the circular economy; encompassing waste prevention and minimization, recycling and reuse over disposal. Overall, African countries are especially in need of home-made and low-cost technologies for HHW management. The following recommendations are offered for guiding HHW management activities:

- Provision of technical norms, training and financial resources if possible to enhance the development of HHW management programs in African countries. Countries such as South Africa with mature recycling programs should share their experience so that mistakes are not repetitive. The information transfer could include state-of-the-art waste management technologies, technical expertise and experiences in administrative and organizational capacity and governance to make adjustments and updates on HHW management methods and practices.
- HHW management decisions should be based on the best available technological know-how. Environmental health threats should be prioritized.
- Due to limited economic resources, African countries may have to take an incremental approach in managing HHW.
- An effective management of HHW needs concerted efforts on integrated and multidisciplinary approaches, including involving all the stakeholders—the public, regulators, academia and nongovernmental organizations. The public is an important stakeholder and their participation in waste management issues is critical to ensure societal acceptance.
- Governmental departments should inform the public about the potential risks of HHW and also encourage residents to separate compostable and recyclable material at the source in the residential households of African cities.
- Optimization of HHW disposal programs, carrying out research on HHW management, to review and implement monitoring methods and tracking of several HHW substances. (e.g., batteries and insecticides) from manufacturing sources to household disposal.

4. Conclusion

This introductory chapter discusses household hazardous waste management in African countries. There are key challenges to manage HHW among the African countries, including codisposal with other household wastes, inadequacies in policy frameworks, inadequacies of

municipalities to create their own databases on HHW, inadequate technical expertise and knowledge on waste management technologies, lack of cooperation of all the stakeholders, inadequate institutional capacity and poor record keeping on how much HHW is generated, where it is going and how much is disposed of. One of the key challenges to HHW management is the lack of capacity building and awareness. Therefore, concerted efforts are needed to involve all the stakeholders and the development of consistent legislation to prevent the environmental health impacts of HHW and reduction of waste. Furthermore, there is an urgent need for farsightedness of the decision makers to develop and implement integrated policy strategies to stimulate societies to manage HHW in a more sustainable manner.

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Dose Response and Exposure Assessment of Household Hazardous Waste

Johan Sohaili, Shantha Kumari Muniyandi and
Rosli Mohamad

Additional information is available at the end of the chapter

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Abstract

This study was conducted to assess the risk of health hazards to employees working in local authorities in Malaysia especially workforce involved in waste management. Therefore, the four steps process of Health Risk Assessment has been identified, which include hazard identification, exposure assessment, dose response assessment and risk characterization. It was estimated approximately 22,388 tons of wastes generated every year in Malaysia and around 2.2 % out of that amount were consisting of hazardous household waste (HHW) with mean average generation for each person per day was around 0.02 kg. The waste generation is expected to increase 2 to 3 % per year and estimated to reach approximately 31 million of tones per day in the year 2020. In this study, the household hazardous wastes (HHW) were analyzed for their permissible dose level and the existing hazard level, hazard index and cancer index. Cancer Index for dermal exposure is found to be 5.8×10^{-7} mg/m³, for Inhalation dust 1.4×10^{-1} mg/m³, which falls under Low Risk and for Inhalation aerosol is 5×10^{-2} mg/m³, under Medium Risk. Extra care must be taken for the management of HHW as if it is improperly managed, it will fall into High Risk.

Keywords: Household Hazardous Waste, Hazard Index, Cancer Index

1. Solid waste and household hazardous wastes

1.1. Solid waste and household hazardous waste generation in Malaysia

Malaysia has undergone rather rapid urbanization since the beginning of the twentieth century and resulted in the development of more urban environment. Level of urbanization in Malaysia

has increased from 26.8% in 1970 to 70.9% in 2010. Between 1970 and 2010, the urban population increased drastically by 557.5% or 16.5 million [1]. Modernization and progress has had their share of disadvantages, and one of the main aspects of concern is the pollution they are causing to human and environment. Increasing in the global population and the rising demand for food and other essentials such as household products lead to the increasing amount of waste being generated daily by each household and resulted in generation of more household hazardous wastes (HHW).

The total population of Malaysia in 2005 was only 25,048,000, and it increased gradually every year. Ministry of Housing and Local Government has reported that the estimated population of Malaysia in 2020 will be about 31,453,353 (Table 1). The increase in population will directly contribute to the increase in waste too.

Year	Population
2005	25,048,000
2010	27,642,193
2015	29,486,262
2020	31,453,353

Table 1. Population of Malaysia from year 2005–2020.

Municipal Solid Waste (MSW) generation had increased to 6.0 million tons in 1998, with an average of 0.5–0.8 kg per capita per day. Per capita waste generalization increased from 0.70 kg/person in 1990s to 1.2 kg/person in 2000, but in the recent past the range has increased to between 0.5 and 2.5 kg/person. The production of domestic and commercial waste in 2000 was 8.0 million tons/year [2]. The estimated solid waste generation in Malaysia in 2007 was approximately 24,000 tons per day (8.64 million tons/year) for a population of approximately 26 million people, and only 70% of waste produced per day were collected [3]. It is known that the greater the economic prosperity of any nation, the higher the rate of urbanization and consequently the greater will be the amount of solid waste produced, and Malaysia is one of such nations. Moreover, as the population of Malaysia increases, the generation of HHW will also increase, where approximately 31 million tons per day are estimated by the year 2020. Increase in residents will increase the generation of wastes from time to time. If no efforts are taken to reduce the generation of wastes, it will contribute to the increase in HHW at landfill. As a result, it will impact the workers and public negatively. It will also contribute to ground water contamination. In addition, if there is open burning at the landfill, it will also lead to air contamination.

Figure 1 shows the composition of solid waste in Malaysia, in which about 60% consist of domestic waste (DW), while 34% consist of other wastes (OW) such as industrial wastes, commercial waste and others; approximately 3.3% of total solid wastes consist of HHW.

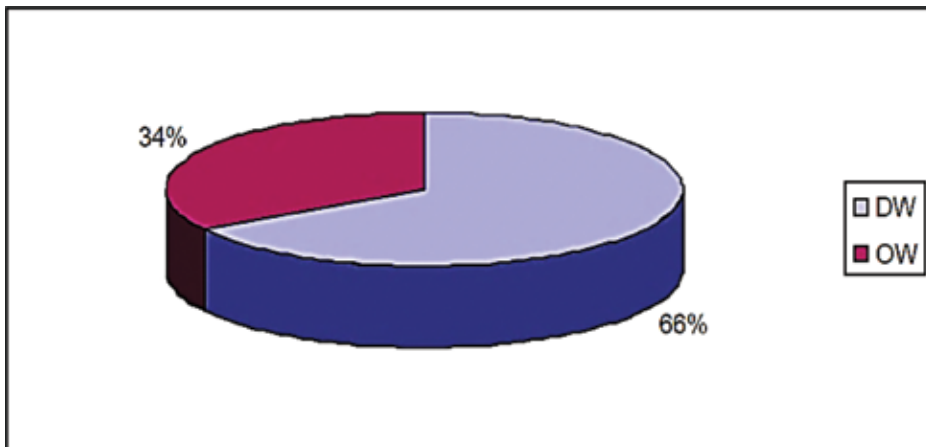


Figure 1. Percentage of domestic waste generated in Malaysia.

1.2. HHW composition in Malaysia

Determination of HHW composition was conducted at 40 local authorities in Malaysia. Results showed that a total of 9408 kg/day (0.02 kg/person/day) of HHW were generated. The category of cleaning products generated the highest portion of HHW of about 18%, followed by 16% of personal products, 12% of automotive products, 11% of fertilizers, 9% of paints and pesticides, 8% of lamps, 7% of stains and their removers, 6% of hobby products and batteries as the least generated HHW of about 5% (Figures 2 and 3).

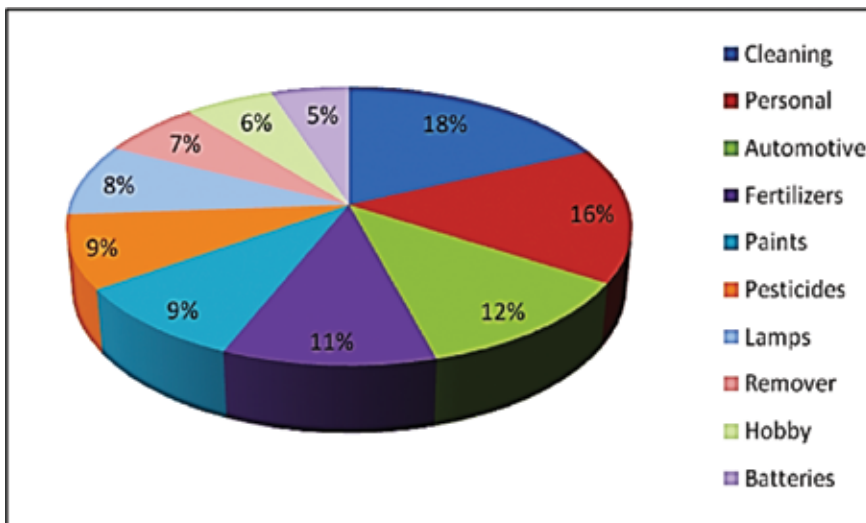


Figure 2. Composition of HHW (% by weight) generation at local authority in Malaysia.

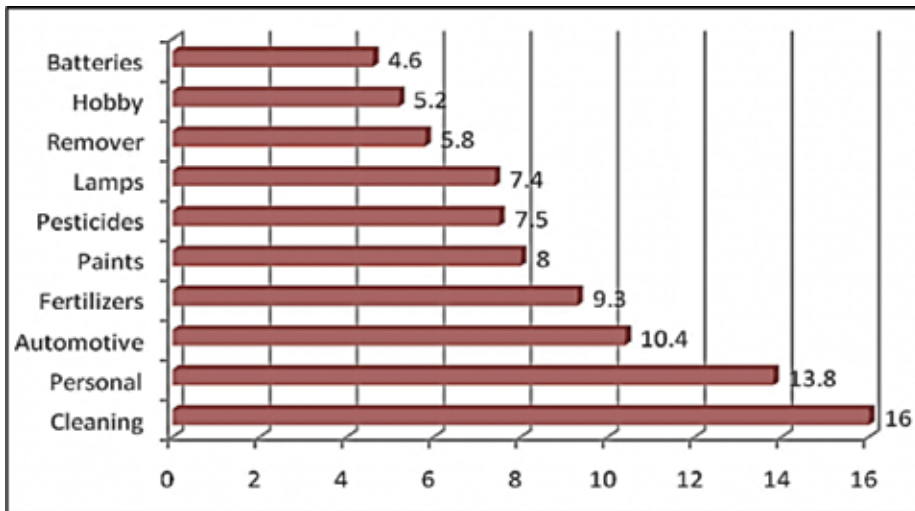


Figure 3. Composition of HHW (g/p/day) in Malaysia.

From the study, it can be seen that the utilization of personal products and cleaning products is high in Malaysia and in line with the era of globalization and modernization process where plenty of these materials are available in the market. In general, it can be said that all the houses are generating HHW and each individual produces approximately about 0.02kg of HHW per day, and it is expected to rise about 2–5% per year. Without the waste minimization measures; “3Rs” and especially HHW waste separation at home, this will increase the waste disposal in landfills and increase the risk of health hazards to workers handling HHW and subsequently increase the occurrence of pollution.

The average generation of household hazardous waste (HHW) in Malaysia is 0.02 kg/p/day. Thus, for a population of 27 million, HHW waste generated will be about 7.3kg/p/year. Pesticides and batteries perhaps showed a small percentage but it could still cause harm to human. They may contaminate underground water and have the potential for causing cancer if not properly managed at local level.

1.3. Estimation of total HHW generated in Malaysia by 2020

Improper management of HHW will result in increasing of waste generation from time to time and contribute to health problems and pollution.

As shown in **Table 2**, estimation of HHW generated in Malaysia is 865,753,484 tons per year in 2010 and is estimated to increase by about 985,119,016 tons per year in 2020. Results from this study showed that 823,492,800 tons of HHW were generated per year, where cleaning products were the highest contributor with the amount of 148,543,200 kg per year, as compared to personal products (128,793,600 kg per year), motor oil (93,974,400 kg per year), pesticides (79,466,400 kg per year), home maintenance (66,362,400 kg per year), fluorescent and menthol

(61,214,400 kg per year), flea and tick control (58,687,200 kg per year), adhesive, glue and varnish (54,288,000 ton per year) and batteries (46,238,400 ton per year).

Year	Population (million)	Kg/p/day	Kg/pop/day	Ton/year
2005	25.05	0.09	2,179,176	784,503.36
2006	26.00	0.09	2,262,000	814,320.00
2010	27.64	0.09	2,404,870	865,753.48
2015	29.49	0.09	2,565,304	923,509.72
2020	31.45	0.09	2,736,441	985,119.01

Table 2. Total of HHW based on all categories generated in Malaysia from 2005 to 2020.

The generation of HHW has been continuously on the rise and in Malaysia its management has been a problem till today due to its rapid increases in the volume and composition [2]. Improper disposal of HHW will lead to the contamination and pollution of river and underground water. The chemicals contained in HHW are hazardous and have the potential to cause cancer in people.

This high generation of HHW in Malaysia is attributed to the rapid economic growth, population growth, developments of town and not forgetting the changing lifestyle that has been experienced in the recent past. If no action is taken to minimize waste in the early stages, it will harm the employees who are handling those waste materials that pollute our environment.

2. Dose response assessment

Garbage collection work is a major responsibility in all local authorities, and all types of waste, particularly domestic waste should be managed properly. Domestic waste contains HHW that need to be managed as efficiently as possible. Hazardous wastes at home are not subjected to the controlled scheduled waste according to the Environmental Quality Act, 1994, thus, the waste is directly disposed into the trash and then to the landfill. The absence of segregation at the source and landfill cause it to be potential water resources pollutant and direct exposure to workers. Improper management of HHW can directly expose the local authorities' workers to the above-mentioned hazard. Every employer must ensure that their employees are safe during the course of their duties as subjected in the provision of Occupational Safety and Health, 1994. Thus, to ensure the safety of workers, human health risk assessment should be conducted to identify the level of risk from HHW so that prevention and control measures can be applied and thus minimize the impact of health and safety of employees during the course of their duties.

Therefore, risk assessment for HHW must be conducted to estimate the increasing risk on health of human due to exposure to toxic substances. Four main steps involved in the process

of assessing risks start from hazard identification, followed by exposure assessment, dose-response assessment and end with risk characterization [4] as shown in **Figure 4**.

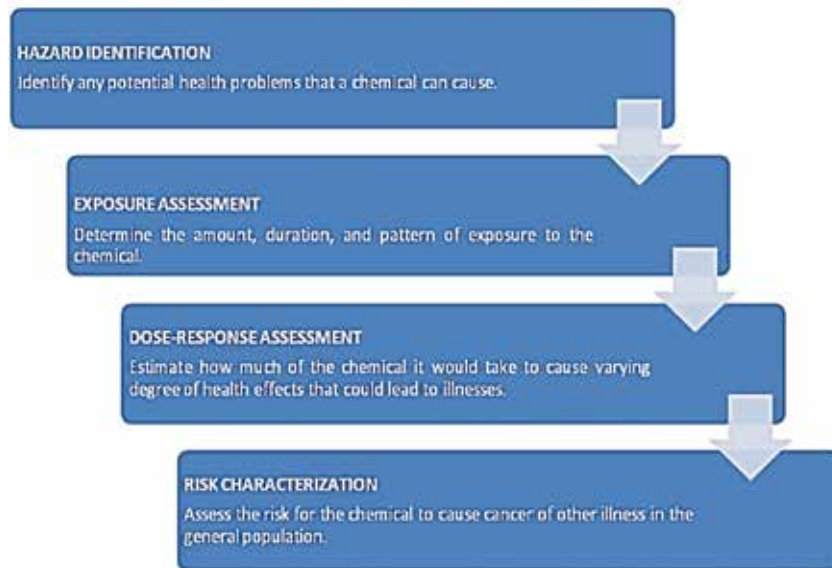


Figure 4. The four steps of risk assessment.

Similar to solid waste management, HHW waste management includes all the activities starting from generation to the final disposal and is defined as the control, generation, storage, collection, transfer and transportation, processing and disposal of solid waste consistent with the best practices with public health and environmental considerations.

Toxicity of the chemicals present in HHW need to be studied in order to provide guidance for the workforce involved directly in the waste management process. Thus, the toxicity studies can be done through dose response assessment. Dose response assessment describes the toxicity of the chemicals identified in HHW using models based on human (including clinical and epidemiologic approaches) and animal studies, and data-based reference by US EPA integrated risk information system (IRIS).

The exposure assessment identifies exposed populations and details on the type, level, duration and frequency of exposure. Typically, exposure assessment consists of a number of steps [5] which are:

- i. Estimation of ambient air concentrations using air pollution monitor or other predictive air quality models, including analysis of spatial and temporal trends and distributions.
- ii. Identification of any special group that may be at risk due to high exposure (due to proximity, diet, or other factors) or vulnerability (due to pre-existing disease or other factor) to the pollutants.

- iii. Development of appropriate exposure assumptions, for example activity factors (e.g. time spent outdoors), location factors (mobility), uptake factors (breathing rates, absorption rates, etc.), and other factors that may affect exposure to pollutants for each group.
- iv. Estimation of the number of exposed individual based on demographic and other data and validation of exposure analysis using monitoring or other means.

2.1. Empirical model of reference dose and exposure assessment of HHW

Referring to the provisions of the Occupational Safety and Health Act [6], the employer must take measures and precautions to prevent the employees from being exposed to safety and health hazards in their course of works. Thus, workers in local authorities involved in waste collection and disposal sites should be aware of the health hazards that exist so that they can be protected and reduce the risk of exposure to the HHW.

Workers and public have their right to know the requirement to inform particular group or individual on the health risk when exposed to HHW. Employers are required to assess chemicals contained in HHW or used in workplace and to make information regarding physical exposure and any associated risks of those agents to their employees.

Categories of HHW	(g/person/day)	(% by weight)
Cleaning	20.74	17
Personal	18.65	15
Automotive	15.62	13
Fertilizers	13.7	11
Paints	10.61	9
Pesticides	10.52	8
Lamps	10.4	8
Remover	9.09	7
Hobby	7.72	6
Batteries	7.36	6
Total	124.41	100

Table 3. Ranking of HHW generated based on categories at city council (% by weight).

