

Review

Hazardous Waste Management: An African Overview

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Abstract: Hazardous waste materials and their management are of prime importance to society. This article gives an overview of the current practices that relate to hazardous waste management. It looks at issues concerning the transboundary or international movement of harmful materials from industrialized nations to the developing and emerging world. This study has shown that Africa, most notably Nigeria, has become a dumping ground for hazardous waste materials as a result of the high importation of scrap computers and electronic devices into the country. The public health hazards, such as birth deficiencies, cancers, and even infectious diseases such as human immunodeficiency virus (HIV) and Hepatitis B and C, respectively, have been traced to the improper management of these waste materials. The review highlights a few models on hazardous waste management as developed by previous literature, which gives a hierarchy, ranging from source reduction, recycling, and landfill options. Studies reveal that hazardous waste management in Africa must revolve around wealth creation, economic, and environmental sustainability. The study provided evidence that the recycling option has high potentials in the areas of energy recovery. The data collected show South Africa to be the most advanced in the African continent in the field of hazardous waste management. For a sustainable environment, keen attention must be paid to hazardous waste management globally.

Keywords: solid waste management; public health; hazardous waste; toxic materials; recycling; environmental sustainability; energy recovery; wealth creation

1. Introduction

The day to day generation of hazardous waste in many parts of the world poses tremendous threats to humans, animals, and the ecosystem at large. The increase in waste generation can be strictly linked to the rise in the global population, thus leading to a rapid boost in industrial activities [1], which are a significant source of hazardous contaminants in the world. According to research by the United Nations Environment Programme (UNEP), about 400 million tons of hazardous waste are generated globally every year, which is estimated to be about 60 kg for every individual in the world [2,3].

On a global scale, several studies have been conducted on hazardous waste materials, which have indicated the rate of generation of unsafe contaminants. China, for example, faces critical challenges in the control of dangerous pollutants, both domestically and internationally. In 2005, about 11.62 million tons of industrial hazardous waste (IHW) was produced, of which an average of approximately 43.4% was recycled, 33% was stored, and 23% was disposed of. This accounts for about 70,000 tons of IHW that were discharged to the environment with no form of control [4]. According to studies carried out by [5], 1.4% of about 13 million tons of industrial waste generated in Portugal as of the year 2001 was reported to be hazardous. This study showed that 5% to 7% of municipal solid waste is considered to be hazardous [5]. Elsewhere in India, about 9.3 million metric tons (MT) of hazardous waste is

generated, of which 1.35 million MT is recyclable, 0.11 million MT is incinerable, and 0.49 million MT is sent away for safe disposal [6]. Some other studies have been able to deal with the quantification of hazardous waste generated at the household and national levels [7–9]. Recent estimations show that 3,000,000 tons/year of industrial waste is produced in Chile, of which 129,918 tons/year of hazardous waste has been reported [10]. Data from research suggest that 100,000–250,000 tons of household hazardous waste (HHW) were expected to be disposed of in the United Kingdom, without considering electronic waste materials [7–9].

Taking into consideration the various types of hazardous waste sources, such as e-waste and biomedical waste, several studies have revealed some critical data concerning their generation. About 500 million PCs (personal computers) are said to have reached the end of their service lives between 1994 and 2003 [11]. These PCs are reported to contain an average quantity of 2,872,000 tons of plastics, 718,000 tons of lead, 1363 tons of cadmium, with an average lifespan decreasing from about six years in 1997 to two years as of the year 2005 [11,12]. Figure 1 shows a global map with the quantity of hazardous waste generation globally. From Figure 1, Russia generates the highest amount of hazardous waste in the world, at about 139,194,000 tons per annum, with the United States following behind at 37,033,000 tons per annum. Most of Africa still shows a low hazardous waste generation rate [13,14].

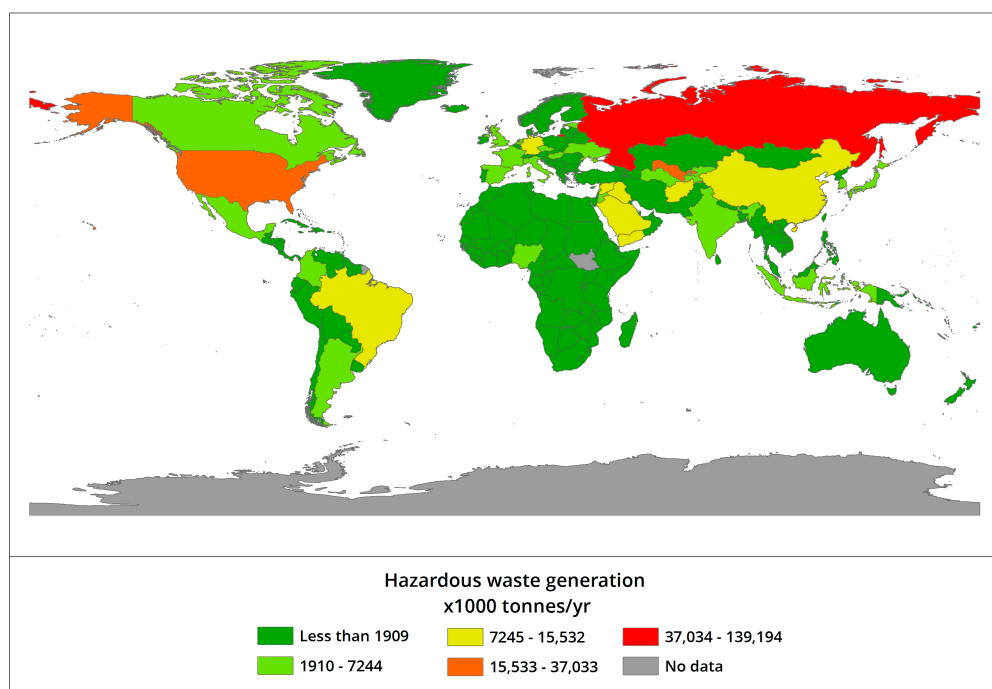


Figure 1. Hazardous Waste Generation. Source: [13].

Table 1 gives a summary of hazardous waste generated in African countries and the hazardous waste generated per capita in Africa and other parts of the world. Table 1 also highlights the same information from randomly selected countries which cut across other regions of the world.