The ranking of the generated HHW, based on categories at City Council, is shown in **Table 3**. It can be seen that the cleaning products generated about 21 g/p/day, personal products 19 g/p/day, automotive 16 g/p/day, fertilizers 14 g/p/day and the rest less than 11 g/p/day. These high utilization figures are due to income disparities, social economic and cultural life of the population of the developed and growing city. These developments were in line with the use of hazardous household products (HHP) growing every day in the market. Overall generated

HHW is 124 g/p/day. Therefore, these developments need to be addressed with the control measures in the management of solid waste and improve the management of HHW to ensure that the health of the workers is protected during the management of waste and the environment is not polluted by the HHW for the developed nation in 2020.

Moreover, it is important to highlight that, domestic wastes contain HHW and chemicals that can cause harm and affect health of human especially general workers who has direct contact with waste operations at dumping site or landfill. Therefore, an empirical model has been produced as given in Section 2.2 with different times and days of exposure at work equivalent with reference concentration (RfC) and reference dose (RfD) to serve as a guideline to employees or employers for minimization of health hazards. By knowing dose response of HHW to employees, preventive measures can be taken when carrying out these tasks.

2.2. Reference dose response of chemical contained in HHW

A dose-response relationship describes how the likelihood and severity of adverse health effects (the responses) are related to the amount and condition of exposure to an agent (the dose provided) [5]. Dose response assessments are determination of the relation between the magnitude of exposure and the probability of occurrence of the health effect in question [7–10]. It examines the relationship between the level of exposure and the resultant toxicity of the hazards. Therefore, establishment of a reference dose is an important aspect of the dose-response assessment. The RfD is the amount of the chemical, if received over a lifetime, that should not cause harmful effects. The RfD of a chemical is based on no observed adverse effect level (NOAEL) and lowest observable effect level (LOEAL) derived from a wide range of toxicity studies. The duration of exposure is important to consider. Varying durations of acute, short-term, intermediate-term and chronic are taken into account when formulating risk as a dose-response evaluation usually requires an extrapolation from the generally high doses administered to experimental animals, or exposures reported in occupational studies, to the exposures expected from human contact with the agent in the environment. There are many reasons for this. First, the possible mechanisms of all action for carcinogens are not fully understood [11, 12].

NOAEL is the highest exposure level at which no statistically or biologically significant increases are seen in the frequency or severity of adverse effect between the exposed population and its appropriate control population. In an experiment with several NOAELs, the regulatory focus is normally on the highest one, leading to the common usage of the term NOAEL as the highest experimentally determined dose without a statistically or biologically significant adverse effect. In cases where a NOAEL has not been demonstrated experimentally, the term LOAEL is used, which this is the lowest dose tested [2].

By referring to RfC and RfD for each classes of HHW as shown in **Table 4**, for class I, the mean RfC is found to be 0.05 mg/m³ and RfD is 0.17 mg/kg/day; for class II, RfC is 0.036 mg/m³, and RfD is 0.39 mg/kg/day; for class III, RfC is 0.0035 mg/m³ and RfD is 0.017 mg/kg/day, for class IV, RfC is 0.002 mg/m³, and RfD is 0.004 mg/kg/day, while for class V, RfD is 0.0094 mg/kg/day and for class VI, RfC is 0.02 mg/m³ and RfD is 0.60 mg/kg/day.

Classes of HHW	Chemical contains	Reference dose		Mean	
		RfC mg/m ³	RfD mg/kg/day	RfC mg/m ³	RfD mg/kg/day
I	Ammonia	0.1	Na	0.05	0.17
	Acrylic acid	0.001	0.0005		
	Acetone	Na	0.9		
	Nitrobenzene	Na	0.0005		
	Potassium cyanide	Na	0.05		
	Sodium azide	Na	0.004		
II	Ammonia	0.1	Na	0.036	0.39
	Allylchloride	0.01	Na		
	Acetophenone	Na	0.1		
	Acetaldehyde	0.009	Na		
	Acetone	Na	0.9		
	Benzyl chloride	Na	0.17		
III	Acetonitrile	0.06	Na	0.0035	0.017
	Allylchloride	0.001	Na		
	Atrazine	Na	0.035		
	Warfrin	Na	0.0003		
IV	Benzene	Na	0.004	0.002	0.004
	Hydrogen sulphide	0.002	Na		
V	Furan	Na	0.001	0.0	0.094
	Toluene	Na	0.008		
	Xylenes	Na	0.2		
VI	Acetone	Na	0.9	0.02	0.60
	Aniline	0.001	Na		
	Acrylic acid		0.5		
	Allylchloride	0.001	Na		
	Acetonitrile	0.06	Na		
	Benzene	Na	0.004		
	Chloroform	Na	0.01		
	Ethylene glycol	Na	2		
Total				0.022 2.2E-2	0.21 2.1E-1

Table 4. Reference dose response of chemical contains in HHW.

These results indicated that the allowable HHW dose level for the RfC is 0.022 mg/m³, while that for RfD is 0.21 mg/kg/day. Exposure exceeding the dose limits specified here will cause risks and health hazards to workers exposed to it.

Therefore, it is the responsibility of the employers to ensure that the allowable dose level of HHW is strictly followed so that the employees are not at risk of health hazards at workplace.

2.3. Toxicity factors of chemical contained in HHW

Table 5 shows the toxicity factors of chemicals contained in HHW. The level of oral exposure to benzene in HHW is allowed to be 0.000013 mg/kg/day while for Cadmium it is 0.001 mg/kg/day. These values are too small and require high prevention measures to avoid the materials contained in this HHW are accidentally swallowed.

Constituents	Oral CSF (mg/kg/day)	IUR* (µg/m³)	Oral RfD(mg/kg/day)	Inhalation (µg/m³)
Benzene	9.1	0.0026	0.000013	0.0455
Cadmium	NA	0.0018	0.001	0.02
Mercury	NA	NA	0.0003	1.05
Toluene	NA	NA	0.08	0.005
Xylene	NA	NA	0.2	100
Lead	0.0015	0.33	NA	NA

*IUR (Inhalation unit risk); US EPA (2005).

Table 5. Toxicity factors of chemical constituents in HHW.

Exposure by dermal	Direct skin contact
Formula for calculated average dose exposure to workers	$[Fl * C * Kp * t * Sder * n] / BW$ $[0.1 * 10 \text{ mg/l} * 3.9 \times 10^{-5} \text{ cm/h} * 0.617 \text{ h} * 1980 \text{ cm}^2 * 10] / 60$
Workers (direct skin contact)	Direct skin contact for the exposure estimated, the terms are defined with following values for the calculation considering a worst-case scenario
Fl	Percentage weight factor of substance in product 10% (0.1) AISE
C	Product concentration in (mg/ml) 10 mg/ml AISE/HERA, 2002
Kp	Dermal penetration coefficient $3.9 \times 10^{-5} \text{ cm/h}$ Prottey,1975
t (0.5h)	Duration of exposure skin 10 min (0.167h) AISE, HERA, 2002
Sder	Surface area of exposure skin 1980 cm ² TGD, 1996
n (30)	Product used frequency (tasks per day) 3 AISE, HERA, 2002
BW	Body weight 60 kg (TGD, 1996)
Formula for HHW (direct skin contact to workers)	$[0.1 \times 0.01\% * 3.9 \times 10^{-5} * 0.167 * 30 * 1980] / 60$ $3.8 \times 10^{-6} / 60 = 6.4 \times 10^{-8}$ Exp sys = 6.4E-8 µg/kg/day
Average dose exposure Daily (ADD)	$6.4 \times 10^{-8} \text{ µg/kg/day}$

Table 6. Average exposure by dermal of HHW.

2.4. Average dose exposure of HHW

To determine the level of exposure to skin where HHW is in direct skin contact, the estimations were made, as given in **Table 6**. The estimate obtained from the average daily exposure dose (ADD) is 6.4×10^{-8} µg/kg/day. Estimation was also made to determine the level of exposure to dust, as given in **Table 7** and the average daily exposure dose (ADD) obtained is 1.35×10^{-2} (0.0135) µg/kg/day. ADD obtained for exposure by inhalation for aerosol is found to be 5.6×10^{-3} µg/kg /day (**Table 8**).

Exposure by inhalation	Dust
Formula for calculated average dose exposure to workers	$[Dp \cdot P \cdot n] / BW$ $[0.27 \mu\text{g} \cdot 0.1 \cdot 30] / 60$ kg
Workers (Exposure by inhalation)	Inhalation dust for the exposure estimated, the terms are defined with following values for the calculation considering a worst-case scenario
Dp	Dust per product/cup used 0.27 µg dust per cup/product Van de Plassche et al. 1998
P	Powder detergent/product maximum level 10% 0.027 µg (AISE, 2002)
n (30)	Product used frequency (Tasks per day) 3 AISE, HERA, 2002
BW	Body Weight 60 kg (TGD, 1996)
Formula for HHW (Inhalation by dust to workers)	$[0.27 \mu\text{g} \cdot 0.1 \cdot 30] / 60$ 0.0135 µg/kg/day Exp sys = 1.35×10^{-2} µg/kg/day
Average dose exposure daily (ADD)	1.35×10^{-2} µg/kg/day

Table 7. Average exposures by inhalation (dust) of HHW.

Exposure by inhalation	Inhalation (aerosol)
Formula for calculated average dose exposure to workers	$[F1 \cdot C \cdot Q_{inh} \cdot t \cdot n \cdot F7 \cdot F8] / BW$ $[0.08 \cdot 0.35 \text{ mg/m}^3 \cdot 0.8 \text{ m}^3/\text{h} \cdot 0.17 \text{ h} \cdot 1] / 60$
Workers (exposure by inhalation)	Inhalation dust for the exposure estimated, the terms are defined with following values for the calculation considering a worst-case scenario
F1	Percentage weight fraction of substance in product 8% AISE internal data, 2002
C	Product concentration in air 0.35 mg/m ³ (P&G, 1974, 1978)
Q _{inh}	Ventilation rate 0.8 m ³ /h (TGD, 1996)
t (0.5h)	Duration of exposure skin 10 min (0.167h) AISE, HERA, 2002
n (30)	Product used frequency (tasks per day) 1 AISE, HERA, 2002
F7	Weight fraction of respirable particles 100% (1)
F8	Weight fraction absorbed or bioavailable 100% (1)
BW	Body weight 60 kg (TGD, 1996)
Formula for HHW (inhalation by dust to workers)	$[0.08 \cdot 0.35 \text{ mg/m}^3 \cdot 0.8 \text{ m}^3/\text{h} \cdot 0.5 \text{ h} \cdot 30] / 60$ 5.6×10^{-3} (0.0056) µg/kg/day Exp sys = 5.6×10^{-3} µg/kg/day
Average dose exposure daily (ADD)	5.6×10^{-3} µg/kg/day

Table 8. Average exposures by inhalation (aerosol) of HHW.

From these results, it can be concluded that if the rate of exposure exceeds the given levels, it can cause health hazards to workers either through the skin or through ingested or inhaled substances containing dangerous materials from HHW. Therefore, it is essential for the employer to know the minimum level of exposure and educate the employees. However, the minimum dose is very small and it difficult to prevent the workers from being exposed to this level. Hence, protection at work is very important, which can be done by providing PPEs to employees, such as gloves, uniforms and so on. What is more important is the knowledge and awareness among employees on the hazards that exist around them when performing their tasks.

2.5. Hazard risk and cancer risk index of HHW

To make estimation of hazard and cancer risk index, it is important and necessary to obtain the value of ADD exposure and the RFC or RfD for the estimations as shown in **Tables 9** and **10**.

Hazard risk	Hazard index = ADD/RfC or RfD
ADD (exposure)	Average daily dose exposure
Calculated cancer risk	
Exposure by dermal	Direct skin contact
Average dose exposure daily (ADD)	$6.4 \times 10^{-8} \mu\text{g}/\text{kg}/\text{day}$
Exposure by inhalation	Dust
Average dose exposure daily (ADD)	$1.35 \times 10^{-2} \mu\text{g}/\text{kg}/\text{day}$
Exposure by inhalation	Aerosol
Average dose exposure daily (ADD)	$5.6 \times 10^{-3} \mu\text{g}/\text{kg}/\text{day}$

Table 9. Value of ADD exposure for hazard risk.

Hazard risk (cancer)	Hazard risk = LADD * CSF
ADD (exposure)	Average daily dose exposure
Calculated hazard index (Cancei')	
Exposure by dermal	Direct skin contact
Average dose exposure daily (ADD)	$6.4 \times 10^{-8} \mu\text{g}/\text{kg}/\text{day}$
Exposure by inhalation	Dust
Average dose exposure daily (ADD)	$1.35 \times 10^{-2} \mu\text{g}/\text{kg}/\text{day}$
Exposure by inhalation	Aerosol
Average dose exposure daily (ADD)	$5.6 \times 10^{-3} \mu\text{g}/\text{kg}/\text{day}$

Note: $\text{NOEAL} * \text{CSF} = \text{RfD}$ or RfC ($\text{CSF} = \text{RfD}$ of RfC/NOEAL).

Table 10. Value of AA exposure for cancer risk.

From these estimates, hazard risk index for HHW has been tabulated in **Table 11** for some of the materials contained in the HHW that affect the health of both exposed workers and the public. The total hazard risk index for HHW was found to be more than 1.

Constituents	Average dose exposure daily (ADD)	IUR ($\mu\text{g}/\text{m}^3$)	Oral RfD (mg/kg/day)	Inhalation ($\mu\text{g}/\text{m}^3$)	Hazard risk
Benzene	6.4×10^{-8} $\mu\text{g}/\text{kg}/\text{day}$ dermal exposure	2.6E-03	1.3E-05	4.55E-02	4.9E-03
	5.6×10^{-3} $\mu\text{g}/\text{kg}/\text{day}$ Inhalation	2.6E-03	1.3E-05	4.55E-02	0.12 1.2E-01
Cadmium	6.4×10^{-8} $\mu\text{g}/\text{kg}/\text{day}$ dermal exposure	1.8E-03	1E-03	2E-02	3.2E-5
	5.6×10^{-3} $\mu\text{g}/\text{kg}/\text{day}$ Inhalation	1.8E-03	1E-03	2E-02	0.28 2.8E-01
Mercury	6.4×10^{-8} $\mu\text{g}/\text{kg}/\text{day}$ Dermal exposure	NA	3E-04	1.05	2.1E-04
	5.6×10^{-3} $\mu\text{g}/\text{kg}/\text{day}$ Inhalation	NA	3E-04	1.05	5.3E-03
Toluene	6.4×10^{-8} $\mu\text{g}/\text{kg}/\text{day}$ dermal exposure	NA	8E-02	5E+03	8E-06
	5.6×10^{-3} $\mu\text{g}/\text{kg}/\text{day}$ Inhalation	NA	8E-02	5E+03	1.12
Xylene	6.4×10^{-3} $\mu\text{g}/\text{kg}/\text{day}$ Dermal exposure	NA	0.2	100	3.2E-07
	5.6×10^{-3} $\mu\text{g}/\text{kg}/\text{day}$ Inhalation	NA	0.2	100	5.6E-05
TOTAL					1.93

Table 11. Hazard risk index of HHW.

Constituents	Average dose exposure daily (ADD)	Oral CSF (mg/kg/day)	Hazard index
Benzene	6.4×10^{-8} $\mu\text{g}/\text{kg}/\text{day}$ Dermal	9.1	5.8E-07
	1.35×10^{-2} $\mu\text{g}/\text{kg}/\text{day}$ Inhalation dust	9.1	0.12
	5.6×10^{-3} $\mu\text{g}/\text{kg}/\text{day}$ Inhalation aerosol	9.1	0.05
Lead	6.4×10^{-8} $\mu\text{g}/\text{kg}/\text{day}$ Dermal	1.5E+03	9.6E-11
	1.35×10^{-2} $\mu\text{g}/\text{kg}/\text{day}$ Inhalation dust	1.5E+03	2.0E-02
	5.6×10^{-3} $\mu\text{g}/\text{kg}/\text{day}$ Inhalation aerosol	1.5E+03	8.4E-06

Table 12. Estimation of cancer risk of HHW.

The estimations for cancer index are shown in **Table 12**. For benzene, the cancer index was found to be 5.8×10^{-7} for exposure through the skin, 0.12 for dust inhalation exposure which

is under low risk and 0.05 for aerosol inhalation exposure under medium risk, as well as for lead with hazard index of 9.6×10^{-11} for exposure through skin, 2.0×10^{-2} for dust inhalation and 8.4×10^{-6} for aerosol inhalation. The total cancer index was less than the value of 1. Risk for dermal are acceptable to workers, however, if the risk can be resolved quickly and efficiently, control measures should be implemented and recorded. Medium risk requires a planned approach to control the hazard and applied temporary measures, if required.

2.6. Summary of short-term (1-hour) references concentration (RfC)

Table 13 shows the materials contained in the HHW that can pose hazards in terms of employee safety. Exposure to these materials should be limited or avoided to minimize the risk that occurs during the tasks, especially for garbage collecting employees and workers at the landfill. Exposure that occurs even in the short term will cause health hazards and adverse effects on them.

Chemical	Exposure limit (1 hour) $\mu\text{g}/\text{m}^3$	References	Exposure limit (24hour) $\mu\text{g}/\text{m}^3$	References
Acetamide (solvent)	2.0×10^{-5} skin irritation	CalEPA (1999)	7.0×10^{-2}	CalEPA (1999)
Acetophenone (soaps, detergent, lotion and perfumes)	0.1 mg/kg/day	US EPA (1999)	4.1 mg/m ³	US EPA (1999)
Allylchloride (varnish, perfume and insecticides)	3 mg/m ³	US EPA (1999)	3.6mg/m ³	US EPA (1999)
Calcium cyanamide (fertilizer, herbicide, fungicide and pesticides)	3 mg/m ³	US EPA (1999)	3.6mg/m ³	US EPA (1999)
Cadmium	1.36E-02 $\mu\text{g}/\text{m}^3$	US EPA (2003)	3.00E+01 $\mu\text{g}/\text{m}^3$	US EPA (2003)
Hg(Elemental Mercury), (bulb, batteries)	1.8	OEHHA (2001)	2.0	OMEE (1999)
Pb (lead oxide (paint))	1.5	AEP (2000)	2.0	OMEE (1999)

Table 13. Summary of short-term (1-hour) references concentration (RfC).

For materials found in solvents such as acetamide, exposure limit (1 hour) is 2.0×10^{-5} mg/m³ while for materials like allylchloride (varnish, perfume and insecticides); calcium cyanamide (fertilizer, herbicide, fungicide and pesticides), the permissible dose is 3 mg/m³. Exposure data should be communicated to employees and thus, safety and protection equipment and personal protective equipment can be provided by the employer and used solely by employees to reduce workplace accidents and health hazards.

For HHW, short-term exposure in an hour shall not exceed 2.0×10^{-5} mg/m³ (min exposure) to 3 mg/m³ (max exposure).