From Table 1, Nigeria is reported to generate the highest amount of hazardous waste in Africa, at 2,469,000 tons per annum, followed by Egypt, at about 1,440,000 tons per annum. Africa is reported to have an average per capita hazardous waste generation of 20.1 kg/person/annum [13,14]. The Benin Republic and Morocco are reported to have the highest per capita hazardous waste generation at 65 and 33 kg/person/annum [13,14]. Table 1 also gives an insight into the per capita generation rates of other regions of the world. Estonia, for example, has the highest per/capita generation of hazardous waste, at 4774 kg/person/year [13,14].

This review identifies the hazardous waste situation in some African countries, based on available data and its impact on public health in the African continent. Challenges faced by Africa in the

effective management of hazardous waste materials are identified with potential mitigative measures. By utilizing a basic model, this review provides a process flow of hazardous waste materials that could be adopted by African nations based on the peculiarities of their countries.

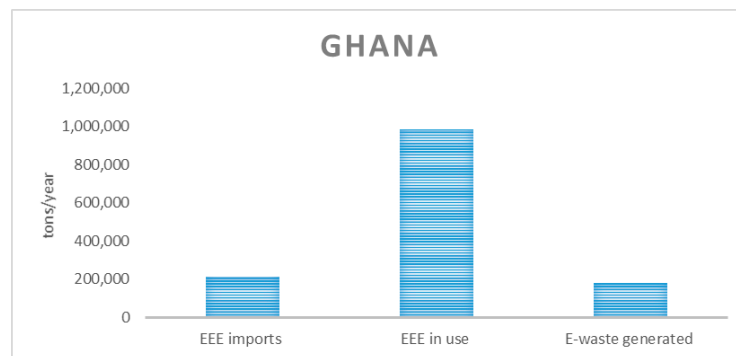
Table 1. Hazardous Waste by Country. Source: [13,14].

African Countries	x1000 tons/yr	kg/Person/yr	Others (Selected Randomly)	X1000 tons/yr	kg/Person/yr
Algeria	185	6	China	9520	7
Angola	270	20	Indonesia	3143	14
Benin	428	65	India	7244	7
Botswana	37	20	Lebanon	2217	616
Burkina Faso	257	20	Malaysia	420	18
Burundi	135	20	Russia	139,194	966
Cameroon	321	20	United Kingdom	5568	94
Cape Verde	10	20	Germany	15,532	188
Central Africa Republic	78	20	Estonia	6206	4774
Chad	170	20	Denmark	374	69
Comoros	14	20	Australia	649	33
Congo	74	20	New Zealand	55	14
Cote d'Ivoire	335	20	Singapore	204	49
Democratic Republic of Congo	1046	20	Philippines	1138	14
Djibouti	14	20	Sri Lanka	41	2
Egypt	1440	20	Syria	10,714	616
Equatorial Guinea	10	20	Mexico	3706	36
Eritrea	82	20	Canada	3245	104
Ethiopia	1409	20	United States	37,033	127
Gabon	27	20	Cuba	941	83
Gambia	29	20	Argentina	2530	67
Ghana	419	20	Belize	1	3
Guinea	172	20	Bolivia	573	67
Guinea-Bissau	29	20	Brazil	11,740	67
Kenya	643	20	Chile	1039	67
Lesotho	37	20	Colombia	2897	67
Liberia	66	20	Costa Rica	273	67
Libya	110	20	Iraq	15,091	616
Madagascar	345	20	Iran	168	2
Malawi	243	20	Kazakhstan	130	8
Mali	257	20	Kiribati	1	14
Mauritania	57	20	Kuwait	25	10
Mauritius	0	0	Kyrgyzstan	6780	1329
Morocco	987	33	Laos	80	14
Mozambique	378	20	Puerto Rico	260	67
Namibia	41	20	Saint Kitts and Nevis	3	67
Niger	24	2	Saint Lucia	0	3
Nigeria	2469	20	St Vincent and The Grenadines	7	67
Rwanda	170	20	Trinidad and Tobago	87	67
Sao Tome and Principe	4	20	Hungary	3413	345
Senegal	202	20	Iceland	13	45
Seychelles	2	20	Ireland	492	126
Sierra Leone	98	20	Italy	4279	74
Somalia	194	20	Latvia	93	40
South Africa	915	20	Liechtenstein	4	118
Sudan	672	20	Lithuania	111	32
Swaziland	22	20	Luxemburg	101	253
Togo	98	20	Panama	206	67
Tunisia	198	20	Paraguay	380	67
Uganda	511	20	Peru	1785	67
Tanzania	741	20	Suriname	27	67
Western Sahara	6	20	Uruguay	226	67
Zambia	219	20	Venezuela	1678	67
Zimbabwe	261	20	Israel	325	52

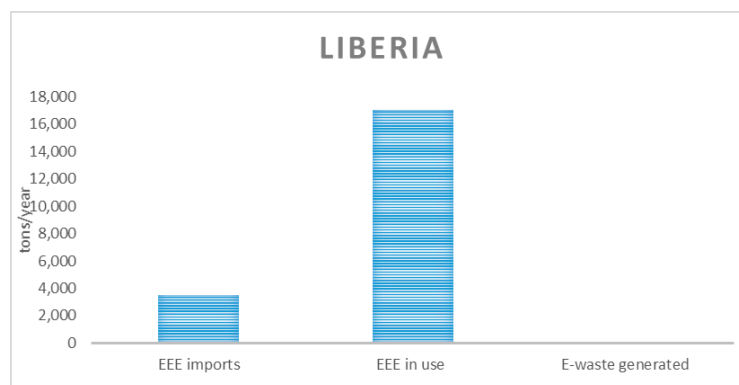
The African Scenario

The case in the African continent differs from that of the developed world. Africa is said to be the dumping ground of preowned and disregarded electronic materials from the developed world [15–18]. Moreover, [16,19] reported that the enormous hazardous waste generated in developed countries is usually sent across to African nations as a result of the high cost of disposing of these wastes in their nations and due to the less stringent environmental laws and regulations in Africa. As of the year 1988, it cost between USD 100–USD 2000 per ton to dispose of hazardous waste in the Organization for Economic Cooperation and Development (OECD) countries, as compared to USD 2.50 to USD 50 per ton to dispose of this same waste in developing countries [19,20]. About 20–50 million tons of e-waste

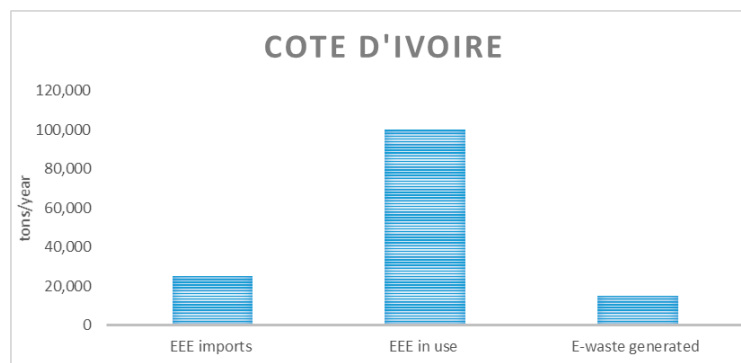
are produced annually, of which most of these are shipped to developing countries, including second hand and inferior e-waste [21]. As a result of these weak regulations, wastes are dumped or incinerated in an unhealthy manner to both humans and the environment [21–23]. To further bolster this point, a study carried out by the Basel Action Network (BAN) in Nigeria revealed that about 500 containers containing approximately 800 monitors and CPUs enter into the country through the Lagos port every month [17,24]. These values indicate that, on average, 400,000 s-hand or scrap computers enter into the country via the Lagos seaport with an estimated weight of about 60,000 MT per annum [24]. In comparison, [25,26] reports that about 1,200,000 tons of electronic materials are imported into Nigeria, with about 6,800,000 tons of electronic equipment being used annually. This study shows that 1,100,000 tons of e-waste is generated in Nigeria, with Ghana following closely, at about 179,000 tons. Figure 2a–e shows the statistics on electronic waste in West African countries, as reported by [25,26].



(a)



(b)



(c)

Figure 2. Cont.



Figure 2. Statistics on electronic waste in West African countries. (a) Ghana, (b) Liberia, (c) Cote d'Ivoire (d) Nigeria (e) Benin. Source: [25,26]

This influx of electronic materials, which is eventually converted to e-waste, is a result of weak legislation on e-waste control in African nations. Studies have shown that there is little legislation in Africa regarding the effective management of electronic waste [27,28]. Reviews by [25,29] have revealed that West Africa has the highest population of people covered by legislation on e-waste at about 53%, with Northern and Southern Africa having no data to show. Figure 3 shows the population of people in Africa covered by the law on e-waste disposal.

In third world countries, sacrifices are often made in the areas of environmental preservation to achieve a short-term economic goal [30]. This is said to be the cause of poverty that several developed nations have exploited. For example, China, for a fee of USD 50 per ton, accepted containers conveying waste materials in the early 1990s [18]. This is not new in the African continent, as there are similar cases, such as the dumping of toxic waste in the Koko fishing village in Nigeria by an Italian firm in 1987 [18,31–35]. In this case, a landowner for a small monthly rent accepted the stacking of toxic radioactive waste by an Italian company on his property [19].

Similarly, a reported contract of about \$600 million was offered to Guinea-Bissau in 1988, to dispose of 15 million tons of toxic waste for five years [36]. Although this contract did not pull through due to public concerns, the contract amount was reported to be roughly four times Guinea-Bissau's gross national product [36]. Other similar activities by developed nations include the storage of nuclear waste in Sudanese desert locations by the Americans and Germans in 1985 [31], the construction and operation of a toxic waste incinerator by a Swiss-based firm in Mozambique in 1992 [31], and the shipping of tons of mercury by the British and Americans into South Africa, thus leading to unacceptable mercury standards (1000–1900 times higher than the World Health Organization standards) [31]. A report by the US National Intelligence Council, as contained in [37], shows that there is a yearly turnover that ranges between 12 to 15 billion Euros in illegal trafficking of hazardous waste. Figure 4 displays the identified and suspected routes of e-waste dumping, as obtained from [38,39].

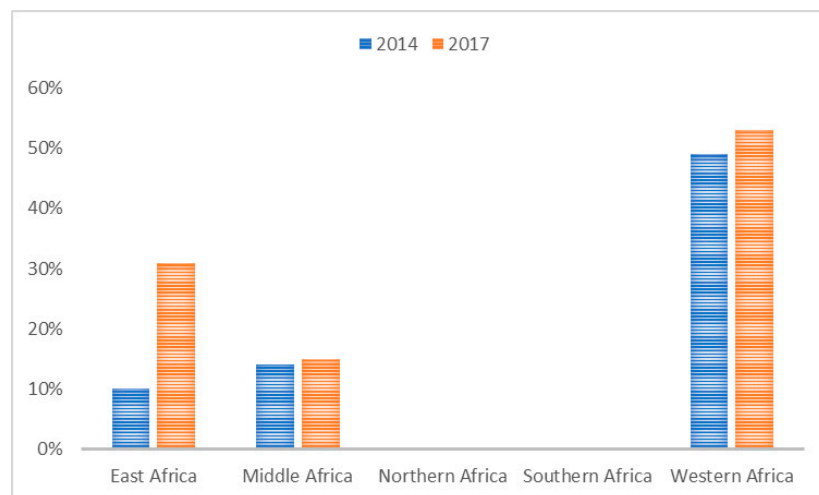


Figure 3. The population of people in Africa covered by legislation on e-waste disposal. Source: [25,29].



Figure 4. Hazardous Waste Illegal Routes. Source: [38,39].

2. Identification and Classification of Hazardous Waste

Hazardous waste can be characterized as waste that can substantially add to an increase in death or an increase in irreversible or debilitating reversible ailment, or represent an ensuing or potential danger to human wellbeing or the Earth when inappropriately treated, moved or discarded [35]. Hazardous waste is waste that has or can have the potential of having properties such as being corrosive, ignitable, flammable, toxic [35], carcinogenic [36], infectious, radioactive [37,38]. According to the United States Environmental Protection Agency (USEPA), solid waste is said to be hazardous when it is explicitly categorized into one of the listed four (4) categories as contained in the code of Federal Regulations (CFR) (F, K, P, and U) [39].

- i. The F list categorizes waste from conventional engineering and industrial processes as hazardous; examples include spent solvent residues, agents used for wood preservation, and others.
- ii. The K list categorizes hazardous wastes from sectors of industry and manufacturing and is source-specific waste. Industries that generate this class of waste are iron and steel production, pesticide manufacturing, wood preservation.
- iii. The P list and U list comprises hazardous waste of pure and marketable grade formulations of certain unused substances that are to be disposed of. Hazardous waste materials can also be classified based on the threat levels they pose. A study by [40] ranked hazardous waste into high-risk wastes, intermediate risk wastes, and low-risk wastes.