2.7. Summary of long-term (chronic) exposure limit for human receptors

Based on **Table 14**, the exposure limit for long-term exposure of the solvent through inhalation is 2.0×10^{-5} mg/m³ for RfC. While for soaps, detergent, lotion and perfumes RfD is

0.1 mg/kg/day. While fertilizers, herbicides, fungicides and pesticides are 0.5 mg/m³ (RfC); varnish, perfume and insecticides are 0.001 mg/m³ (RfC); the bulbs and batteries are 0.3 mg/m³ (RfC); and for Pb (lead oxide (paint)) is 1.85 mg/kg/day (RfD), accordingly.

Chemical	Route	Units	Exposure limit		References
			Type	Value	
Acetamide (solvent)	Inhalation (Possible human carcinogen)	µg/m ³	RfC	2.0 × 10 ⁻⁵	CalEPA (1999)
Acetophenone (soaps, detergent, lotion and perfumes)	Oral	mg/kg/day	RfD	0.1	US EPA, IRIS (1999)
Allylchloride (varnish, perfume and insecticides)	Inhalation	mg/m ³	RfC	0.001	US EPA, IRIS (1999)
Calcium cyanamide (fertilizer, herbicide, fungicide and pesticides)	Inhalation	mg/m ³	RfC	0.5	ACGIH (1999)
Hg (elemental mercury) (bulbs, batteries)	Inhalation	µg/m ³	RfC	0.3	US EPA, IRIS (2001)
Allylchloride (varnish, perfume and insecticides)	Inhalation	mg/m ³	RfC	0.001	US EPA (1999)
Pb (lead oxide (paint))	Oral inhalation	µg/kg bw/day	RfD	1.85	OMME (1999)

Table 14. Summary of long-term (chronic) exposure limit for human receptors.

Above values showed that the solvent material is highly sensitive and hazardous because the dose limit allowed has the smallest value compared to other hazardous materials, in which it can cause risk to health, followed by the bulbs, batteries and paint. Therefore, these materials should be given priority for a more orderly management in each local authority in Malaysia.

3. Conclusion

The increasing scale of economic activity, urbanization, industrialization, rising standard of living and population growth has led to a sharp increase in the quantity of the generated waste. It can be said that almost every household is producing hazardous wastes as HHW is a part of domestic waste. Moreover, many fail to realize that the ingredients of some of the products that they use in their daily routine in house contain hazardous substances. Generally, out of the total solid waste generated, 64.7% ended up in the garbage bin, 27% are disposed down the drain and 2.4% are burnt while remaining 20.2% are disposed of by other means such as burying [13]. Improper use, storage and disposal of hazardous household products can harm humans and contaminate the environment [14]. Therefore, extra care must be taken when disposing used hazardous products as it can harm sanitation workers if thrown in with regular trash. Exposure to chemicals contained in some of the waste products in our home can cause

health problems where the effects can range from minor problems such as watery eyes and irritation to skin to more serious problems such as poisoning, burns or may even lead to cancer. The exposures can be through ingestion by swallowing the hazardous substances if it is accidentally transferred onto food or cigarettes, through inhalation by breathing dust or fumes or through contact with skin or eye.

Referring to the flow chart in **Figure 5**, the work process undertaken would contribute to the potential hazards of exposure to garbage collection workers and in landfills if HHW existed in the operation during the handling. HHW disposal directly into the public dustbin and no separation at source caused nearly 80% of HHW disposed in the trash and then to the landfill. This is repeated when each truck at least run the collection for two to three trips a day. This situation will increase the potential of chemical exposure to the employees.

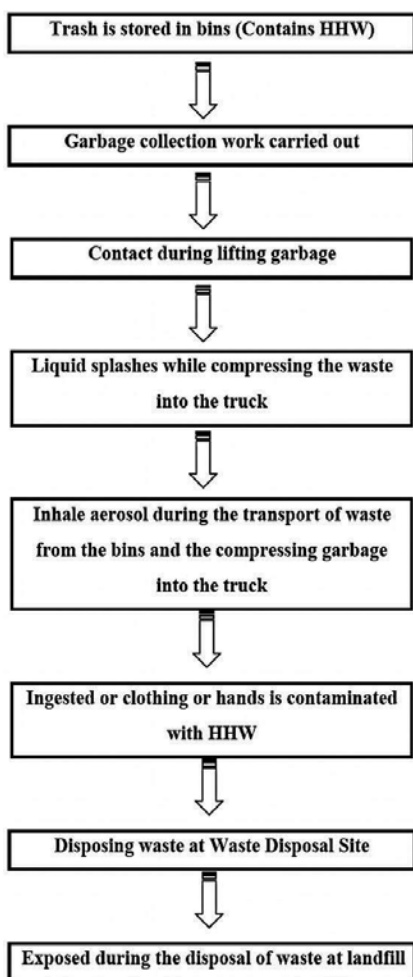


Figure 5. Work process flow of sanitary workers and disposal site.

The workers who do not practise health care and has no knowledge of the health hazards are more vulnerable and coupled with their lack of safety clothing such as gloves and safety helmets can hamper their safety and health.

In this case, employers must provide adequate training to staff regarding exposure to chemical hazards, toxic residues that affect the health and potentially cause cancer. The employers should provide adequate and appropriate personal protection equipment (PPE) to avoid direct exposure to workers during the work carried out. Preventive controls should also be done on a few trucks to transport the waste to prevent leakage of waste water from the garbage during operation and should provide covered and comfortable lorries for the workers.

Cases of accident and health can be prevented from occurring and recurring by adopting the concept of ergonomic principles in the management of solid waste, especially hazardous waste at home and steps like the separation at source is the best way to reduce exposure of workers to the HHW and prevent pollution in all local authorities in Malaysia.

4. Recommendation

The result from this study showed that HHW can affect humans. Hazardous household products most likely to contribute significantly to the input of hazardous substances were then identified as being the most problematic for the current waste management and disposal routes, namely paints, pesticides, arsenic treated wood and fluorescent lamps. Therefore the wastes must be properly managed. Separation of HHW at an early stage at home, such as separating HHW in separate plastic bags to reduce and minimize the waste dumping directly into public trash bin and eventually to the landfill must be practiced by all local authorities in Malaysia. A study on reviewing compliance with the provisions of OSHA, 1994 is necessary to ensure the implementation of the welfare, safety and health of employees in local authorities in Malaysia. Employees need to know the level of risk that exists in the workplace so that prevention and control measures can be carried out. Research also needs to be done for compliance with the labelling of hazardous products used at home in terms of their content of hazardous materials to serve as guidance and revisions for the consumers and facilitate local authorities in implementing the HHW collection program. The local authorities are proposed to play a more active role in the safety and security of workers with preventive measures; either by administrative or engineering and the usage of personal protective equipment among workers in local authorities should be strictly enforced, in an effort to improve and create a comfortable and safe workplace.

Therefore, the results of this study and recommendation can be used to increase and improve the management of solid waste in order to minimize health hazards and safety risks among workers, and surveillance. This chapter can be a guideline for proper management especially in HHW at local authorities in Malaysia.

Proper management of HHW will enhance the comfort of living and solve the problem of pollution of the earth and water resources that affect sources for drinking, and also overcome

the air pollution due to open and uncontrolled burning. The contamination of groundwater due to improper disposal of HHW will continue if no concrete steps are taken by local authorities as well as the Ministry of Housing and Local Government to ensure that disposal sites are secure and proper management of waste is being practiced. Apart from that, human health risk assessment of HHW is important in determining the safety and health of employees and the public security and reduces the danger of existing risks. The contribution from proper management of HHW will make the management of solid waste more robust and ensure the comfort and health improved in line with community aspirations towards a developed nation by 2020.

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Chemical Recycling of Household Polymeric Wastes

Ali Karaduman

Additional information is available at the end of the chapter

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Abstract

This chapter provides insights on the disposal of household polymeric wastes and chemical recycling of household polymeric wastes for chemical feedstock. Waste generated may cause environmental, economic and health problems. In 2012, the EU (European Union) generated 2514 million tons of waste, of which 213,410 million tons is household waste. Household waste has lots of polymeric materials. The two most important of the polymers are polystyrene (PS) and low-density polyethylene (LDPE). In this study, the results of PS and LDPE obtained from various processes related to polymeric wastes' chemical recycling were given. Main products of PS chemical recycling were obtained as follows: styrene monomer, toluene, ethylbenzene, α -methyl styrene and other valuable chemicals. When LDPE undergoes thermal degradation in a solvent setting in autoclave, oil like diesel can be obtained.

Keywords: chemical recycling, plastic wastes, pyrolysis, thermal degradation, polystyrene, LDPE

1. Introduction

The development of technology has led to an increased welfare level throughout the world and also increased consumption per capita. As a result of this consumption, waste amount has increased gradually. The efficient management of wastes generated, the efficient usage of energy sources and creating new energy source are important aspects for the abatement of environmental pollution and health. The European Union (EU) is one of the most important waste generating regions worldwide. The household waste amount in the EU waste is 213,410 million tons [1]. Composition of these wastes is given in **Table 1**.

Municipal solid waste	Composition, wt%
Kitchen waste	25
Paper and board	18
Plastic (polymeric materials)	12
Other combustible products	10
Garden wastes	6
Rubble	5
Glass	5
Textiles	4
Nappies and other sanitary	3
Steel	2
White goods	1
Aluminum	1
Others	8

Table 1. Municipal solid waste composition in EU [1, 2].

Table 1 shows that plastic wastes (polymeric wastes) is the third predominant consisting of 12% in household wastes. Plastic wastes in household waste comprise lots of polymeric materials. In the EU-27, 6.9% polyethylene terephthalate (PET), 12.1% high-density polyethylene (HDPE), 10.4% polyvinyl chloride (PVC), 17.5% low-density polyethylene (LDPE), 18.9% polypropylene (PP), 7.4% polyurethane (PUR) and 19.7% other polymers are used in the generation of plastic material [1, 2]. Although they differ in polymer, other materials are added mostly in plastic materials as they (polymeric materials) are generated from polymers. The amount of polymer from which plastic material would be generated without adding any material is restricted. Each additive used in the production of plastics has got different purposes except for the ones, such as calcium carbonate, carbon black and caolin, which are used to provide economical production of polymers. These additives are materials such as plasticizers (phthalates), antioxidants, antistatic agents (tertiary amine derivatives, ethylene oxide/propylene oxide copolymers, glycerol derivatives and ethoxylated amines), UV stabilizer (thioethers, hindered amine light stabilizer), antimicrobial agent (10,10-oxybisphenoxyarsin, copper-bis-(8-hydroxyquinoline), trichloromethyl thiophthalimides), colorants (azo dye, anthraquinone dyes, quinophthalone, benzodifuranones) and blowing agents (chlorofluorocarbons, hydrochlorofluorocarbons, methylene chloride, pentane, cyclopentane and isopentane, azodicarbonamide, azoisobutyronitrile, hydrazine derivatives). Even if these materials are insignificant in plastic generated, it is known that they have toxic, carcinogenic and endocrine deforming chemicals that are harmful to human health [3]. Moreover, it is possible for polymeric wastes in household wastes to cause pollution. The usage of plastic and the disposal of waste following acceptable environmentally sound standards are important [4, 5].

2. Disposal of household polymeric wastes

The disposal of household polymeric wastes differs from one country to the other and also it is not generally possible to collect and eliminate them. In 2013, nearly 25 million tons of polymeric wastes were collected and processed in EU-27+Norway and Switzerland [1, 2]. Plastic wastes (polymeric materials) are utilized using three methods: recycling, landfill and energy recovery. 26% of these wastes were regained by recycling, and energy was obtained from 36% by energy recovery and 38% of eliminated by landfill [2].

2.1. Landfill

In this process, household wastes are neatly stored underground. Landfill process has several disadvantages such as wastes have great volumes, decrease of the areas in which the wastes are stored, high cost and contamination of water and soil. Due to these reasons, the process of landfill should be preferred in a situation when the process of chemical recycling cannot be performed [4, 5].

2.2. Energy recovery

In this process, wastes are burned and their energy is used. Even if the disposal of wastes through burning process has advantages in terms of obtaining energy, it has disadvantages because of toxic, carcinogenic and endocrine deforming components generated during this process [5–7]. Moreover, facilities using burning process are not cost-effective and environmentally friendly [8].

2.3. Recycling

The main goal is to make plastics (polymers) using mechanical processes (mechanic recycling) or to produce various chemicals or valuable raw materials (chemical recycling) from household polymeric wastes. Even if mechanic recycling has economic advantages, it has been decreased in the molecular weight of polymer and lost of mechanical and physical properties. Therefore, qualified products cannot be manufactured. In other words, there is difference between the material being obtained from the used plastic and the product being obtained from original polymer during mechanical recycling and also it is not processed after definite cycling. In this case, the main solution to eliminate household polymeric wastes is chemical recycling. Although chemical recycling methods may seem economically disadvantaged compared to other methods, in terms of bringing a final solution to waste disposal is important.

3. Chemical recycling of household polymeric wastes

Household polymeric wastes mainly include materials which are made of PET, HDPE, PVC, LDPE, PP, polystyrene (PS) and PUR. The two most important of these polymers are PS and LDPE. PS is used for producing disposable plastic cutlery and dinnerware, CD, smoke detector,

license plate frames, plastic model assembly kits, Petri dishes, test tubes, microplates and many other objects. LDPE is used for production of plastic bags, containers, dispensing bottles, wash bottles, tubing, plastic bags for computer components and various molded laboratory.

In recent years, research has been done concerning the management of household plastic wastes by chemical recycling [9–12]. Thermal decomposition (pyrolysis and thermal degradation) gasification, hydrolysis methanolysis and glycolysis by the type of household polymeric material are the different methods applied in chemical recycling. Thermal decomposition was applied into great part of polymers. During the thermal decomposition, reactive radicals occur in the body of plastic as a result of bond rupture or chain fracturing, and these radicals reveal gas, liquid and solid products as reacting in serial. This method is applied to polymers as pyrolysis and thermal degradation. Pyrolysis is a chemical recycling method. It can be described as degrading a polymeric waste under nonoxygen media (inert, reductive/oxidative etc.) by heat effect. Necessary thermal amount in pyrolysis should be at a level to degrade the chemical structure of polymeric material and to provide the formation of new chemical materials. Polymeric material is fully transformed to solid, liquid and gas products without getting any additives by pyrolysis. The process does not cause air, water and soil pollution. All of the obtained products can be used as raw materials in other industries. There are many kinds of pyrolysis such as batch, semibatch, vacuum, catalytic pyrolysis, etc. Important pyrolysis parameters are heating rate, temperature, medium and time. The medium may be catalytic, inert, oxidative or reductive. According to heating rate, pyrolysis can be classified as slow pyrolysis and flash pyrolysis. The most definite feature distinguishing flash pyrolysis from slow pyrolysis is the stay-duration of products in pyrolysis setting occurring in the splitting and heating rate. Heating rate is in the range of 1–10°C/min in slow pyrolysis and it is higher than 100°C/hour in flash pyrolysis. Thermal degradation is the deformation process of polymeric materials as thermal in a solvent setting at respectively lower temperature as pyrolysis.

In this chapter, chemical recycling of PS and LDPE wastes was investigated. The results of the experiment of PS and LDPE obtained from various processes related to polymeric wastes' chemical recycling are discussed in the following sections. These experiments demonstrated that valuable chemicals and feedstock can be produced from household polymeric wastes with chemical recycling.

3.1. Pyrolysis of polystyrene waste in batch reactor under inert medium

Polystyrene can be degraded to the monomer and other valuable chemicals by slow pyrolysis. Schematic representation of the system, including polystyrene plastic wastes' chemical recycling by slow pyrolysis is shown in **Figure 1**. The system comprises of Pyrex glass reactor, PID controlling oven to heat reactor (1.5 kW), condenser and liquid product gathering container (phase median). Reactor is in diameter of 4.2 cm and at the length of 40 cm. Internal and external temperatures of reactor were measured by Ni-Cr-Ni thermocouple. Plastic waste was located in the bottom of the tube part in a reactor. Reactor was vertically located in high-temperature ceramic oven. Pyrolysis was done in nitrogen atmosphere.

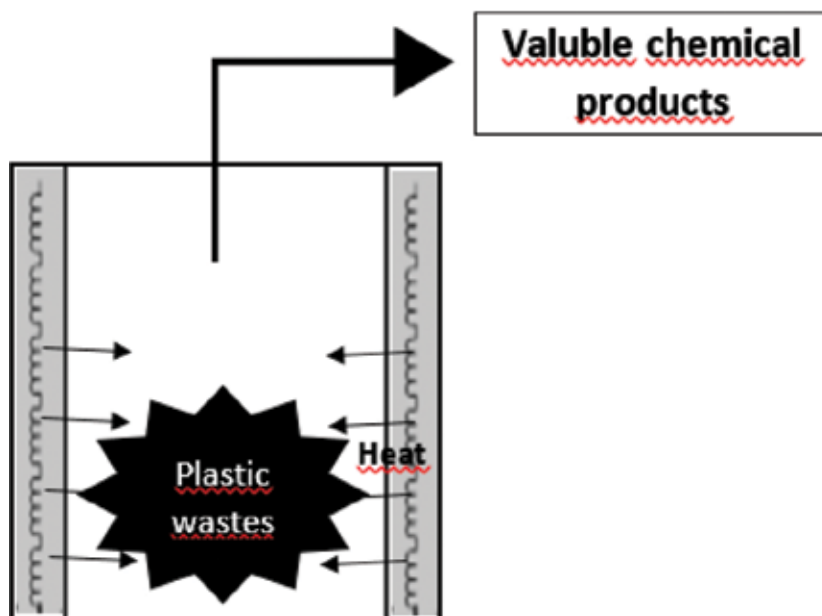


Figure 1. Chemical recycling of plastic wastes via slow pyrolysis.

Liquid products of PS pyrolysis were obtained in a condenser located out of reactor and from liquid-receiver plug vessels (phase separator) having salt-ice mixture in its cover added to its output. Moreover, total conversion was calculated by the amount of liquid and gas products. The liquid products were analyzed to illuminate the content of liquid products by Thermo Finnigan DSQ-250 gas chromatography-mass spectrometry (GC-MS). Rtx-5MS capillary column at a length of 30 m and 0.25 mm in internal diameter was used as a column. The analysis terms of GC-MS: injection temperature is 225°C, temperature of transfer line is 300°C and helium flow rate is 0.7 ml/min. Temperature program being applied to column was heated to 300°C at the heating rate of 5°C min⁻¹ after 5-min stand-by at 50°C and it was waited for 20 min at this temperature (300°C).