- iv. High-risk waste: Materials that contain high concentrations of toxic, mobile bioaccumulative constituents, such as chlorinated solvents and cyanide waste PCB (polychrome biphenyl).
- v. Transitional risk wastes: These wastes contain metal hydroxide sludges.
- vi. Low-risk wastes: Waste that provides a high volume of low hazard waste and some putrescible waste.

Hazardous wastes are not just peculiar to industries and medical facilities, but are also common in households. A study carried out by [41,42] classifies household hazardous waste materials into six classes, as given in Figure 5.

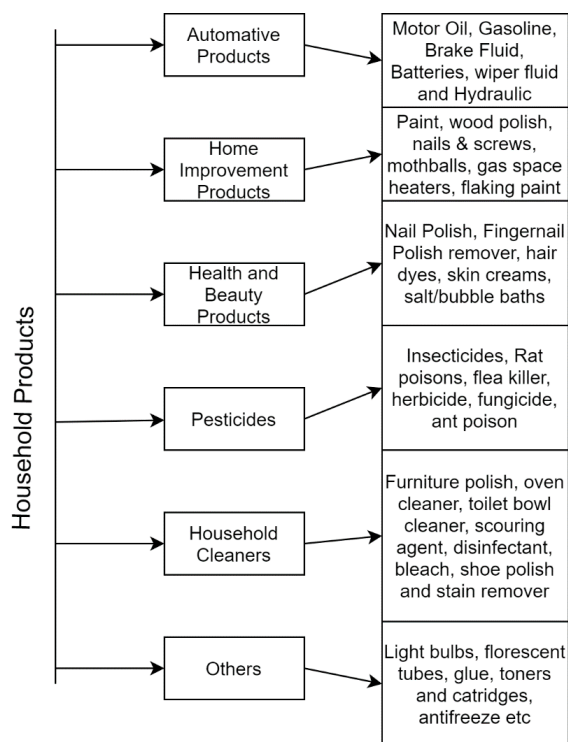


Figure 5. Household Hazardous Waste Materials [41,42].

3. Public Health Concerns

Developed, developing, and underdeveloped nations genuinely understand the threats that this influx and generation of hazardous waste materials could cause. Harmful contaminants that escape into the environment have a high tendency of polluting both water and surrounding air, thus causing significant harm to humans, animals, and the ecosystem [43,44]. Hazardous wastes usually contain toxic chemical substances such as mercury, lead, sulfur, arsenic, and cyanide, which are dangerous both to individuals and the ecosystem. Exposures to these elements, for example, can be seen as a result of mining activities in Zamfara and Plateau states in Nigeria [45]. A report shows that over 400 children were affected by lead contaminations in Zamfara state in 2013. Similarly, lead poisoning has led to the death of about 28 children so far in the Rafin Local Government of the Niger state in Nigeria, due to small scale gold mining in the area [46]. Exposures to lead can lead to an increase in blood pressure, sleep disorders, kidney damage, nerve disorders, amongst others [21]. Similarly, Mercury is known to be a neurotoxin in several forms, which could lead to mental deficits in low exposure levels and severe neurologic effects at extreme levels of exposure [47]. A study carried out by [47,48] on the artisanal mining of gold in Zimbabwe and Tanzania reveals that about 1.46 g of Mercury (Hg) is lost to the environment for every gram of gold mined, of which 70–80% of these goes to the atmosphere. Several other studies have shown that women and children are the most vulnerable due to their engagements in gold mining activities in Africa [47]. The mining and sale of gold have been described

as all-women activities in Gaoua, Burkina Faso [47,49]. The proportion of these artisanal miners, which comprises women and infants, can range from as low as 5% in South Africa to 50% in Mali (i.e., $n = 500$ to $n > 100,000$) [49]. Another study by [50] on 248 patients in Malaysia revealed some high levels of toxicity due to exposures to arsenic-contaminated water [51]. Other manifestations ranged from burning eye sensations, leg swelling, liver fibrosis, chronic lung disease to skin cancer [52].

Furthermore, research has shown that the improper treatment and disposal of medical waste, for example, could expose humans to potentially harmful microorganisms [53]. The World Health Organization (WHO) in a report revealed that, as of the year 2010, unsafe injections accounted for about 33,800 new HIV infections, 1.7 million hepatitis B infections, and 315,000 hepatitis C infections [54,55]. A research study conducted in Egypt showed that the lack of written policies and protocols in the country has led to deficiencies in the processing of hazardous biomedical waste in hospitals and primary health care facilities [56]. Hazardous waste requires a high level of monitoring and management, as humans interact with them every day. An action as simple as burning hazardous waste is reported to release dioxins, which are said to be one of the most toxic chemicals known [57–59]. Hazardous waste management is extremely critical for a healthy environment. There are reportedly increased risk of cancer mortality in US counties containing dangerous waste dumpsites [60,61]. This is similar to research conducted in Europe by [62], which shows that there is a raised risk of congenital abnormality in newborn babies whose mothers reside close to sites that handle hazardous waste materials.

Figure 6 gives a summary of some hazardous materials and the potential health threats they pose when humans and other living organisms are exposed to them [38].

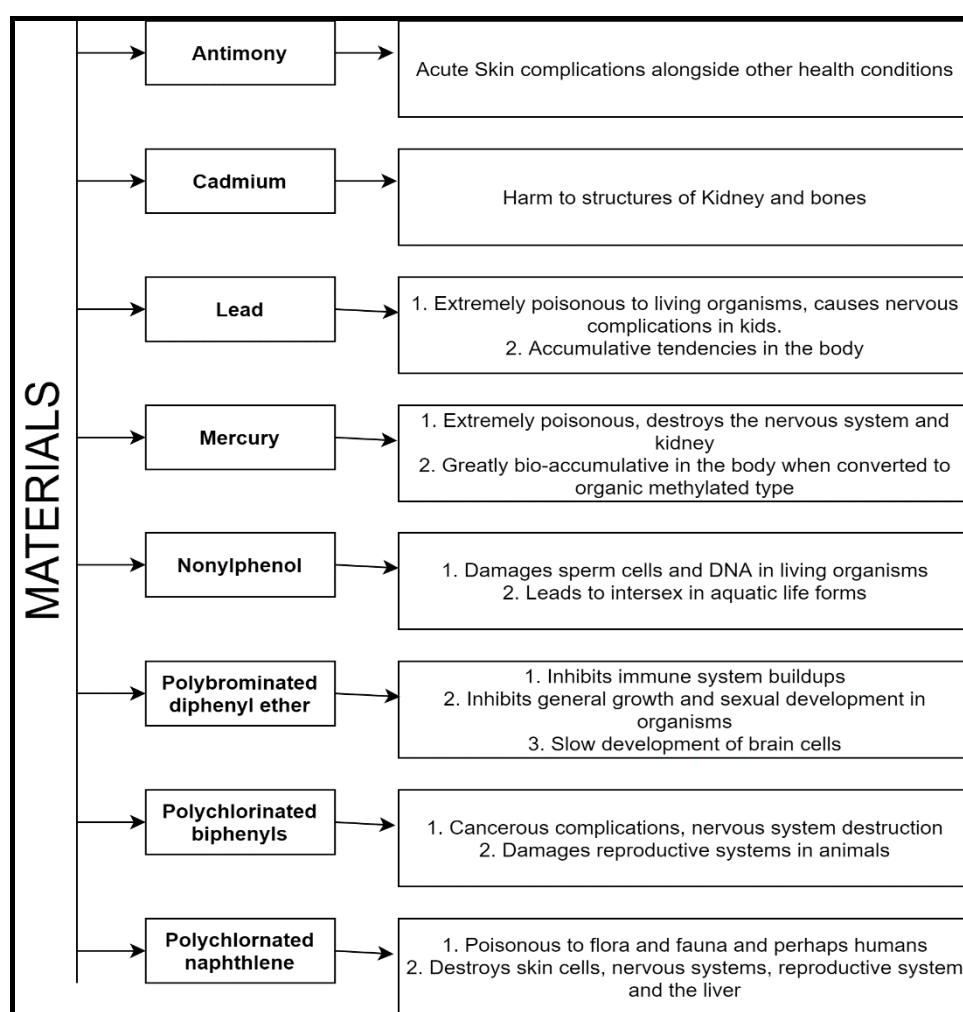


Figure 6. Materials and health threats. Source: [38].

4. Management and Control of Hazardous Waste in Africa

The management and control of toxic, hazardous waste should be of the utmost priority to any nation, to foster a healthy living amongst its citizens and, in the long run, enhance environmental sustainability. In most developing countries such as Nigeria, a well-recognized system for the separation, storage, collection, transportation, and disposal of hazardous waste materials has been highly neglected [63]. In Nigeria, quite a few regulations concerning waste management include the Environmental Impact Assessment Act, 1992; the National Environmental Standards and Regulations Enforcement Agency Act, 2007; and the Harmful Waste Act, 1988 [42,64]. The Harmful Waste Act of 1988 in Nigeria outlaws the trade and generation of toxic, lethal, and potentially harmful substances [42,64].

Furthermore, no legislations are guiding the effective handling of e-waste, thus leading to an overall complacency in waste and its management generally [24]. The situation has deteriorated further as a result of governments' complacency towards the trans-boundary movement of electronic waste materials into the nation and the regular sub-standard recycling activities. Governments and administrators in many unindustrialized countries seem to be uninvolved in the material flow and ecological repercussions of e-waste importations into their different nations [24,65]. This has led to the low-level management of e-waste in Nigeria, such as open dumps, backyard recycling, and ocean dumping [24,66]. Inadequate financing and the lack of a unified structure on the subject of the monitoring and control of toxic, hazardous waste have also caused significant weaknesses to the efficient management of these waste materials [24]. This situation has led to slow growth and development in technologies to curb these toxic waste materials.

Nigeria and several other nations in the African continent have been plagued with a low level of awareness when it comes to hazardous waste management. A study carried out by [42] amongst students of tertiary institutions revealed that the majority of people within the Sub-Saharan regions of Africa do not read the labels on purchased products, which gives details on the efficient management of these products. Their study targeted an age group of people between 15–40 years in Nigeria, South Africa, and Kenya. The study revealed that the participants in Nigeria had the highest level of awareness on household hazardous waste materials at a 69% level of consciousness, followed closely by South Africa at 68%, and the least was reported in Kenya, which only had a level of awareness of 36%. In the area of management, 62% of participants in South Africa were able to manage their HHW. In comparison, 48% of participants in Nigeria could do the same, and 32% of the participants from Kenya could achieve their HHW. Figures 7 and 8 give the charts for the level of awareness and management knowledge and ability, as contained in [42].

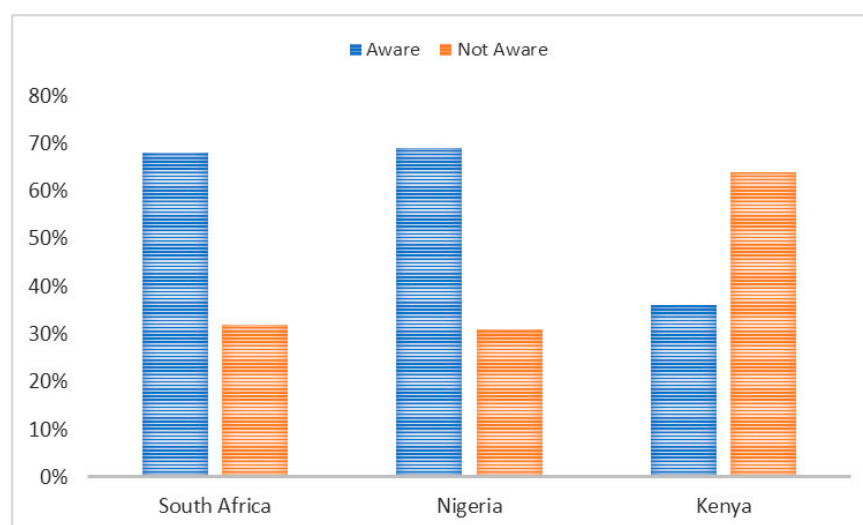


Figure 7. Level of Awareness among participants. Source: [42].