For chemical recycling of PS polymeric wastes, PS wastes were pyrolyzed using this experiment system. The yields were investigated in the experiment at 450°C. Those values were respectively 59.46% liquid, 2.29% solid, 43.46% gas + loss and 92.92% total conversion. According to the results, the majority of the polymer was converted into liquid and gas chemicals. GC-MS chromatogram of the liquid products obtained from chemical recycling of PS polymeric waste is given in **Figure 2**.

Compounds in this chromatogram were defined by using Wiley library. The list of chemical materials defined is given in **Table 2**.

As depicted in **Table 2**, carbon number ranges of liquid products were found as % 68.8 C₆-C₉, % 4.36 C₁₃-C₁₅ and % 26.8 C₁₆-C₁₈.

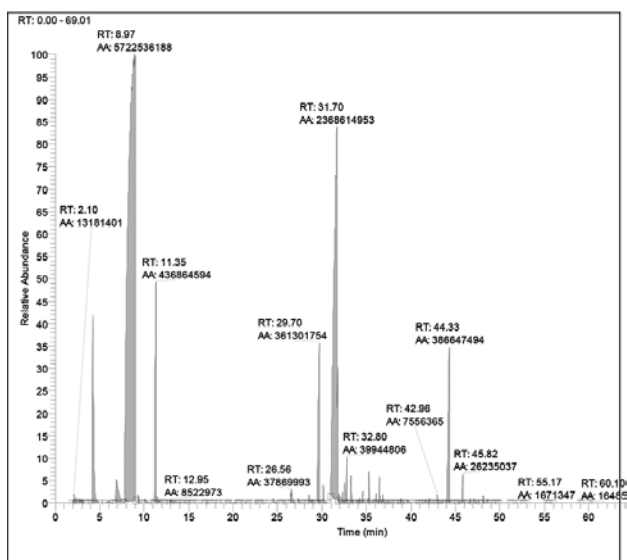


Figure 2. GC-MS chromatogram of pyrolysis liquid products obtained from chemical recycling of PS.

Residence time, min	wt%	Compound
2.34	0.08	1-Hexane
2.65	0.07	Bütane-2,3-dimethyl
3.07	0.12	Hexane-3-methyl
4.23	3.62	Benzene methyl
6.03	0.1	1-Heptene-5-methyl
6.9	0.97	Ethylbenzene
8.97	55.52	Styrene
11.35	4.24	Alpha-methylstyrene
24.51	0.1	Diphenylmethane
26.56	0.37	Bibenzyl
28.55	0.12	1,2-Diphenyl cyclopropane
29.7	0.12	Benzene-1,1'(1,3-propanedyl)bis-
31.7	22.98	Naphthalene 1,2,3,4-tetrahydro-2-phenyl
31.91	0.09	Benzene-1,1(1,4-butanedyl)bis
32.34	0.1	Benzene-1,1(1,4-butanedyldiene)bis
32.56	0.16	1,3-Pentadiene-1,1-diphenyl
32.8	0.39	Benzene, 1,1'-(2-pentene-1,5-diyl)bis-
33.29	0.43	3,5-Diphenyl-1-pentene
34.21	0.09	Benzene-1,1(1-methyl-2-butyldiene)bis
34.58	0.1	2,5-Diphenyl-1,5-hexadiene
35.28	0.35	Benzene-1,1(2-pentene-1,5-dyl)-bis
36.07	0.09	1,3-Pentadiene-1,1-diphenyl
36.46	0.3	1-Pentadiene-1,5-diphenyl
36.85	0.11	1,5-Diphenyl-1,5-hexadiene
38.87	0.08	5(2-Propylvinyl)dibenzocycloheptane
42.96	0.07	1-Ethyl-2-methyl-3-phenylindane

Table 2. Compounds of PS pyrolysis liquid products at 450°C.

3.2. Thermal degradation of LDPE in autoclave with solvent

Thermal degradation is a thermal deformation of polymeric wastes in a solvent setting. In this study, LDPE polymeric wastes were put to thermal degradation with vacuum gas oil (VGO) as a solvent supplied from Kirkuk refinery (Iraq). The schema of experiment system where chemical recycling has been done by thermal degradation is given in **Figure 3**. Experiments were done in a stainless steel reactor called autoclave being durable against high pressure and temperature, gastight, having 250 ml volumes, having pressure and temperature indicator and being screw-capped one. Heating reactor was done by a PID controlling high-temperature oven. Experiments were carried out under nitrogen atmosphere.

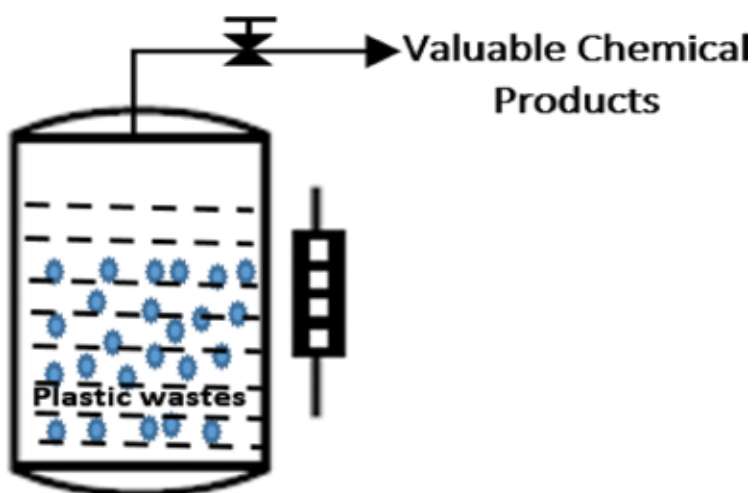


Figure 3. Chemical recycling of plastic wastes via thermal degradation.

At the end of the experiments, autoclave was cooled to room temperature and gas product obtained was taken. Then, the content amount in the reactor was determined as being separated into liquid and solid. The amount of gas product was found from variation in the beginning of process. On thermal degradation, experiments being done as getting LDPE/VGO: 1/1, 85.94% liquid, 5.76% solid, 8.3% gas and 94.24% total transformation (liquid + gas) were found.

The content of liquid products for thermal degradation has been illuminated by GC-MS device which is given above. However, the column temperature program has been set at 50°C at the beginning and after 2-min duration, it has been set at 270°C at the heating rate of 5°C/min and it was waited for 20 min at this temperature. GC-MS chromatogram of the liquid products is given in **Figure 4**. As it can be seen in **Figure 4**, each pick of the liquid products has tripled. One of them is alkane (saturated hydrocarbon), another is alkene (unsaturated hydrocarbon) and the other is diene (hydrocarbon that contains two carbon double bonds).

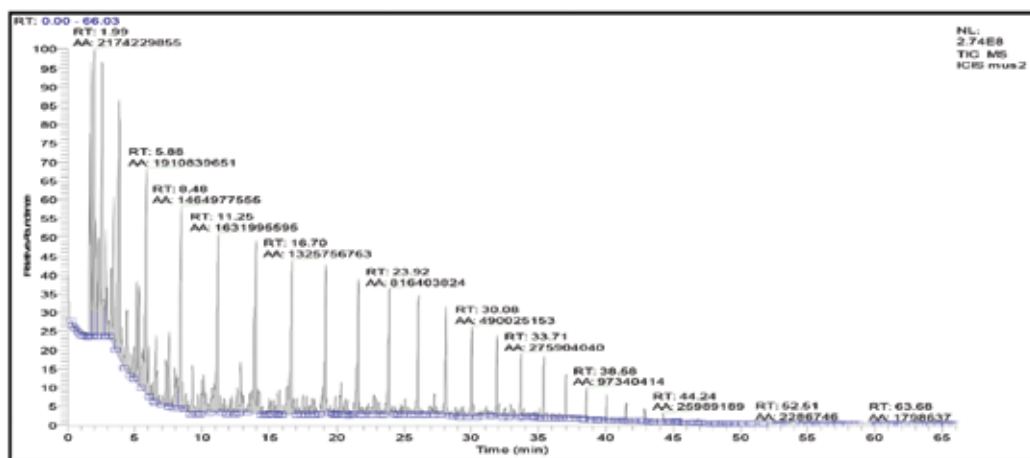


Figure 4. GC-MS chromatogram of LDPE/VGO:1/1 and at 400°C.

Thermal degradation liquid products obtained from Autoclave were analyzed by using GC-MS. The list of chemicals is given in **Table 3**.

Residence time, min	wt%	Compound
1.76	5.67	Pentane
1.99	7.46	Hexane
2.58	8.47	Heptane
2.83	1.87	Methylcyclohexane
3.44	3.51	Toluene
3.84	6.55	Octane
4.43	1.71	Ethylcyclohexane
4.7	0.48	Unknown
5.14	3.46	Ethylbenzene
5.88	6.56	Nonane
6.31	0.35	2-Methyl-bicyclo-octane C9
6.58	1.24	7,7-Dimethyl-tetracycloheptane
7.34	0.98	n-Propylbenzene
7.57	1.11	1,3,5-Trimethylbenzene
7.96	1.31	Cyclodecane
8.48	5.03	Decane
8.79	0.50	Cyclodecane C10
9.27	0.84	Cyclodecane C10
10.09	1.44	Undecane C11
11.25	5.60	Undecane
11.65	0.36	Unknown
12.24	0.51	1-Dodecene C12
12.57	0.54	1-Cyclopropyl-1-methyl-benzene C12
12.87	1.06	1-Cyclopropyl-1-methyl-benzene C12

Residence time, min	wt%	Compound
14.04	5.36	Dodecane
15.28	0.46	Dodecane
16.7	4.55	Tridecane
17.04	0.38	Spiro(tricycloundeca-2,4,6-triene),7,1-cyclopropane
17.77	0.43	7-Tetradecene
19.24	3.54	Tetradecane
20.34	0.64	Unknown
21.63	3.10	Pentadecane
22.79	0.71	Unknown
23.92	2.80	Hexadecane
25.15	0.49	Hexadecane
26.07	2.16	Heptadecane
27.01	0.34	2,6,10-Trimethyl tetradecane
27.24	0.33	Unknown
28.12	1.88	Octadecane
29.24	0.41	Unknown
30.08	1.68	Nonadecane
31.93	1.25	Eicosane
32.95	0.41	Docosane C22
33.71	0.95	Docosane
35.39	0.73	Tricosane
37.03	0.47	Pentacosane
38.58	0.33	Pentacosane

Table 3. Compounds of LDPE/VGO:1/1 thermal degradation Liquid products at 400°C.

Liquid products of LDPE/VGO:1/1 at 400°C were examined to evaluate the cetane number of fuel specifications. Cetane number of liquid products from thermal degradation has been found to be nearly 50. This value can be an initiative indicator for this product as it would be used for diesel oil. Consequently, when LDPE is put to thermal degradation in a solvent setting in autoclave, an oil like diesel can be obtained.

3.3. Flash pyrolysis of household polymeric wastes in free fall reactor (FFR)

Flash pyrolysis, one of the chemical recycling methods of household polymeric wastes, can be used with various reactors such as fluidized bed and rotating cone. One of these reactors is FFR. Valuable chemicals can be obtained by flash pyrolysis of household polymeric wastes in FFR. The schema of flash pyrolysis system with FFR is given in **Figure 5**. Polymeric wastes are made as a granule at a definite size in this system and it is fed suddenly to high-temperature heated reactor by a solid feeding system.

Reactor of FFR experimental system using chemical recycling of PS and LDPE household polymeric wastes is 140 cm in length and in 5 cm diameter quartz. It is heated to pyrolysis temperature with a high-temperature oven of 120 cm length and 10 cm internal diameter. Reactor was fed at 2 g/min feeding rate with a polymeric waste feeding system. There is tar receiver under reactor, serial condenser connected on outlet of tar receivers (which has got salt-

ice mixture in its cell) and vacuum pump getting all system under vacuum. Temperature measurements were done in the inner and outer parts of the reactor.

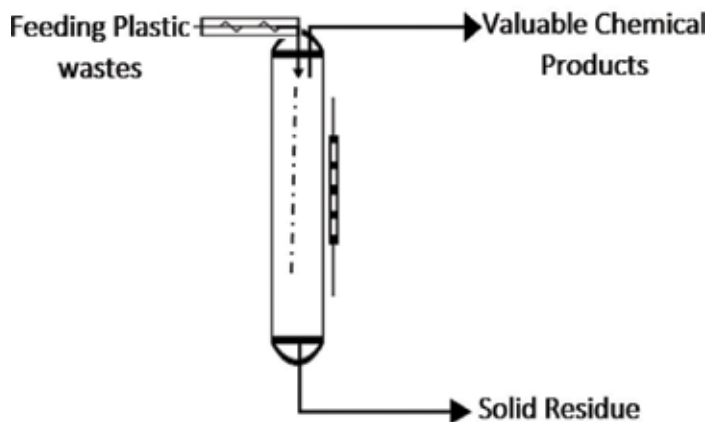


Figure 5. Flash pyrolysis of polymeric wastes in FFR.

Particles of PS and LDPE polymeric wastes at size range of 150–75 micro particle were used in PS and LDPE's flash pyrolysis in FFR. 825°C flash pyrolysis liquid products were analyzed in GC-MS in conditions of the above given PS and LDPE liquid product analysis both for PS and LDPE in FFR.

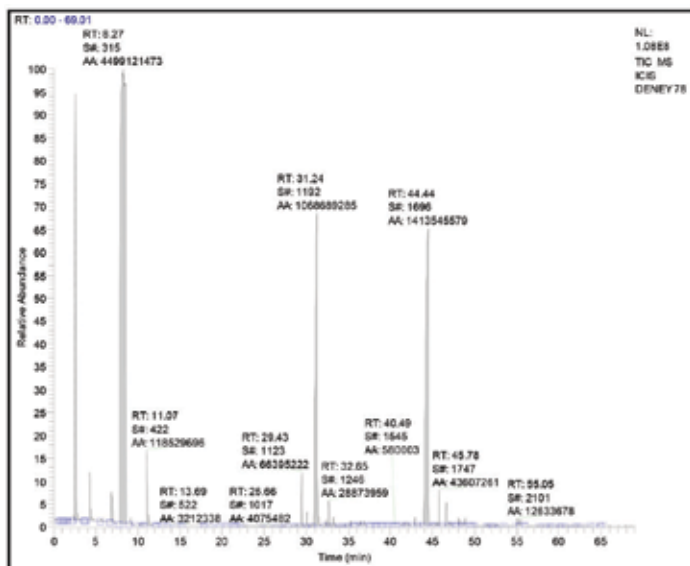


Figure 6. GC-MS chromatogram of PS flash pyrolysis liquid.

GC-MS chromatogram of liquid products from 825°C flash pyrolysis of household polystyrene polymeric wastes is given in **Figure 6**. Moreover, the description study of chemical compounds in liquid products was done and the obtained results are given in **Table 4**.

Residence time, min	wt%	Compound
4.26	1.29	Toluene
6.85	1.05	Ethylbenzene
8.27	53.60	Styrene
11.07	1.41	α -methylstyrene
29.43	0.79	1,3-Diphenyl propane
31.24	12.73	1,1-Diphenyl-2-methyl propane
32.65	0.34	1,3-Diphenyl-butane
33.23	0.21	1,1-Diphenyl-2-methyl propane
42.87	0.14	Dimer
44.44	16.84	Trimer (2,4,6-triphenyl-1-hexane)
45.78	0.52	Trimer
	11.60	Others

Table 4. Compounds of PS flash pyrolysis liquid products in FFR at 825°C.

Table 4 depicts that the main product is styrene monomer. Flash pyrolysis of polystyrene in FFR showed that it can obtain important liquid chemicals such as toluene, ethylbenzene, α -methyl styrene and others besides styrene monomer.

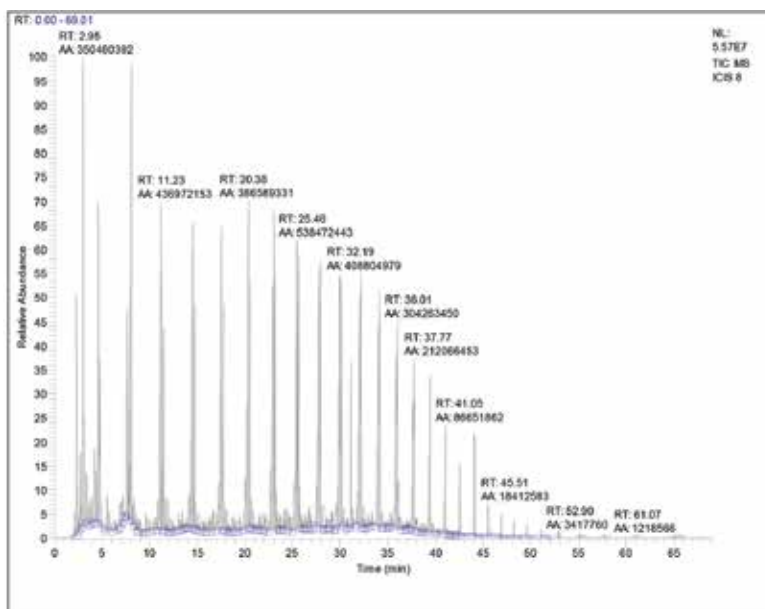


Figure 7. GC-MS chromatogram of liquid products for LDPE wastes in FFR at 825°C.

GC-MS chromatogram of liquid products for LDPE polymeric wastes in FFR from 825°C is given in **Figure 7**. As it can be seen from **Figure 7**, peaks in chromatogram were given respectively as homologues. This indicates that products have got aliphatic character. LDPE pyrolysis liquid products were described by using GC-MS library.

The products obtained with the use of GC-MS are given in **Table 5**. As it can be seen in **Table 5**, the liquid product which obtained LDPE is paraffinic hydrocarbons. Liquid products obtained from chemical recycling of LDPE polymeric wastes at 825°C in FFR were divided into three groups. The percentage of groups, The percentages of the groups are % 30.44 C₆-C₉, % 42.83 C₁₀-C₁₃ and % 26.73 C₁₄-C₁₈.

Consequently, gathering, dissection and innovator chemical recycling processes are important for the method of HHW plastic wastes. Gathering and dissection processes for polymeric wastes in HHW have direct effect on chemical recycling. Thus, polymeric wastes should be collected separately from other wastes without being contaminated and should be distinguished from each other. Each of separated polymeric waste should be put to chemical recycling by a proper process. An innovator chemical recycling process should create a harmful waste for environment, health and economy. Recycling of polymeric wastes is advantageous with pyrolysis. Pyrolysis of polymeric waste is carried out in a closed area, where gas, liquid and solid products are obtained. An innovator pyrolysis process should include units making these products usable as raw materials. The following situation is suitable: to gather polymeric wastes in HHW, to dissect them by polymer and their chemical recycling method by polymer. Pyrolysis is suggested for the recycling of PS polymeric wastes and thermal degradation is suggested for LDPE.