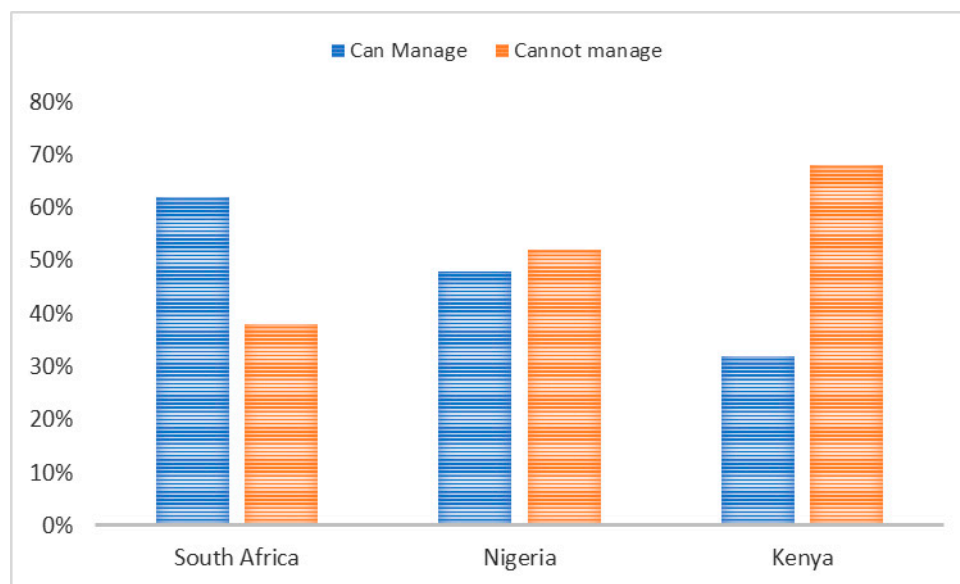


Figure 8. Ability to manage household hazardous waste (HHW). Source: [42].

Furthermore, a comprehensive study was carried out by the United Nations Economic and Social Council on four African countries, namely Ghana, Egypt, Kenya, and the Zambia [67]. The report investigates the management practices of waste materials and hazardous waste materials within those countries. The selected nations cut across the different regions of Africa. The findings from this study are summarized in Table 2.

Table 2. Summary of Hazardous Waste Management Practices from Select Countries in Africa.

Country	Situation and Challenges	Management Schemes and Bodies	National Regulatory Laws	Notable Achievements	Source
Egypt (North Africa)	An annual environmental deterioration of about \$10–\$19 billion due to improper waste disposal 6–6.5 million tons with hazardous potentials	Ministry of State for Environmental Affairs Egyptian Environmental Affairs Agency (EEAA)	Law 4/1994	Been able to develop a standard legal framework for the management of Hazardous waste materials but will still require consistent enforcement methods	[67,68]
Ghana (West Africa)	Bio-medical waste is managed via landfills. Heightened e-waste control and management challenges as e wastes show recycling difficulties	Environmental Protection Agency	Local Government Act (1994) Environmental Protection Agency Act (1994) Pesticides Control and Management Act (1996) Environmental Sanitation Policy of Ghana (1999) Guidelines for Bio-medical waste (2000)	The life cycle approach helps to manage hazardous waste in an integrated manner.	[67]
Kenya (East Africa)	No national statistics on hazardous waste materials generated. Approximately 909,182 tons/year of healthcare waste is generated, with about 75% declared as infectious. Incineration is the most common practice for hazardous waste with some toxic waste finding its way to dumpsites	National Environmental Management Authority (NEMA)	Local Government Act cap 265 Public Health Act Cap 242	Cities such as Nairobi and Kisumu with the backing of UNEP and Un-Habitat are developing their unique Integrated Solid Waste Management Schemes	[67,69]
Zambia (South Africa)	Nonregistered dumpsites have led to a spike in illegal and indiscriminate disposal of waste materials within the country	The Environmental Council of Zambia (ECZ) Radiation Protection Authority	Environmental Protection and Pollution Control Act of 1990		[67,70]

From Table 2, African countries have been able to develop some legal frameworks for the control of hazardous waste substances, although challenges, especially in the areas of enforcement and overlapping objectives, persist [67].

Furthermore, African nations are signatories to treaties, such as the Basel Convention and the Stockholm Convention on Persistent Organic Pollutants. These treaties give general guidelines on the handling of hazardous waste disposal and the transboundary movement of hazardous waste [71,72]. As a result, African regulations on the processing of hazardous waste are modeled to correspond to international standards. Further down in 1998, the Bamako convention came into force to bridge the gap of the Basel convention within Africa, with about 27 parties [73]. The Bamako convention prohibits the importation of hazardous waste into Africa, prohibits the incineration of hazardous waste materials, and gives provision for the efficient management of hazardous waste within the African continent [73]. This shows that a lot of African countries possess adequate laws and regulations on the handling of hazardous waste, but are limited due to several factors, such as lack of data, financial instability, lack of waste management infrastructure, lower recycling rates, and weak law enforcement [74–77].

Developed communities have been able to tackle their hazardous waste management issues more efficiently due to the availability of adequate data and infrastructure to manage these waste materials. For example, [78] reports that there are about 155 installations for hazardous waste treatment in about 11 European countries. These hazardous waste management installations have been able to reduce CO₂ emissions by about 4 million tons/year, achieve a high degree of material recovery, and are responsible for over 630,000 MWh in energy recovery [78]. Furthermore, seven (7) European countries have been able to close the gap between the hazardous waste generated and treated within their borders. These seven countries are reported to have a gap of less than 20% on hazardous waste generated and treated [79].

Table 3 gives a summary of seven European countries with close to optimal hazardous waste management, as reported by [79]

Table 3. Hazardous Waste Generated and Treated in selected European countries. Source: [79].

S/n	Country	Generation Tons/2015	Treatment Tons/2015	Export Tons/2015	Import Tons/2015	Difference (Gen-Exp + Imp)-Trt. Tons/2015	Gap %/2015
1	Bulgaria	13,407,042	13,389,620	2083	30,039	45,378	0%
2	Cyprus	31,288	24,201	4997	0	2090	8%
3	Germany	21,983,895	21,098,397	334,327	3,077,329	3,628,500	15%
4	Estonia	9,159,139	9,131,275	3331	17,957	42,490	0%
5	Finland	1,653,942	1,411,308	95,455	20,459	167,638	11%
6	Netherlands	4,859,942	4,456,188	788,476	870,338	485,616	10%
7	Poland	1,737,024	1,434,985	13,373	78,112	366,778	20%

The highlighted European countries in Table 3 show an impressive gap between hazardous waste generated and that treated within their borders. A country like Germany is still able to handle over 3 million imported hazardous waste materials with an impressive gap of 15% [79]. This is not the case throughout Europe as countries like Luxemburg, Malta, and Ireland have generation to treatment gaps of over 95% [79]. On the European level, the average gap is about 28% (29 million tons), up from 26% in 2012 (26 million tons) [79].

In North America, the United States has developed a highly sophisticated guideline on the management and handling of hazardous waste materials. These laws and guidelines are contained in [80]. Globally, the hazardous waste service industry is seen as a profitable source of revenue for countries. The United States has specifically created the largest market for hazardous waste at over 34%, thus accounting for over \$45 billion in revenue [81]. This proves that, if professionally managed, hazardous waste could potentially become a source of revenue for developing nations. Table 4 gives a summary of hazardous waste revenue generated in the United States, as reported by [82].

Table 4. Revenue for Hazardous Waste in the United States. Source: [83].

Revenue in Million Dollars				
Year	Revenue of Hazardous Waste Collection	Revenue of Hazardous Waste Treatment and Disposal	Year	Revenue of Hazardous Waste Management Industry
2008	2.016	5.85		
2009	1.89	5.697	2000	3.155
2010	2.096	6.221	2005	4.532
2011	2.04	6.57	2010	6.221
2012	2.249	6.698	2011	6.569
2013	2.618	6.491	2012	6.698
2014	2.899	8.019	2013	6.491
2015	3.225	7.915	2014	8.019
2016	3.471	8.121	2015	7.915
2017	3.68	8.285	2016	8.536
2018	3.844	8.408	2017	9.106
2019	3.973	8.503	2018	8.925
2020	4.076	8.579		

From Table 4, the revenue derived from hazardous waste management in the United States was about \$9 billion in 2018. This signifies a 182.88% increase in revenue from the year 2000.

In India, hazardous waste management possesses similarities to what is attainable in many African countries. The informal sector is responsible for the management of most of India's waste including hazardous waste, thus leading to inconsistency in India's hazardous waste management data [84]. Although India possesses some stringent rules on hazardous waste management, such as huge fines and imprisonment for negligence, the country still suffers from poor enforcement, lack of data, and inadequate infrastructure [85]. Furthermore, [85] reports a significant shortage in hazardous waste treatment facilities in India. India is said to have about 220 recycling facilities, 88 incinerators for hazardous waste, and two engineered landfills. However, this is not enough, as 70% of India's hazardous waste does not receive any form of treatment [84,85].

Developed society has embraced some hazardous waste management strategies, which could serve as recommendations for the developing community. A study carried out by [86] suggested the following:

- i. Establishment of public enlightenment on the potentials of hazardous materials recycling.
- ii. Source reduction from the point of generation
- iii. Development of human capacity on effective recycling technologies.
- iv. Assessment and evaluation of management schemes alongside reporting platforms.
- v. Improvement of suitable structure, practical awareness, and know-how.
- vi. Solidification and restructuring of current regulatory structures.
- vii. The endowment of finance for the development of modern infrastructure to curb these hazards.
- viii. Provincial hazardous waste control systems.

Besides, the gaps identified in hazardous waste management within the continent of Africa can be bridged by following a systematic approach, as suggested in Figure 9. This approach, coined from several studies, would aid in the sustainable management of all sorts of hazardous waste products and solid waste in general [67,87,88]. From Figure 9, African nations need to develop a sophisticated legal framework for the management of hazardous wastes and on the transboundary movement of hazardous waste materials from one country to the other. Strict enforcement methods must be put in place to tackle defaulters and noncompliant industries or institutions regarding hazardous waste management. Secondly, national governments would have to identify relevant stakeholders and properly coordinate their practices. This stakeholder participation would include private sector coordination and other international NGOs.

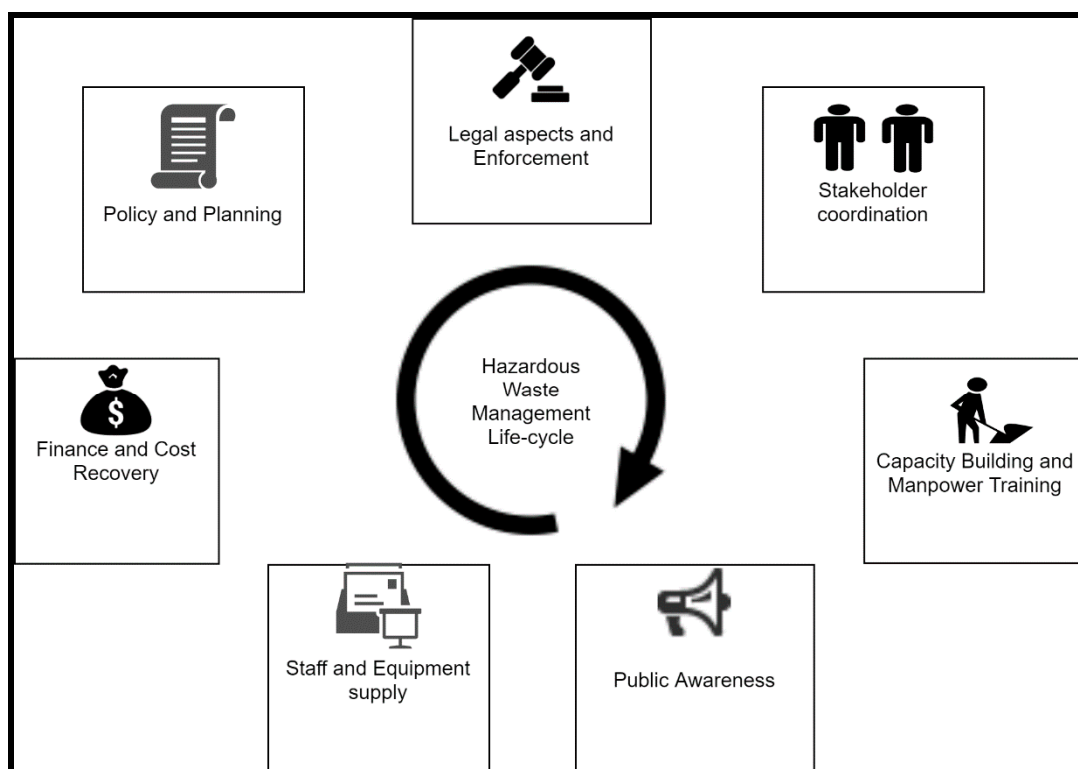


Figure 9. Hazardous Waste Lifecycle. Source: [67,87,88].