Residence time, min	wt%	Compound
2.37	2.06	1-Hexane
2.74	0.28	1,3-Pentadiene-2-methyl
3.03	4.15	1-Heptene
3.42	0.77	Cyclohexane-1-methyl
3.99	0.24	Cyclopentane-1-methyl
4.28	1.06	Cyclohexane-1-ethyl
4.91	6.83	1-Octane
5.6	0.79	Cyclohexane-1,2-dimethyl
6.03	0.38	1-Hexadiene-2,5-dimethyl
6.95	0.68	Cyclohexane-1-ethyl
8.18	10.12	Nonane
8.98	0.4	Cyclohexane(1-methylethyldiene)
9.65	0.27	Cyclopentene-1-butyl
11.33	5.49	1-Decane
11.57	3.48	2-Decene
11.69	0.33	Cyclohexene-1-butyl
11.96	0.32	2-Decyne
12.46	0.34	Bicyclo(3,1,1)heptane-2,6,6-trimethyl
14.63	4.88	Undecane

Residence time, min	wt%	Compound
14.87	3.86	Undecyne
16.73	0.51	1,3-Di(1-propyl) cyclopentane
17.67	4.76	Dodecane
17.91	4.23	3-Dodecyne
18.17	0.38	3-Dodecyne
18.83	0.37	1,1,2-Tridecadiene
19.51	0.36	4-Tridecene
20.43	4.83	4-Tridecene
20.71	4.13	Tridecane
20.95	0.39	1,1,2-Tridecadiene
21.73	0.37	4-Nonene-5-butyl
22.2	0.4	1,1,2-Tridecadiene
23.04	5	1-Tetradecene
23.31	4.09	Tetradecane
24.54	0.37	5-Tetradecene
25.74	7.61	Pentadecene
27.95	4.76	Pentadecene
30.02	2.01	Hexadecane
32.01	0.77	1-Octadecene

Table 5. Compounds of LDPE flash pyrolysis liquid products in FFR at 825°C.

4. Conclusion and assessment

Pyrolysis of PS, thermal degradation of LDPE and flash pyrolysis of PS and LDPE are chemical recycling methods of household polymeric wastes. It is possible to obtain valuable chemicals and oil from these wastes by chemical recycling. Results and evaluations from the experimental results are given below.

Most of the liquid products from slow pyrolysis of PS polymeric wastes constitute styrene being its own monomer. Moreover, valuable chemicals such as toluene, ethylbenzene and methylene styrene have been produced. It is possible to obtain valuable chemicals via chemical recycling of PS wastes without damaging environment and people's health. In other words, successfully designed chemical recycling processes are not harmful for environment and people's health.

Products from heated degradation of LDPE household polymeric wastes in autoclave in a solvent setting are hydrocarbons in the aliphatic structure. Liquid product obtained from the experiments using VGO is oil like diesel. It is seen that condensable liquid products are obtained when this polymer's flash pyrolysis in FFR is made. It is thought that alpha-olefins, lubricating oil, alcohols, surface chemicals, carboxylic nitrogen and similar valuable products would be obtained with the evaluation of LDPE household wastes.

Products in reactor in flash pyrolysis occurring under the vacuum in FFR are excluded quickly from reaction region. Polymer falling from upper part to bottom in reaction setting goes beyond

as having degradation. In this case, low-molecule-weighted chemicals occur as thermal splitting occurs in macromolecules with the effect of temperature in polymeric waste. Degradation in molecule changes depending on temperature and size of particle. Parameters such as temperature, particle size, feeding rate and reactor size (standby duration) should be considered in chemical recycling in such reactors.

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Polystyrene as Hazardous Household Waste

Trisia A. Farrelly and Ian C. Shaw

Additional information is available at the end of the chapter

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Abstract

Polystyrene (PS) is a petroleum-based plastic made from styrene (vinyl benzene) monomer. Since it was first commercially produced in 1930, it has been used for a wide range of commercial, packaging and building purposes. In 2012, approximately 32.7 million tonnes of styrene were produced globally, and polystyrene is now a ubiquitous household item worldwide. In 1986, the US Environmental Protection Agency (EPA) announced that the polystyrene manufacturing process was the fifth largest source of hazardous waste. Styrene has been linked to adverse health effects in humans, and in 2014, it was listed as a possible carcinogen. Yet, despite mounting evidence and public concern regarding the toxicity of *styrene*, the product of the polymerisation of styrene, *PS*, is not considered hazardous. This chapter draws on a series of movements called the ‘new materialisms’ to attend to the relational, unstable and contingent nature of PS, monomers and other additives in diverse environments, and thus, we highlight the complexities involved in the categorisation of PS as ‘hazardous’ and the futility of demarcating PS as ‘household waste’. While local examples are drawn from the New Zealand context, the key messages are transferrable to most policy contexts and diverse geographical locations.

Keywords: polystyrene, styrene, hazardous waste, New Zealand, materiality, carcinogen, new materialism

1. Introduction

This chapter is the product of an interdisciplinary collaboration between a social anthropologist and a toxicologist. This collaboration has allowed us to present polystyrene with a critical social anthropological approach that is underpinned with the scientific facts about this ubiquitous plastic pollutant. The anthropological contribution to this chapter is its new materialist lens through which the life and afterlife of polystyrene (PS) can be more clearly viewed. To the new materialists, objects are ‘alive’ because of their capacities to make difference in the world, to have effects and to shape the webs of interrelationships of which they are a part.

Therefore, bacteria, bees, a dead dog or charcoal all have the capacity to ‘animate, to act, to produce effects dramatic and subtle’ [1, 2]. One notable new materialist and physicist, Karen Barad [3] brings our attention to the propensity for science to examine one or a few things (e.g. monomers or species) in isolation from their natural context. She argues that these singular foci result in limited understandings about the full and complex life of matter involved in often unpredictable relationships with other materials, biological systems and ecosystems.

PS is a petroleum-based plastic made from styrene (vinyl benzene) monomer [4] (**Figure 1**). Since PS was first commercially produced in 1931, it has been used for a wide range of commercial, packaging and building purposes, and it has grown to be one of the world’s most ubiquitous household items. Most PS is used to make rigid durable products, such as television and computer cabinets and appliances, and nearly all of the rigid PS packaging manufactured in New Zealand (NZ) is used for food contact purposes. PS used for food packaging includes general purpose PS (GPPS) such as disposable cutlery and plates; high-impact PS (HIPS) such as yoghurt containers and single-use cold drink cups; and expanded PS (EPS) foam used as meat trays, coolers and cups [4].

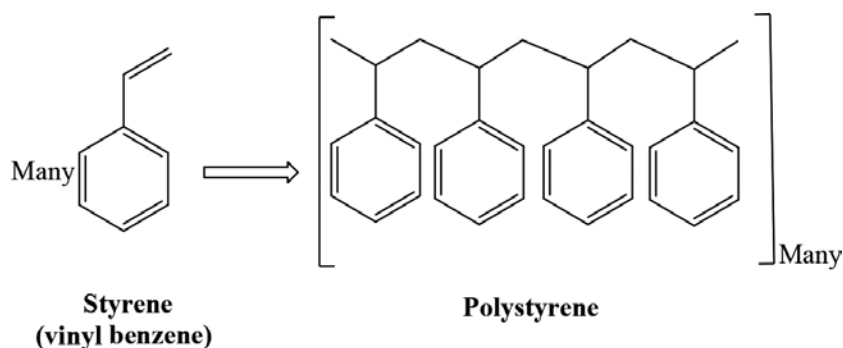


Figure 1. The manufacture of PS by chemically bonding many styrene (vinyl benzene) monomer units to form a long styrene polymer chain.

EPS is made of pre-expanded closed-cell foam beads. The manufacturing process involves carrying out the styrene polymerisation in droplets suspended in water. This leads to the formation of PS beads. EPS is useful because it is an excellent insulator (e.g. used to line cool boxes or chilly bins), and it absorbs shock and so it is a good moulded or bead-based packing material for transporting fragile cargo. It is used for a wide range of food contact packaging, such as meat trays, egg cartons and ‘clamshell’ fast food containers. EPS is often referred to by its trademark ‘Styrofoam’ invented by Dow Chemical in 1941. The trademark is informally used (not only in USA and Canada but also in NZ) for all foamed PS products, although strictly it should only refer to the ‘extruded closed-cell’ PS foam (XPS) made by Dow Chemicals and commonly used for building insulation.

While PS is popular because of its light weight and insulating properties, there is a downside to its high rate of production, consumption and disposal. In 2012, approximately 32.7 million

tonnes of PS were produced globally [5]. This figure is concerning, considering the lack of waste management of this man-made material. For example, Plastic NZ estimates that over 6784 tonnes of NZ-produced PS were consumed for packaging in NZ in 2003, with as little as 450 tonnes collected for recycling [4]. There are currently no PS residential collection services in NZ. This figure is also concerning because of the hazardous nature of the product and its components as will be explained.

In 2013, Chelsea Rochman, a scientist who studies the migration of chemicals from plastics when ingested by animals, was the lead author in an article in *Nature* which argued for the reclassification of some key plastics as hazardous so that they could be regulated by environmental protection agencies [6]. These key plastics are PVC, polyurethane, polycarbonate and PS.

Today, tens of towns and cities around the world prohibit the sale, possession and distribution of EPS, including Portland (Oregon, USA), Toronto (Canada), Muntinlupa (Philippines), Paris (France), and Tainan (Taiwan). While it still has been unable to enact a statewide ban, in 2016, the state of California has 65 ordinances (i.e. laws or regulations made by a local government body) on EPS, see Refs. [7, 8] (for full list). The reasons cited for ordinances banning or regulating EPS are primarily based on its potential as an environmental hazard: more specifically, a concern for the environmentally polluting potential of the physical properties of one type of PS rather than the chemical instability and potential for PS (as a family of plastics) to leak toxins into bodies and ecosystems.

Plastics harm in two key ways: chemically, when monomers, plasticisers and other hazardous PS additives leach from PS objects when poorly manufactured; physically, when PS breaks down into microplastics in the environment. The manufacture, composition and interrelationships of PS *in situ* are profoundly important in determining whether it is a 'hazard' [9].

Where the manufacture of PS is complete, the resulting styrene polymer has covalent (i.e. strong) bonds between the styrene monomer units; these bonds are difficult to break to release styrene. For this reason, styrene is not released from PS during environmental degradation. However, if the PS manufacturing process does not result in complete polymerisation, free styrene might remain in the PS product. This free styrene is not strongly bonded to the PS structure and so can, and likely will, leach out into the environment or into food stored in PS containers. In addition to the ability of styrene to leach from PS poorly manufactured products, this chapter will also outline the hazards resulting from the breakdown of PS into microparticles over prolonged periods.

2. Styrene monomer

While the level and nature of the hazard posed by styrene have historically been hotly disputed, a growing body of evidence indicates cause for policy action to protect populations from its misuse. For example, in 2014, the International Agency for Research on Cancer (IARC) determined that styrene is a possible human carcinogen. This is based on studies in animals and emerges from research into styrene's metabolite (i.e. styrene oxide) as a chemically highly

reactive epoxide, which might chemically bond to DNA and thus initiate carcinogenesis (**Figure 2**). It is now largely accepted that styrene oxide is likely to be responsible for styrene's carcinogenicity, and since there are likely to be species and inter-individual differences in metabolism, there are also likely to be differences in susceptibility to carcinogenicity between species and individuals [10].

The EPA National Human Adipose Tissue Survey for 1986 identified styrene residues in 100% of samples of human fat tissue taken in 1982 in the USA [11], which indicates widespread exposure. In laboratory studies (e.g. in rats), styrene monomer and some other ingredients of PS have been shown to be carcinogenic and, in some cases, affect organisms in a similar way to the hormone oestrogen [9, 12, 13] because of their molecular mimicry of the female hormone 17 β -oestradiol and occupancy and activation of oestrogen receptors.

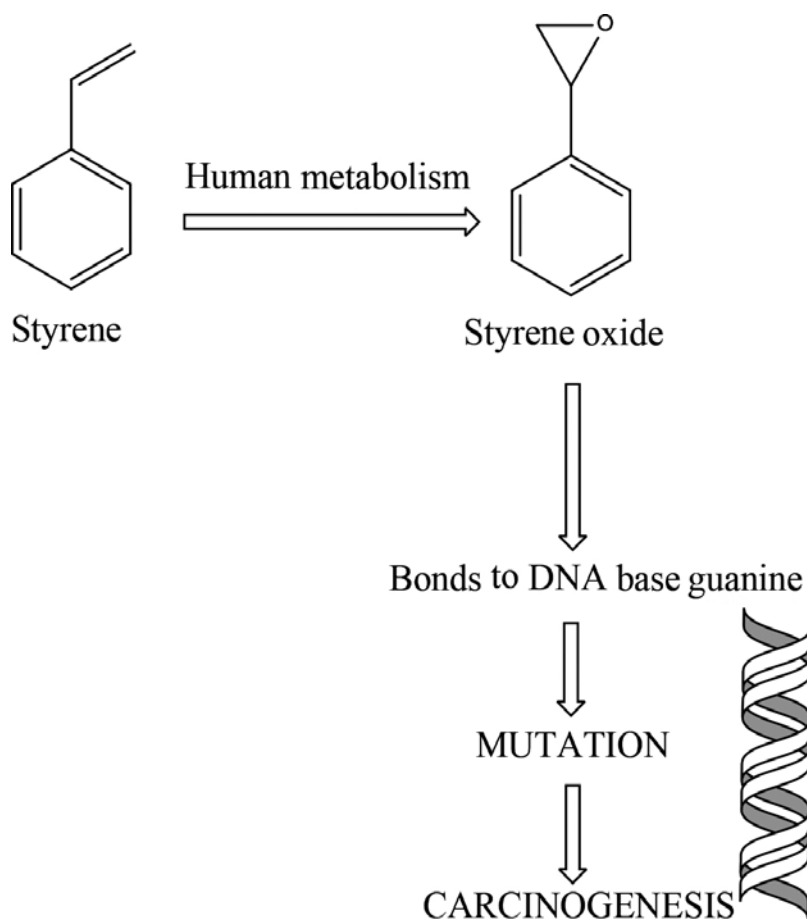


Figure 2. Styrene is metabolised to a highly reactive and toxic epoxide, styrene oxide, which can interact with DNA causing a mutation which might initiate carcinogenesis.

The National Toxicology Programme's Report of Carcinogens states that styrene is

reasonably anticipated to be a human carcinogen. First listed in the Twelfth Report on Carcinogens (2011) HC CH 2 Carcinogenicity Styrene is reasonably anticipated to be a human carcinogen based on limited evidence of carcinogenicity from studies in humans, sufficient evidence of carcinogenicity from studies in experimental animals, and supporting data on mechanisms of carcinogenesis [14].

The National Regional Council concurred in 2014:

Review of the Styrene Assessment in the National Toxicology Program 12th Report on Carcinogens concurs with the NTP determination that there is limited but credible evidence that exposure to styrene in some occupational settings is associated with an increase in the frequency of lymphohematopoietic cancers. Additionally, the NRC report authoring committee independently reviewed the scientific evidence from studies in humans, experimental animals, and other studies relevant to the mechanisms of carcinogenesis and made level-of-evidence conclusions. Based on credible but limited evidence of carcinogenicity in traditional epidemiologic studies, on sufficient evidence of carcinogenicity in animals, and on convincing evidence that styrene is genotoxic in exposed humans, this report finds that compelling evidence exists to support a listing of styrene as, at a minimum, reasonably anticipated to be a human carcinogen [14].

More recently, on 22 April 2016, the Office of Environmental Health Hazard Assessment OEHHA added styrene to the list of chemicals known to the state to cause cancer [15]. The NZ EPA (and similarly, the US EPA) determines that styrene is 'possibly carcinogenic to humans' and classifies the chemical as otherwise hazardous due to its following characteristics: flammable, acutely toxic, suspected human mutagen, carcinogen, and human reproductive or developmental toxicants, toxic to organs/systems, very ecotoxic in the aquatic environment to algal and crustaceans, slightly harmful to fish and ecotoxic to terrestrial vertebrates [16].

The categorisation of styrene as 'toxic' is unequivocal because, due to its high chemical reactivity, it interacts with cell systems causing widespread metabolic damage. In particular, styrene can chemically react with specific components of DNA resulting in changes, which affect the rate of division of cells (**Figure 2**). This mutation is the basis of chemical carcinogenesis and explains why styrene is a carcinogen in animal studies and reasonably anticipated to be a carcinogen in humans [14].

The IARC's statement that styrene is a possible human carcinogen is reinforced in statements made by the USA and NZ Environmental Protection Agencies (EPAs). The USA and the NZ EPA, among other EPAs globally, classify styrene as 'hazardous' under a wide variety of ecotoxic and toxic categories (see later in this chapter). The NZ EPA rates the environmental hazards associated with styrene as follows: 9.1A (algal): very ecotoxic in the aquatic environment; 9.1B (crustacean): very ecotoxic in the aquatic environment; 9.1D (fish): slightly harmful in the aquatic environment or otherwise designed for biocidal action; 9.3B: ecotoxic to terrestrial vertebrates [14]. In addition, the European Union currently places styrene in Category 1 in their list of potential endocrine disruptors,ⁱ see Ref. [17], also Refs. [12, 18]. These new categorisations align with a growing global interest in the hazardous nature of the ingredients used in the production of plastics. Interestingly, according to a hazard-ranking model based on the United Nations' Globally Harmonized System of Classification and Labelling of Chemicals, the chemical ingredients of more than 50% of plastics have now been determined to be hazardous [19].

3. The polymerisation of styrene

Despite building evidence and public concern regarding the toxicity of styrene, the product of the polymerisation of styrene, PS, is not listed as 'hazardous' in any policy documents. Regardless, some community groups [20] and a growing number of independent scientists [6] now treat PS as a hazardous waste item. When styrene is fully polymerised in the manufacturing process to form PS, the reactivity of the styrene component of the polymer is removed completely because the chemical bond that forms between the monomer units changes the nature of the reactive moieties of the styrene molecule. This explains why PS has very low mammalian toxicity. In addition, as discussed earlier, the monomer units are very strongly bonded together which means that styrene monomer cannot be released, in an environmental context, from its polymerised form. The bacterial degradation (e.g. in landfill) of PS does not liberate styrene, but rather produces substances such as 4-phenylvaleric acid which is of low toxicity [21].

However, if the styrene polymerisation process used in the manufacture of PS is *not* complete, styrene monomer might contaminate the PS (termed 'residual monomer'). This styrene can migrate into food packed in styrene-contaminated PS. Since styrene is reasonably fat soluble (LogP_{ow} [styrene] = 3.6; i.e. styrene is $10^{3.6}$ times more soluble in fat than water), migration is greater in fatty foods (e.g. milk) in PS containers [22]. On these solubility grounds, migration of styrene into a water-based ecosystem is less likely than into fat-containing foods, but taking account of the vast quantities of water in the environment, even at low water solubility, significant transfer of styrene to aqueous ecosystems will occur. Once in the aquatic environment, styrene will be rapidly absorbed via the lipid-based cell membranes of aquatic organisms and will concentrate up the food chain. Thus, styrene is more likely to affect animals at high trophic levels (i.e. predators).

Other chemicals (e.g. plasticisers) are sometimes added to PS to modify its physical properties for particular applications. For example, tris(4-nonyl-phenyl) phosphite is sometimes added as an antioxidant to prevent PS degradation. Such molecules can leach from PS and contaminate both the environment and products (e.g. food) stored in PS containers.

Regardless of whether styrene is completely polymerised or not during the manufacture of PS, all PS waste have significant implications for the environment. This is because the complete environmental degradation of PS is very slow and produces small PS particles *en route*. These PS particles have significant implications in ecosystems as they build up in, for example, marine environments. In addition to the physical hazards they pose, hydrophobic plastics such as PS are the most hazardous of plastics in fresh water and marine ecosystems because of their ability to adsorb persistent organic pollutants (POPs)—such adsorbed POPs can be released following ingestion of PS microparticles by animals (e.g. fish).

4. Polystyrene as an environmental hazard

While PS is highly valued for its light weight, strength, thermal insulation and shock absorbing properties, its production and disposal reveal significant threats to the environment. Today, most plastic waste goes to landfills where chemicals can leach from the plastic and

contaminate soil and groundwater [23]. The US EPA reports that '[e]ach year Americans throw away 25,000,000,000 [25 billion or 47,565 per minute] Styrofoam cups. Even 500 years from now, the foam coffee cup you used this morning is likely to survive intact in a landfill' [24].

There is no domestic kerbside collection of any form of PS provided by councils in NZ. The lack of PS recycling services available to householders in NZ and the volume of EPS make disposal via council rubbish bags expensive. Consequently, littering or 'fly tipping' and household Burning of PS can become residential alternatives, thus raising the likelihood of releasing PS and its potentially toxic combustion products into the environment.

4.1. Ecotoxicity in the manufacture of polystyrene

In 1986, a US EPA report on solid waste declared PS manufacturing the fifth largest source of hazardous waste in the USA [16]. In addition, the manufacture of PS is energy intensive, creating large amounts of greenhouse gases (e.g. CO₂) and liquid and solid waste. To add to this life-cycle-based harm to the environment, PS is manufactured from petroleum: a non-sustainable and heavily polluting resource. Consequently, the environmental production costs of PS have been ranked the second worst in the USA by the California Integrated Waste Management Board [25].

It is possible that differences in manufacturing practices might lead to different levels of monomer residues remaining in the final product. For example, very preliminary studies on polycarbonate plastics showed that very different amounts of bisphenol A (BPA) monomer leached from different plastic products manufactured in Korea, China and NZ [26]. While very preliminary, this might reflect differences in manufacturing processes and controls between these countries. As Asia becomes the region of choice (on economic grounds) for manufacture of many plastic products, it is possible that PS products made with residual plastic monomers will increase. Consequently, the risk of monomer leaching into the environment and into products stored in plastic containers will rise as a result. The increase in free trade of these PS objects across geopolitical boundaries means that regulating the manufacture and responsible disposal of PS is very complex indeed [26].

4.2. Physical and ecotoxic threats in marine environments

Plastic pollution in marine environments has become so dire that the term 'plastic pollution' is now synonymous with 'marine pollution' [7]. A 2016 World Economic Forum report predicts that the ratio of plastic to fish in the ocean is expected to be 1:3 by 2025 [27]. Currently, 60–80% of waste found in marine environments is plastic [28], and in 2014, it was estimated that more than 226,796 tonne of plastic is currently afloat at sea [29]. Because of its light weight, PS is highly mobile and can transport invasive species across marine boundaries. PS is prevalent in NZ coastal areas: for example, in a 2016 study of microplastics on Canterbury's (NZ) coastlines, the majority of plastics (55%) found were PS [30].

Douglas McCauley, a marine biology professor at the University of California, Santa Barbara, USA studied the mechanical and chemical causes of harm to marine animals from EPS. The environmental degradation of PS (e.g. by bacteria) leads to the production of small fragments (microplastics) which survive for a very long time in the environment (e.g. in marine systems)

and cause physical effects. For example, fish mistake the PS particles for food and eat them. This leads to malnutrition as PS provides fish with no nutritional benefit while making them feel full, thus suppressing a desire to eat [6, 31]. Plasticisers and other additives are less common in PS products than in other plastics (e.g. polyvinyl chloride [PVC]). However, the antioxidant tris(4-nonylphenyl) phosphite sometimes used in PS products is a potent oestrogen mimic and is part of a cocktail of estrogenic environmental contaminants that is thought to be responsible for male feminisation in animals and humans [32]. To be clear, styrene is *not* produced by the environmental degradation of PS but by the leaching of residual styrene from incomplete polymerisation.

As outlined above, there is a further, very important, property of PS that has a significant bearing on its environmental and human toxicity: its extreme hydrophobicity. Since, in a chemical context, like chemical properties attract like, PS attracts and adsorbs (i.e. sequesters on its surface) other hydrophobic molecules (e.g. POPs). This is important because it means that micro PS particles (produced as part of the environmental degradation of PS) will sequester and transport POPs and other hydrophobic toxins in the aquatic environment. If PS microparticles are ingested by animals (or humans), the sequestered POPs might be stripped from the PS and absorbed into the animal's system. This makes PS an excellent vector for highly toxic hydrophobic chemicals.

Seabirds that have consumed plastic waste have been found to have polychlorinated biphenyls (PCBs) and POPs in their tissues at 300% greater concentrations than in similar birds that have not eaten plastic [31]. PS is particularly good at attracting oily (i.e. hydrophobic) chemicals such as PCBs, flame retardants such as polybrominated diphenylethers (PBDEs), pesticides (e.g. DDT) and surfactants (e.g. 4-nonylphenol an endocrine disruptor). These chemicals have been estimated to be adsorbed by PS at concentrations up to a million times greater than in the surrounding water [33].

The chemicals PS attracts are regarded as 'priority pollutants':

...[C]hemicals that are regulated by government agencies, including the US EPA, because of their toxicity or persistence in organisms and food webs. These chemicals can disrupt key physiological processes, such as cell division and immunity, causing disease or reducing organisms' ability to escape from predators or reproduce [6].

Rochman and her team found that at least 78% of priority pollutants listed by the EPA and 61% listed by the European Union (EU) were associated with plastic debris (either ingredients of plastic or adsorbed from the environment) [6]. PS microplastics contaminated by these POPs enter the food chain when eaten by marine species and might end up on our dinner tables at home [34].

Taking all of these chemical and toxicological properties of PS into account, PS *per se* is one of the less problematic plastics in a purely toxicological sense. However, its high rates of production, poor waste management, slow environmental degradation to form microparticles and adsorption of hydrophobic toxic chemicals have led, at the macro level, to huge quantities of PS waste presenting physical problems at all environmental levels, and, at a micro level, PS transporting adsorbed toxins to unsuspecting marine ecosystem consumers. It is

clear that a policy connection has not yet been made between these hydrophobic polymer 'carriers' and priority pollutants in the marine environment. If there were, it would be more likely that there would be cause to categorise hydrophobic plastics as 'hazardous.' Growing evidence, however, continues to highlight the previously unforeseen and complex relational behaviours of PS and its additives with other materials and bodies in marine environments. This growing evidence supports Liboiron's [9] argument that the governance of plastic pollution via 'safe levels' may not adequately capture the 'afterlives' of plastic polymers. The next section will further advance the argument that a more nuanced and context-specific approach is needed. This approach attends to the complex relational nature of polymers, monomers and other additives when they come into contact with other matter and materials in diverse environments.

4.3. Polystyrene combustion

The incomplete combustion (at temperatures that equate to household burning) of PS produces myriad products including styrene, PAHs, including fluoranthene which has been shown to be carcinogenic in mouse studies [35, 36] and the IARC, have classified it as a Group 3 carcinogen (i.e. not classifiable as to its carcinogenicity to humans). Concerns have also been raised about PS as a hazard during house or commercial building fires or the disposal of PS by burning due to the toxins it releases when PS is combusted, particularly when incinerated as household waste in residential areas. The National Bureau of Standards Center for Fire Research identified 57 chemicals released during the combustion of EPS. Of these, perhaps the most toxic include, PAHs, carbon black (i.e. the copious soot produced when PS burns) and carbon monoxide [11].

The use of extruded XPS and EPS in building construction is also a focus of concern due to the persistence, toxicity and ecotoxicity of the brominated flame retardant HBCD used in the manufacture of these PS foams. In response to these growing concerns, the EU (under the Stockholm Convention) banned the use, import or export of HBCD on 26 November 2015 [37].

5. Polystyrene and food safety

PS can be hazardous to human health in the following circumstances: eating marine animals contaminated with the residual monomers and additives in PS and the POPs adsorbed onto PS; inhalation of gases created when PS is heated or combusted; chemical exposure in the manufacture of PS; and exposure to tropospheric ozone caused by HFCs in the manufacture of PS. In this section, we will discuss the possibility that PS food containers that have been exposed to certain conditions [fats (e.g. Vitamin A) and heat] can increase the potential for styrene contaminants to migrate into food and bodies.

New scientific research is raising some doubt about the safety of food when in contact with PS under certain conditions. One of those conditions has been recognised in the US FDA guidelines in contact with fat above ambient temperature [22, 38, 39]. In 2014, the European Food Safety Authority (EFSA)'s Panel on Food Contact Materials, Enzymes, Flavourings and

Processing Aids (CEF) conducted a study requested by the Food Standards Agency (FDA), UK. They concluded the following:

...substances (butadiene, ethyl acrylate, methyl methacrylate, styrene) copolymer, (butadiene, ethyl acrylate, methyl methacrylate, styrene) copolymer crosslinked with divinylbenzene and (butadiene, ethyl acrylate, methyl methacrylate, styrene) copolymer crosslinked with 1,3-butanediol dimethacrylate, in nanoform do not raise a safety concern for the consumer if used as additives individually or in combination at up to a total of 10% w/w in non-plasticised PVC used in contact with all food types at ambient temperature or below including long-term storage [40].

However, household PS is not always used in contact with food at ambient temperatures; food is often heated in PS containers in microwave ovens; polystyrene cups and food containers are most commonly used for hot beverage consumption. This again raises the question of safe levels of styrene monomer and safe conditions of use when PS items are exposed to a wide range of untested conditions introducing a toxic risk.

One notable study emphasising the need for further attention to the potential leaching of styrene from PS containers into food is that of Matiella and Hsieh [41]. The researchers reported that volatile styrene monomer was found in shells of eggs after they were stored for 2 weeks in PS containers at supermarkets. Dishes cooked with these contaminated eggs contained seven times more ethylbenzene and styrene compared to those prepared from fresh farm eggs not packaged in PS. Not surprisingly, the American Chemistry Council (representing the plastics industry) vehemently denies any health risks posed by PS food packaging to the US public [42].

6. Discussion

The central dogma of modern toxicology is the Paracelsus principle: 'the dose makes the poison' [43] (the higher the dose, the greater the effect). However, some plastic monomers have a high biological impact at low doses (e.g. oestrogen mimics work at 10^{-5} M) meaning that testing regimes and the policies they inform need to change to address these trace environmental and food contamination exposure levels [44]. Testing regimes and their subsequent 'safe limits' significantly influence what is defined as 'hazardous' or 'safe'.

Under current testing regimes, we can no longer be certain about the production of risk-free objects (arguably nothing is risk free) [45]. Laboratory testing for safety may not provide us with a clear indication of how monomers may act within a variety of ecological and biological contexts, and what the consequences may be. Specifically, toxicity testing regimes simply do not mimic environmental systems and the interrelationships between pollutants well enough for them to give us a reliable indication of the environmental fate and behaviour of complex plastics.

The work of the new materialists is valuable in illuminating the complex nature of materials, the politics of testing regimes and the interpretation and categorisations of what is 'hazardous'. Objects, discourses, identities and politics emerge through particular relationships. In this case, whether PS is 'hazardous' or not largely depends on how scientists establish testing regimes and categorise, analyse, and interpret data. The ethics of categorising PS as

'hazardous' (or not) is not fixed and predetermined; it changes and unfolds as scientific findings, and their interpretations are negotiated [3].

The current approach to defining something as 'hazardous' or 'safe' involves an almost singular focus (e.g. on styrene monomer). However, if we are to safely manage PS production, consumption and disposal, we must scrutinise the life and 'afterlife' of each component that is used in the production of each PS product in the context of its fate and behaviour in the environment. This involves the engagements of its additives and intended end-products to other matter, materials and ecological and biological systems. This brings to question the term 'PS end product' and 'end of life'. If the 'end product' or the 'end of the life' of the product is defined as when the product no longer serves its original function, we are missing the ongoing impacts of the product on bodies and environments long after it is considered 'defunct'. The toxicity of PS continues long after its useful life.

The new materialisms also require a mobile approach. This would involve following PS objects and their interrelationships with other things. This is a call to reimagine PS in its various forms as unstable and impermanent with indeterminate consequences and trajectories. This is also a political call to scrutinise *how* PS is culturally constructed as 'hazardous' or 'safe' and by *whom*: a concern captured by what has been referred to recently as 'the politics of plastics' [46, 47]. In addition, this scrutiny might encompass the cumulative impact of substances in bodies. For example, chemicals that humans are exposed to from food and the environment might have additive effects both physiologically and toxicologically and thus should be considered together rather than individually [32].

This chapter also serves as a reminder that 'household waste' is a misnomer as it implies a kind of simplistic demarcation of space, whereas PS enters the home and can only be intentionally removed intact as solid 'waste'. Yet, PS household waste items can never be fully and successfully 'managed' by waste management infrastructures to a final resting place in landfills or recycling centres where they magically disappear from our lives and no longer impact on the environment. The PS items that enter households often originate from far flung places, diverse components and industrial processes (with varying levels of regulation). They enter bodies and become entangled with other materials and matter in the household, while other PS solid objects are constructed as 'waste items' and their invisible, ungoverned and now free-floating chemical components move on. They leave households to continue their unpredictable journeys to landfills or to impact other ecosystems and bodies. Outside the regulatory and technological structures of policy and waste management systems, the kinds of risks PS poses become even more difficult to detect and mitigate.

7. Conclusion

As Liboiron reminds us, the 'afterlives' of industrially produced objects are the longest part of their lives' [7]. This means that we can no longer limit our analyses and determinations of the hazardous nature of PS within the bounded spaces of the factory, retail store, home, landfill, marine environment and their return via the food chain to the dinner plate back home. That

said, shall we continue to treat polymers and monomers as discrete points of analysis in the development of legislation, policy and activism around hazardous waste and follow each one through all these spaces and beyond? Or in combination? And with other matter as they move through these spaces? How do we determine safe levels; or whether a PS is, or is not, 'hazardous' (considering the infinite and indeterminate contingencies and contexts of PS's interrelationships with other chemicals and bodies)? And who determines the safety of PS when this determination depends on pre-existing cultural values and agendas [48]?

While humans have the capacity to produce PS, we can never make it go 'away' when it no longer fulfils its, often short-term, function. However, at current rates of consumption, another 33 billion tonnes of plastic will be produced by 2050. Rochman et al. suggest that if the most problematic plastics were to be classified as hazardous immediately and replaced with safe alternatives, this rate could be reduced to 4 billion tonnes [6]. PVC, polystyrene, polyurethane and polycarbonate make up 30% of all plastic production. They are considered 'priority' plastics by Rochman and her team because they are particularly difficult to recycle and are made of potentially toxic materials. However, as we have argued, these plastics may only be considered 'hazardous' when in certain biophysical or ecological contexts. Does this mean that we should continue to produce these plastics and seek ways to ensure these hazard-causing scenarios do not occur? Or are the possibilities for PS to be located in contexts where they are hazardous unavoidable, meaning that a blanket ban on the production of these plastics is the only option?

This chapter has raised more questions than it can answer. However, we hope that it broadens attention to the 'aliveness' [1] of PS. The material quality of PS (its materiality) allows it to slip through the net of human intention, and outside the waste management infrastructure, the economic system and the policies and legislation designed to contain it, profit from it, and keep us safe. We have created these rogue materials and like Pandora's Box, they have escaped human management systems. Now, we need to recapture them, if only in our mind's eye for now, if we are to act to mitigate their real and future risks for human and non-human life—inside and outside the household.

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Household Hazardous Waste Management in Sub-Saharan Africa

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Additional information is available at the end of the chapter

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Abstract

Household hazardous wastes (HHWs) have not been given serious attention in sub-Saharan Africa. There is little or no information on HHWs in many developing countries of the world. This is regardless of the fact that they are very toxic and contain constituents which are persistent in nature. Once released into the environment, they can remain stable for exceptionally long periods of time. They have the potential to be harmful to public health and the environment if not handled, used, and disposed properly. This study reports the level of knowledge and management of HHWs in three tertiary institutions in sub-Saharan Africa. Several factors were found to be responsible for poor management of HHWs. These include lack of awareness, inadequate treatment technologies, financial constraints, lack of realistic policies and legal frameworks, and unplanned settlements, among others.

Keywords: Environment, Hazardous wastes, public health, sub-Saharan Africa, waste management

1. Introduction

Household hazardous wastes (HHWs) are a subset of wastes which are used and/or generated at the household level [1]. These wastes have the potential to cause irreversible damage to public health and other living organisms when disposed into the environment without proper treatment. Greater risks are often posed by hazardous substances to the environment and

public health than nonhazardous substances. Therefore, it requires a strict control regime. HHWs have a significant adverse effect on public health, other living organisms, and the environment because of their inherent toxic, chemical, and physical characteristics at low concentration [2]. Therefore, these types of waste stream require stringent control and management in order to protect the environment and human health from potential negative impacts. Although HHWs only make up a small percentage of household wastes in general, they are considered to be potentially harmful [3].

The WRc [4] defines HHWs as “such wastes that could potentially increase the hazardous properties of municipal solid waste when landfilled, incinerated or composted.” HHWs can also be described as leftovers from household products containing corrosive, toxic, ignitable, or reactive ingredients [5, 6]. The National Household Hazardous Waste Forum (NHHWF) in the United Kingdom defined HHW as “any discarded material by a household, which is difficult to dispose of, or which puts human health or the environment at risk because of its chemical or biological nature” [7]. Certain types of HHWs may pose potential physical injuries to sanitation workers, contaminate septic tanks, or wastewater treatment systems if poured down drains or toilets. They can also present hazards to children and pets if left around the house unattended [1].

HHWs must be separated from other domestic wastes and should not be disposed of together with municipal wastes because they require special treatment before disposal. They are harmful and are potential risks to humans [1]. HHWs vary in forms; some exist as liquids, solid, and gases making their treatment and management a bit complex. The list of HHWs differs between countries. Common examples include pesticides, paints (latex, nonlatex antifungal), motor oil, varnishes, antifreeze, various types of batteries (such as laptop batteries, car batteries, cellphone batteries), fluorescent light bulbs, fertilizers, thermometers, thermostats, solvents, unused medicines, bathroom and tile cleaners, brake fluid, asbestos, household cleaners (spot remover, degreaser, oven cleaner), stain, adhesives, lead acid, used gasoline, polish, wax, several electronics (such as television, computers, radio, and cellphones), photographic chemicals, flea powders, insect repellents, polish, rodent control, fabric, transmission fluid, and microfilm [1, 5–11]. The above examples of HHWs contain hazardous ingredients and require special attention for their disposal and treatment.

Improper disposal of HHW may change the way the biosphere functions, depletes the ozone layer and causes irreversible damage to domestic water sources. This could result in reduction of the productivity of global ecosystems at a time when millions of people are looking for livelihoods and sustenance to be provided by the environment [12]. For several reasons ranging from inadequate knowledge, lack of educational campaigns, lack of awareness on the impacts of HHWs and financial mismanagement are responsible for their improper disposal. HHW management is not usually given priority in most developing countries of the world, priority is mostly given to poverty alleviation, unemployment, and other economic problems. HHWs are usually disposed of with other domestic wastes such as disposal in drains, on the ground, into storm sewers, or in some cases with regular trash (**Figure 1**). Hence, HHW management, including disposal and recycling, seems to be urgent especially in the developing countries (sub-Saharan Africa) where domestic waste management technologies are still limited.



Figure 1. Illegal disposal of solid waste with HHW in different countries in sub-Saharan Africa.

Household hazardous wastes discarded in the trash may ignite or explode in the collection truck. Trash collectors may be injured from fumes and splashing chemicals. In landfills, leachate from the waste pollutes soil, surface water, and groundwater aquifers [4]. Disposal of hazardous household wastes in drains might also pollute drinking water [5]. In septic systems, hazardous wastes can kill the organisms that make the system work [3]. This may cause the bulk of untreated wastes to drain into the soil and eventually seep into the groundwater. Sewage treatment systems such as septic systems can be contaminated by improper disposal of hazardous household wastes [2–5, 13]. Due to the danger and risk posed by household hazardous wastes, good practices of handling, treatment, and disposal of these wastes should ideally begin in the household [1, 5, 14].

The use of materials with hazardous ingredient is likely to increase in sub-Saharan Africa due to increased industrialization and population growth [15–17]. If industrial and population growth is not balanced with efficient interventions to manage HHWs, most surface and groundwater sources are prone to varying degrees of pollution, some of which is irreversible. The effects of inadequate disposal of HHWs are not usually felt at the time of disposal, but with time, they pose significant risks to users of the resource further downstream [16, 17]. Most constituents of HHWs are persistent in nature and nonbiodegradable; once released into the environment, they transform from one form into a more toxic form [5, 9, 11]. Fauziah and Agamuthu [15] stated that one of the reasons for inadequate disposal and management of HHWs is inadequate awareness among the public as hazardous waste such as medicines, clinical bandages, and batteries that are commonly found in the refuse sent to landfill. This is one of the reasons why high concentrations of heavy metals are often detected in landfill leachate [16].

2. Classification and effects of household hazardous wastes

Household chemicals—a subset of hazardous wastes—are contaminants that are released during the use of various products in daily life. Several studies indicate that indoor air pollution

is far worse than that of outdoor because homes, for energy efficiency, are made somewhat airtight [17, 18]. Moreover, household chemicals are trapped in houses causing further deterioration of indoor air quality. Household hazardous chemicals are potentially dangerous chemicals that can be found within households [19]. Some very important products needed for comfortable living in various households contain hazardous ingredients. Hazardous products generally divided into six groups as shown in **Table 1** [17]. Household hazardous products may cause health and environmental problems to their users and when disposed into the environment. If the unwanted portions of these products go down the drain, into the trash, or get burned, they may cause harm to the environment.

Class	Hazardous products	Examples
I	Automotive products	Gasoline, motor oil, brake fluid, wiper fluid, hydraulic oil, and car batteries
II	Home improvement products	Paint (oil-based and latex), caulk, varnish, air freshener
III	Health and beauty products	Nail polish, finger nail polish remover, nail varnish, hair dye, bath salts/bubble bath, and skin creams
IV	Pesticides	Rat poison, flea killer, insecticide, fungicide, moth balls, ant poison, and herbicide
V	Household cleaners	Furniture polish, oven cleaner, toilet bowl cleaner, scouring agent, shoe polish, stain remover, disinfectant, and bleach
VI	Miscellaneous items	Fabric dyes, fluorescent tubes, low energy light bulbs, ink cartridge and toner, glue, antifreeze, and among others.

Table 1. Classification of the household hazardous products.

As stated earlier, household products are considered hazardous if they are radioactive, have dangerous biological characteristics, toxic, or flammable [6]. Many hazardous products have more than one of these hazardous characteristics. Corrosive substances destroy metal surfaces and living tissues and have the ability to chemically change whatever they come in contact with. Corrosive substances are acidic (pH less than or equal to 2) or caustic (pH higher than or equal to 12.5) [20]. Reactive substances are very unstable and interact with the substances around them. They are explosive and can sometimes create toxic fumes. Flammable substances will burst into flames if they come into contact with sparks or flames at certain temperatures. The temperature at which this occurs is referred to as the flash point. Flammable liquids have a flash point of 60°C [21]. Toxic substances cause immediate or long-term negative health problems. Exposure to toxic materials may result in injury, illness, or death [21, 22].

The effects of hazardous substances on humans and other organisms vary greatly [23–26]. This often depends on the extent of exposure, the concentration of the substance, the nature of the hazardous substance, and the unique characteristics of individuals [20, 21]. The characteristics that influence toxicity of a substance include:

- Genetic factors: For example, the efficiency of the kidney can affect the ability to excrete toxins.
- Lifestyle of the individual: Smoking, alcohol consumption, obesity, and previous medical history all affect how the body reacts to toxins. In general, healthier individuals are able to fend off some toxins.
- Gender: Some toxins have different effects on males and females. Generally, women have a larger percentage of fat in their total body weight, meaning they can accumulate more fat soluble toxins in their bodies than men.
- Age: Old and very young people are more vulnerable to the effects of toxic substances. Because infants and young children (less than 5 years old) have underdeveloped immune systems, they are the most susceptible to HHWs. In addition, because children have high respiration rates, they are more susceptible to toxins through inhalation.
- Allergic sensitivity: Individuals who are particularly sensitive to chemicals will experience allergic reaction to some toxic chemicals at low concentrations.

Table 2 presents some household products and their hazardous components as well as the potential health hazards. The health risks associated with HHWs are numerous and these substances must be managed appropriately in order to prevent possible risks to public health.

Product type	Class	Hazardous components	Hazardous status	Potential health hazards
1. Air fresheners and deodorizers	II	Formaldehyde	Toxic flammable	Carcinogen; irritates eyes, nose, throat, and skin; nervous, digestive, respiratory system damage
2. Bleach	V	Sodium hypochlorite	Corrosive toxic	Irritates and burns skin and eyes; nervous, respiratory, digestive system damage
3. Disinfectants	V	Sodium hypochlorite	Corrosive toxic	Irritates and burns skin and eyes; nervous, respiratory, digestive system damage
		Phenols	Toxic flammable	Respiratory and circulatory system damage.
		Ammonia	Toxic	Vapor irritates skin, eyes and respiratory tract
4. Drain cleaner	V	Sodium/potassium hydroxide	Corrosive toxic	Burns skin and eyes; nervous, digestive and urinary system damage
5. Flea powder	IV	Carbaryl	Toxic	Irritates skin; causes nervous, respiratory and circulatory system damage
		Dichlorophene	Toxic	Irritates skin; causes nervous and digestive system damage
		Chlordane and other chlorinated hydrocarbons	Toxic	Irritates eyes and skin; cause respiratory, digestive and urinary system damage

Product type	Class	Hazardous components	Hazardous status	Potential health hazards
6. Floor cleaner/wax	V	Diethylene glycol	Toxic	Causes nervous, digestive and urinary system damage
		Petroleum solvents	Flammable	Carcinogenic; irritate skin, eyes, throat, nose and lungs
		Ammonia	Toxic	Vapor irritates skin, eyes and respiratory tract
7. Furniture polish	V	Petroleum distillates or mineral spirits	Flammable toxic	Carcinogen; irritates skin, eyes, nose, throat and lungs
8. Oven cleaner	V	Sodium/potassium hydroxide	Corrosive toxic	Burns skin, eyes; causes nervous and digestive system damage
9. Paint thinner	III	Chlorinated aliphatic hydrocarbons	Toxic	Cause digestive and urinary system damage
		Esters	Toxic	Irritates eyes, nose, and throat
		Alcohols	Flammable	Cause nervous system damage; irritate eyes, nose, and throat
		Chlorinated aromatic hydrocarbons	Flammable toxic	Digestive system damage
10. Paints	II	Ketones	Flammable toxic	Respiratory system damage
		Aromatic hydrocarbon thinners	Flammable toxic	Carcinogenic; irritates skin, eyes, nose and throat; respiratory system damage
		Mineral spirits	Flammable toxic	Irritates skin, eyes, nose and throat; respiratory system damage
11. Pool sanitizers	V	Calcium hypochlorite	Corrosive	Irritates skin, eyes, and throat; if ingested cause severe burns to the digestive tract
		Ethylene (algaecides)	Flammable toxic	Irritation of eyes, mucous membrane and skin; effects reproductive system; probable human carcinogen of medium carcinogenic hazard
12. Toilet bowl cleaner	V	Sodium acid sulfate or oxalate or hypochloric acid	Corrosive toxic	Burns skin; causes digestive and respiratory system damage
		Chlorinated phenols	Flammable toxic	Cause respiratory and circulatory system damage.
13. Window cleaners	V	Diethylene glycol	Toxic	Cause nervous, urinary and digestive system damage
		Ammonia	Toxic	Vapor irritates skin, eyes and respiratory tract.
14. Motor oil	I	Heavy metals	Toxic	Can cause nerve and kidney damage; is thought to cause cancer
		Hydrocarbons	Flammable	Some forms thought to cause cancer

Product type	Class	Hazardous components	Hazardous status	Potential health hazards
15. Batteries (car, boat, tractor)	VI	Sulfuric acid	Toxic corrosive	Can cause severe skin burns, and blindness
		Lead	Toxic corrosive	Can cause nerve and kidney damage; is thought to cause cancer
16. Windshield washer fluid	I	Methanol	Flammable toxic	Can damage the nervous system, liver, kidneys; inhalation can lead to lung disease; ingestion can cause blindness
		Ethylene glycol	Flammable toxic	Can cause severe damage to heart, kidneys, and brain. Inhalation can cause dizziness
		Isopropanol	Flammable	Can irritate mucous membranes; ingestion results in drowsiness, unconsciousness and death
17. Laundry detergent	V	Cationic, anionic, or nonionic solutions	Reactive	If swallowed, cationic detergents can cause nausea, vomiting, shock, convulsions, and coma. Nonionic detergents can irritate skin and eyes
18. All-purpose cleaners	V	Ammonia	Toxic	Fumes can irritate eyes and lungs; can cause burns or rashes on skin; can produce deadly chloramine gas if mixed with chlorine-containing products
		Ethylene glycol monobutyl acetate	Flammable toxic	Can cause severe damage to heart, kidneys, brain. Inhalation can cause dizziness
		Sodium hypochlorite	Corrosive	Corrosive to skin and lining of nose mouth and throat; fumes irritating to eyes and respiratory tract
19. Pet flea and tick treatments	IV	Organophosphates and carbamates	Toxic	Can cause headache, dizziness, twitching, nausea; known to cause cancer in animals
20. Insecticides	IV	Organophosphates and carbamates	Toxic	Can cause headache, dizziness, twitching, nausea; known to cause cancer in animals
21. Household foggers	IV	Pyrethrins	Toxic	Can cause severe allergic dermatitis, systemic allergic reactions. Large amounts may cause nausea, vomiting, tinnitus, headache, & other CNS disturbances
		Permethrin	Toxic	Can cause itching and burning of the skin and eyes; irritates the upper respiratory tract
		Methoprene	Toxic	Can irritate the skin and eyes
22. Swimming pool chloride tablets	II	Sodium (or calcium) hypochlorite	Corrosive reactive	Corrosive to skin and lining of nose mouth and throat; fumes irritating to eyes and respiratory tract
23. Insect repellants	IV	Butopyronoxyl	Toxic	Can cause mild necrosis in liver and kidney –in animals
		Dimethyl phthalate	Toxic	Can cause central nervous system depression if swallowed

Product type	Class	Hazardous components	Hazardous status	Potential health hazards
		Diethyltoluamide (DEET)	Toxic	Can irritate sensitive skin and respiratory tract tissues as well as loss of coordination, anxiety, behavioral changes, and mental confusion
24. Weed killers	IV	Diquat, 2,4-D, and glyphosate	Toxic	Can irritate the eyes and skin; can cause abdominal pain, nausea, vomiting, and diarrhea
25. Rodent control	IV	Warfarin	Reactive	Causes internal bleeding if ingested in large amounts
26. Rug, carpet, upholstery cleaners	V	Perchloroethylene	Toxic	Fumes cause dizziness, sleepiness, nausea, loss of appetite and disorientation; can cause cancer with long-term exposure
		Naphthalene	Reactive toxic	Can damage liver; prolonged vapor exposure has led to cataract formation
27. Antibacterial cleaner	V	Ammonia, detergents, lye	Toxic	Fumes can irritate eyes and lungs; can cause burns or rashes on skin; can produce deadly chloramine gas if mixed with chlorine-containing products
		Cresol	Corrosive	Can be corrosive to tissue; damages liver, kidneys, lungs, pancreas and spleen
		Phenol	Corrosive	Can cause central nervous system depression; severely affect circulatory system; corrosive to skin; suspected of causing cancer
		Pine oil		Can irritate eyes and lining of nose, mouth, and throat
28. Hair dyes	III	Pigment ammonia	Toxic	Can cause burns or rashes on skin; can produce deadly chloramine gas if mixed with chlorine-containing products
29. Skin creams	III	Heavy metals	Toxic	Can cause nerve and kidney damage; is thought to cause cancer
30. Glue	VI	Xylene, toluene	Flammable toxic	Irritation of eyes, mucous membrane, and skin; effects reproductive system; probable human carcinogen of medium carcinogenic hazard

Source: [14, 15, 18, 20–23].

Table 2. Household products containing hazardous components and their health hazards.

3. Method

To test the level of awareness and management of HHWs in sub-Saharan Africa, 50 questionnaires were administered to students at various levels of study in tertiary institutions in Kenya, Nigeria, and South Africa. The collected data were analyzed using Microsoft Excel 2013 version and the results were presented in bar charts.

4. Management of household hazardous wastes

The management of hazardous wastes remains a central environmental issue internationally [2]. Otoniel et al. [27] reported that measures have been taken for the HHW management in some developed countries such as the USA. In developing countries, many of which are in sub-Saharan Africa, there is little information concerning the management of HHWs. Although there is a great challenge to the effective treatment and disposal of HHWs in most developing countries of the world, huge success has been recorded in some developed countries (such as the USA, Austria, Germany, Italy, Denmark, the Netherlands, and some other European nations) of the world. The key to this success involves creating adequate awareness on the potential health and environmental risk of HHWs through various informational campaigns [4]. Some of the developed countries have recycling and collection sites where citizens can drop HHWs at no cost. In other cases, there are collection centers such as shops take back or containers parked at public places where individuals can drop HHWs [4]. The success of this method depends largely on active participation from the public. Apart from this system, some countries also incorporate the collection of HHWs in special containers alongside with general municipal wastes, or sometimes by other special arrangements already known to the citizens. The citizens are taught to separate these wastes at the household level [4].

Due to the complexity of HHWs, they are not often collected as a composite waste from households. They are usually separated into different forms such as used and expired batteries, used oil, pesticides, low energy light bulbs and fluorescent tubes, pharmaceuticals, e-waste, fertilizers, and paints. Most recyclable HHWs such as batteries and florescent lamps are recycled and reused, while others that require further treatment are sent to chemical-physical treatment plants, thermal treatment and recovery plants, specialized treatment and recycling plants, biomechanical pretreatment plants for residual waste, sorting plants for separately collected waste, and internal thermal treatment plants [4]. There are also adequate policies and legislation on the use of HHWs in most of these countries. Otoniel et al. [27] reported that measures have been taken for the HHWs management in some developed countries but this is not true for many other developed and almost all developing countries of the world.

In developing countries, many of which are in sub-Saharan Africa, there is little information concerning the management of HHWs. Generally, solid waste management which is simpler compared to the management of HHWs in sub-Saharan African does not meet international collection, recycling, and disposal guidelines. Most wastes generated including HHWs are disposed along roads, highways, vacant land, river banks, and canals, and among others (**Figure 1**). A few cities in sub-Saharan Africa (such as Cape Town in South Africa and Mbabane in Swaziland) have a well-planned solid waste collection system comparable to that of developed countries; while majority of cities (e.g. Onitsha in Nigeria and Kumasi in Ghana) have poor solid waste collection and disposal management. Many villages in the region do not have any form of waste collection and disposal system (**Figure 1**).

Recently, some contaminants, known as emerging contaminants, have been detected in drinking water of most places in the world. Notable emerging contaminants include: pharmaceuticals and personal care products (PPCPs), flame retardants, endocrine disrupting

compounds (EDCs), pesticides, hormones, and disinfection by-products (DBPs) [28]. Most of these contaminants have been linked to the use and improper disposal of HHWs. They are currently receiving global attention due to the perceived threat they could pose to public health and the environment.

In most sub-Saharan countries, the common methods for HHWs management and treatment include open burning of wastes, incineration, and landfilling. These methods are preferred over other methods because they are cheap, easy to operate, and generally accessible. As stated earlier, HHWs in domestic wastes are not separated from the nonhazardous components and are treated as a composite waste.

1. Open burning technique which include all forms of controlled and uncontrolled waste combustion practices is used in for the treatment of HHWs [29, 30]. This method is often used because it is cheap and easy to operate and its energy requirement is low. It does not require any formal training to burn hazardous materials. A major disadvantage to this method is the formation of harmful products such as polycyclic aromatic hydrocarbons that are easily formed from the combustion reaction of carbonaceous materials with free oxygen in air [5]. The combustion of chlorine-containing substances can lead to the formation of dioxins and furans that are highly carcinogenic to humans [9]. Also, smoke and unpleasant odors often accompany open burning practices which is a threat to public health (**Figure 2**) [31]. The use of open burning techniques of HHWs has been reported in Nigeria, Cameroon, Ghana, Kenya, Tanzania, South Africa, and other countries in sub-Saharan Africa [29–34].



Figure 2. Open burning of some HHWs [31].

2. Incineration technique is a very useful method for the treatment of HHWs globally. It is one of the methods still in use in different developed countries of the world [4]. Incineration of HHWs should be done in a controlled environment where the release of toxic substances is eliminated [4]. This is not true for most developing countries as incineration is usually done in an uncontrolled environment [29]. This technique is very useful for the treatment of wastes with low-water content but its application is inefficient in treating wastes containing high

quantity of water; hence, it is not suitable in developing countries [34]. The release of toxic metals such as mercury, cadmium, and lead into the environment has been linked to the incineration of HHWs under the uncontrolled environment.

3. Landfilling is not accepted as an efficient way of treating HHWs in most developed countries due to various health and environmental risks associated with it. However, in most developing countries, HHWs end up in landfill sites as mixed waste with other domestic and medical wastes. This practice has been reported to have several environmental consequences including contamination of groundwater resource, injury of waste workers, and risks to local waste collectors who collect some discarded materials for recycling [5]. Landfilling of hazardous wastes has been reported to be unsuitable due to the complexity and nature of the wastes [2, 5, 9]. Fauziah and Agamuthu [35] reported a mixture of HHWs and nonhazardous wastes in a municipal landfill in Malaysia, of which about 1.5% of household wastes were classified as hazardous waste. Such a system of disposal is very dangerous to scavengers of valuable and recyclable wastes as they are faced with all forms of risk going through a pile of solid wastes. Cases of HHWs in landfills of developed countries have been reported despite several measures that have been setup [36].

Apart from the general methods discussed above, several countries in sub-Saharan have devised other initiatives for the management of certain classes of HHWs. In South Africa, a private company that makes rechargeable batteries organized with a well-known food stores nationwide to collect all types of batteries. The recyclable batteries are sorted from the nonrecyclable batteries and are sent to France for recycling because there are no facilities in South Africa that can recycle batteries. The nonrecyclable batteries are encapsulated in concrete and disposed of safely to a licensed landfill [37]. Similarly, a nonprofit organization known as Recycling Oil Saves the Environment receives used oil from various locations in South Africa and recycles them for use [38]. In Maldives, Bluepeace [39] reported the use of a ditch (Figure 3) at the waste collection center for the disposal of used engine oil. This consequently led to groundwater contamination.



Figure 3. Used engine oil in a ditch in Male, Maldives contaminates the groundwater [34].

Other methods reported for the treatment of HHWs include using them as a fuel in cement kilns, as components of building materials (roads, bricks etc.), and autoclaving and electro-thermal deactivation. These methods are used in some sub-Saharan Africa countries but the unintended consequences of these technologies are still not known [37].

4.1. Factors affecting effective management of HHW

Several factors that usually interfere with the management of HHWs in sub-Saharan Africa include:

1. Lack of awareness: One of the major factors affecting HHW management is lack of awareness of what household hazardous wastes are. The limited information on the management of HHW in sub-Saharan Africa attests to the fact that very little is known about them in the region. Most people in sub-Saharan Africa hardly read the labels on the product they purchase to follow the disposal procedure. Even those that read the labels ignore the disposal instructions from the manufacturers of those products. This is because there is limited understanding of the possible risk HHWs have on humans and the environment. Children play with flammable substances at home or after improper disposal. One of the greatest successes that can be recorded in HHW management is the separation of these substances from other wastes at the household level.

From the results obtained from the questionnaires administered, the participants were majorly undergraduate and postgraduate students within the age group of 15–40 years. The participants were males comprising 58, 88, and 40% from South Africa, Nigeria, and Kenya, respectively (Figure 4).

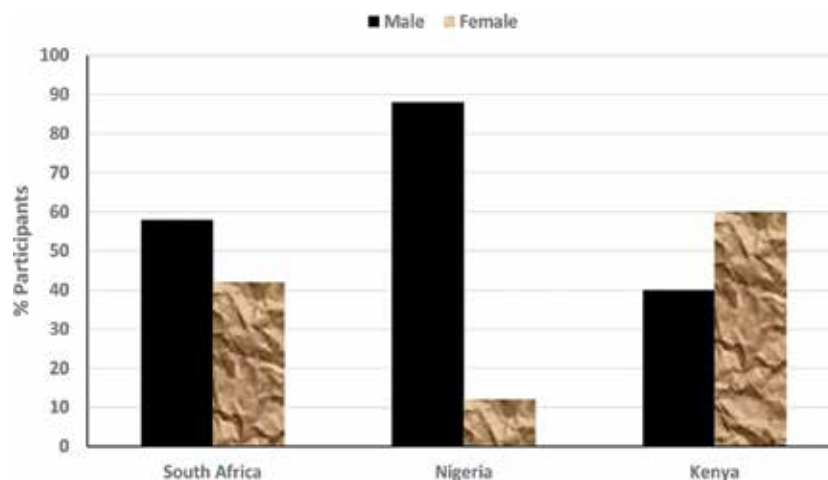


Figure 4. Gender distribution of participants.

In South Africa, 68% of the participants claimed to have adequate knowledge of household hazardous wastes, while 32% of the participants did not know (Figure 5). In the classification

on the types of HHWs, various types of HHWs were included in the questionnaire as a follow-up question to help in estimating those who truly have adequate knowledge of HHWs. Based on this classification, 43% (out of this 68%) of the participants actually knew what HHWs were while 57% of the participants did not know. There was high variation in the awareness of HHWs, inferring partial awareness of HHWs among tertiary students of South Africa. In Nigeria, 69% of the participants also claimed to have adequate knowledge of HHWs while 31% lacked adequate knowledge of HHWs (**Figure 5**). But based on the classification on the types of HHWs, 40% (out of the 69%) of the participants actually knew what HHWs are and 60% of the participants did not know. The awareness level in Nigeria is similar to that in South Africa. In Kenya, a different scenario was obtained compared to South Africa and Nigeria. 36% of the participants claimed that they had adequate knowledge of HHWs and 64% of the participants did not know (**Figure 5**). From the classification of various types of HHWs, all the participants who claimed to have adequate knowledge of HHWs truly had a good level of awareness on HHWs based on the follow-up questions. The level of awareness in Kenya seemed to be low compared to other two countries used in this study. The awareness level in each of the three countries could be as a result of literacy level of individual country [40] but this may not only be the case as the sincerity of each participant in answering the questions can be a contributing factor. Some people who claimed to have adequate knowledge of HHWs from South Africa and Nigeria actually did not have adequate knowledge, as demonstrated from a follow-up question on the classification of various substances as HHWs and nonhazardous wastes. Some of the respondents who initially claimed to have adequate knowledge on HHWs classified hazardous substances as nonhazardous.

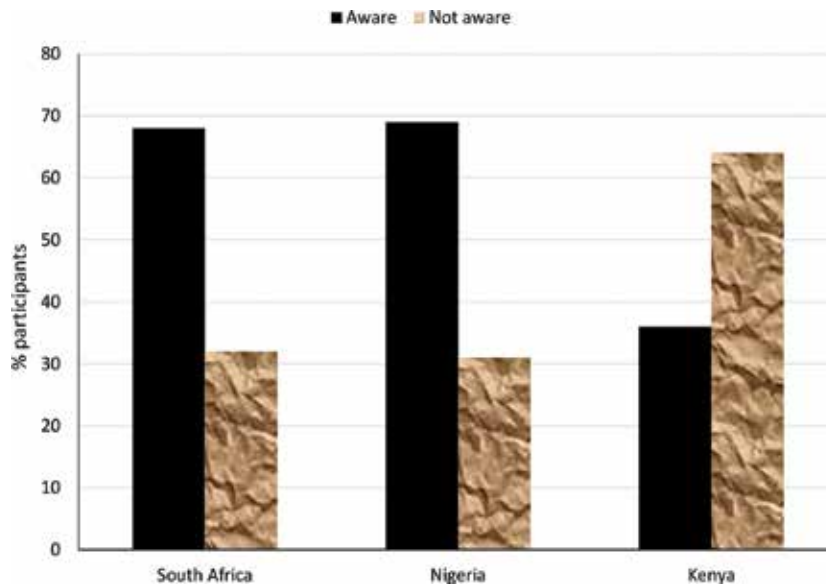


Figure 5. Percentage level of participant's knowledge on HHWs.

With the exception of level of knowledge of the respondents, many participants claimed to know how to manage HHWs from their homes. In South Africa, 62% of the participants had adequate knowledge of HHWs management whereas 38% did not know (**Figure 6**). The participants suggested various ways of storage of HHWs which included: closed container (64%), open container (2%), plastic bag (14%), pile in yard (2%), recycling (4%), and do not know at all (14%). 74% of the participants admitted that HHWs could have many negative effects on humans and the environment; 14% suggested that they will only have mild effects; 2% agreed that HHWs would have no effect on man and the environment. In Nigeria, 48% of the respondents claimed to have adequate knowledge of HHWs management, while 52% did not know (**Figure 6**). 73% of the participants suggested that HHWs should be separated from other household wastes. Similarly, 71% of the participants suggested that HHWs should be stored in a closed container; 2% suggested open container; 2% plastic bags, and 25% did not know how to store HHWs. 56% of the participants admitted that HHWs could have many ill-effects on humans and the environment while 17% believed they may have mild effects and 27% were not sure of their effects. In Kenya, 32% of the participants had good knowledge of HHWs management whereas 68% did not know how to manage HHWs (**Figure 6**). A majority of the participants suggested that HHWs should be separated from other household wastes and that closed container was the best way to store HHWs in the household. 68% of the participants admitted that HHWs could have many ill-effects on humans and the environment while 32% claimed that they will only have mild effects.

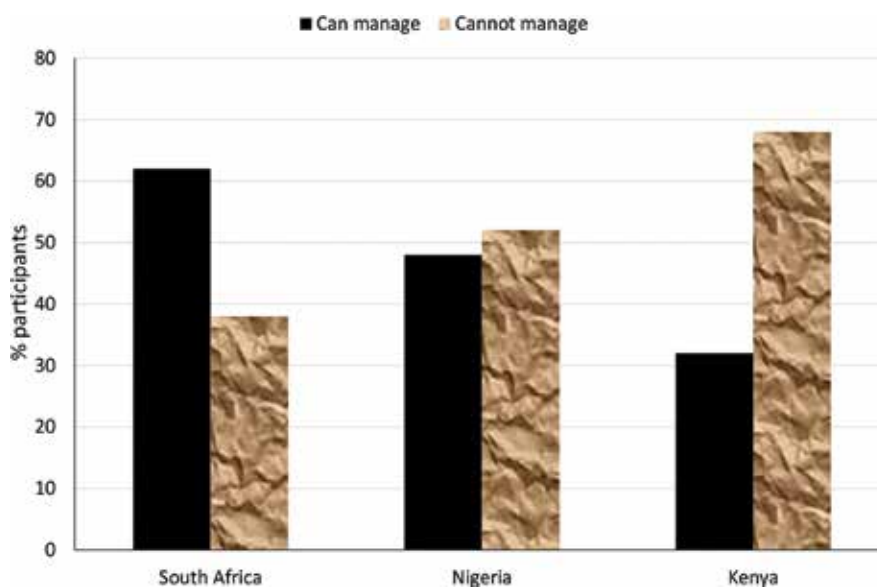


Figure 6. Percentage of participant's level of knowledge on HHWs management.

The government and other private bodies such as NGOs must educate people in sub-Saharan Africa on HHWs and their management. This can be achieved through rallies, posters, social

media (such as Facebook, twitter, WhatsApp), newspapers, television, and using other respected authorities like traditional leaders (e.g., chiefs), school teachers, university lecturers, and religious leaders.

2. Financial constraints: Most countries in sub-Saharan Africa are faced with unprecedented population growth which is often unbalanced with much of the disposable municipal expenditure devoted to high profile infrastructure whereas waste disposal and management are low on the list of priorities in terms of allocation of funds [41]. Poverty and unemployment are the major focus of most governments in sub-Saharan countries. The treatment of HHWs is cost intensive and without proper allocation of funds such management systems cannot be effective. Most countries in the region have attempted to carry out solid waste management in one form or the other and have reported minimal success due to limited financial commitment from government, the people and NGOs. Most people in the region are striving to meet their basic needs and are not willing to pay an extra cost for waste disposal. Several countries in developing countries have placed a ban on certain product containing hazardous ingredient. The accumulation of such products already in the country occurs due to financial constraints and lack of appropriate technologies to treat and dispose them. Also despite the ban, illegal importation of such products is common due to poor monitoring for compliance and corruption [42].

3. Unplanned settlements: Very few cities and villages within the region have planned settlements; the latter make collection of HHWs easy but within most cities, slums and high rate of urbanization make it very difficult for the government or private companies to effectively distribute waste bins and collect them. Some of the places where people live are not accessible to the collection vehicles.

4. Lack of appropriate technology: Government officials in most countries, as stated earlier, are more concerned with poverty eradication, solving unemployment problems, and provision of basic health care and education and are unwilling to invest in the technology for the management of HHWs. Most facilities present in a few countries lack the appropriate technology from the waste collection to disposal. If progress is to be made in this regard, there is an urgent need for the appropriate technologies and skillful personnel. Agamuthu [8] and Gatke [43] reported that the main components of HHWs in Malaysian landfills are batteries, aerosol cans, paints, pesticides, adhesive, drugs, and syringes. They lamented the reason of these contaminants in the landfills as the Malaysian government did not have the appropriate technologies for the management of HHWs hence their inclusion with general domestic wastes. Similar observation has been reported in many countries in sub-Saharan Africa.

5. Lack of proper legislation and enforcement of the legislation: Most countries within the region lack the legal framework for HHWs disposal; therefore efforts to control it would be unsuccessful. Most developing countries in sub-Saharan Africa have a legislative framework for solid waste management and wastewater whereas some developed countries such as Canada, Germany, and the USA have a realistic policy on household hazardous wastes with the aim of reducing it at the household level [4, 36]. The legislative framework for both liquid and solid wastes has not been enforced, even though present. There is no accountability system in the legal structure' thus, even when the laws exist there is no structure to ensure strict

compliance. South Africa has quite a number of legislations governing waste and these include: the South African constitution Act 108 of 1996, Hazardous Substance Act 5 of 1973, Environmental Conservation Act 73 of 1989 and Minerals and Petroleum Resources Development Act 28 of 2002, National Environmental Management: Waste Act 59 of 2008, and among others but there is no legislation that strictly governs HHWs in the country [44]. In Nigeria, several legislations regarding waste management include the National Environmental Standards and Regulations Enforcement Agency Act, 2007; the Environmental Impact Assessment Act, 1992; and the Harmful Waste Act, 1988 [34, 45]. The Harmful Waste Act of 1988 in Nigeria prohibits the sale, purchase, and generation of toxic, poisonous, and potentially injurious substances [34, 45]. Similarly in Kenya, the Environmental Management and Co-ordination Act (EMCA) No. 8 of 1999 prohibits the mismanagement of wastes and has a deterrent fine for industries that refuse to comply with the tenets of the policy. The Act also compels polluters to manage and recycle their wastes. There are several portions of the Act dealing with hazardous wastes [46]. Most countries in sub-Saharan Africa have different legislations on solid wastes and wastewater but specific legislations on HHWs management is completely missing. Several part of the legislations and policies deal with hazardous wastes in a broader sense but HHW was not the sole target of the legislations [15–18]. This may be one of the contributing factors to the low level of awareness and management of HHWs in the region.

4.2. Improving HHWs management in sub-Saharan Africa and recommendations

The way forward for effective management of HHWs in sub-Saharan Africa is to first create active awareness through information campaigns on HHWs and the health and environmental risks associated with them. The use of substances without hazardous components should be encouraged as this will lead to a reduction of total HHWs generated in sub-Saharan Africa. Collection, recycling and treatment centers should be opened by the government where hazardous wastes can be disposed without any financial cost on the citizens. Different types of HHWs such as batteries, engine oil, paints, and light bulbs should be collected separately and recycled for reuse. The government should make HHWs management a priority and should invest in it. Also, the government through the various ministries should seek for funding through the writing of good proposals soliciting for grants from donors to assist in the management of HHWs. Adequate technologies for HHWs treatment should be introduced and where there are no skilled personnel, scholarship should be given to interested individuals to study HHWs treatment and management from countries such as France and Austria where HHWs management have been successfully implemented for decades. Such individuals should be encouraged to return back to their respective countries to implement what they have learnt. Adequate policy and legislation on HHWs should be enacted and enforced through proper monitoring for compliance.

5. Conclusion

HHWs have high potential risks. In order to avoid this, it is desirable that strict monitoring be given to the use, storage, and disposal of hazardous substances at the household level.

Improper handling and disposal of these materials can be detrimental to human health and the environment at large. Results from this study have shown low level of awareness of HHWs among university students who are expected to be more enlightened than those who did not have the privilege to acquire tertiary education. Therefore, more ignorance on HHWs is expected from other citizens of the region because if university students could not identify what HHW substances are and do not understand the potential risk they pose to public health and the environment, then other less-educated people are not likely to have enough information on HHWs. Major steps to the efficient management of HHWs includes creating adequate awareness on HHWs, encouraging citizens to use alternative substances in lieu of them. People in the region should be enlightened on the use, disposal and the potential risk associated with HHWs. There should be adequate policies on HHWs management and the enforcement of such policies in sub-Saharan Africa. Little information and data exists on HHWs in sub-Saharan Africa, more studies should be encouraged and conducted to assess their levels.

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Rapid global urbanization and increases in living standards in recent decades have led to changes in the household hazardous waste (HHW) generation characteristics due to increases in buying power and easier access to products that are convenient but not always safe. In recent years, the amount of diversified hazardous materials and/or potentially hazardous materials, such as cleaning products, medicines, personal care products, packaging and container products, phthalates, and antibacterial agents, poses a serious threat to the environment and public health. As a result developed countries have adopted well-functioning policy measures and innovative technologies to deal with HHW. On the other hand, developing countries have weak institutional structures and poor policy performance and have adopted ad hoc approaches to manage HHW. The book contains five chapters covering topics of household hazardous waste management and exposure assessment. This book will be useful to many research scientists, solid and hazardous waste managers, administrators, librarians, and students in the scope of development in solid and hazardous waste management program including sources of household hazardous waste, exposure assessment, and government policies on waste generation and treatment and processing of HHW.

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