Additionally, communities must be given public awareness of identifying hazardous waste materials or products and given adequate training on how to handle toxic substances. Lastly, finance or capital must be injected into the management of hazardous waste materials, such as transportation, disposal, recycling, or reuse processes. These will ensure that profits are being recovered from huge hazardous waste management investments. Moreover, African institutions and their global partners must ensure that hazardous waste management schemes are sustainable for the African continent, and not just a direct copy and paste from the worldwide community. This approach can quickly be adopted by any developed or developing nation, with emphasis given to the most significant shortcomings of each country. The situation in country A will be peculiar to that country and will require tweaking these management strategies to suit the nation optimally.

5. Hazardous Waste Models and Process Flow

Several studies have been done on hazardous waste management, and models have been arrived at. Notably, [88] explains hazardous waste management as a carefully organized system that hazardous waste materials pass through up to their final disposal. Moreover, [87] developed a similar but more sophisticated model. In their study, a hierarchy of waste management was employed with a greater emphasis on source reduction, which would involve processes such as the design of new products, product changes, and source elimination. Furthermore, [40], in a study on hazardous waste management, suggests that it is of the utmost importance to consider how system components interact with one another to attain a dangerous optimum waste management scheme. For example, it would be more efficient to opt for a treatment option which generates less residue, such as incineration, in the case where there are limited landfill capacities [40]. Other methods, such as chemical fixation, might pose fewer threats to the environment when compared to incineration, but have a higher residue generation [40,89]. Furthermore, a mixed-integer programming model was developed by [90] for the location-routing of industrial hazardous waste materials. This model is tasked with the objective of total cost minimization and transportation risk minimization. The model developed by [90] can enable

decision-makers to quickly identify waste treatment, recycling, and disposal facilities, thus giving waste routes between these facilities at optimal costs. A similar location-routing model was developed by [91], to identify where best treatment facilities can be situated, where disposal facilities can be sited, and how to find the best facility for a selected type of identified hazardous waste material.

More routing models were developed by [92,93]. Another study carried out by [94] utilizes data such as spatial data, laws, extensive socioeconomic, and environmental data to design a multi-criteria analysis technique. These data, coupled with the capabilities of GIS, aids the system to identify the best disposal sites for hazardous waste materials [94]. There is a similar approach being developed in Iran, as defined in a study carried out by [95]. A model that investigates the general profitability of an entire hazardous waste management system was developed by [96]. This model is a polluter pay system, which tries to locate hazardous waste generation centers and processes the extent to which the polluter would be involved in the waste management processes [96]. For the prediction of healthcare and medical waste generation, an optimized artificial neural network model was developed by [97]. Figure 10 gives a simple process flow for hazardous waste management, that could be utilized by developing African communities.

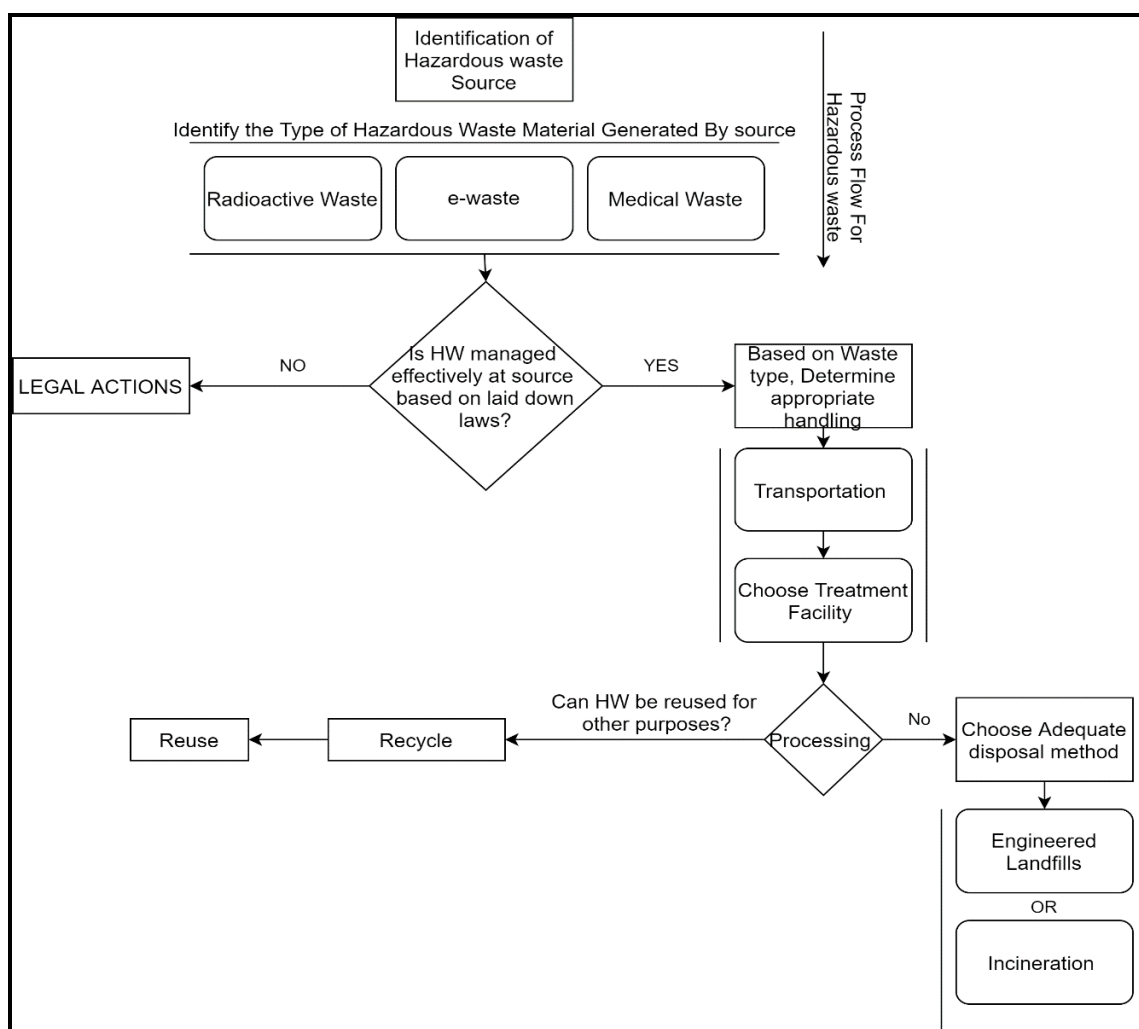


Figure 10. Hazardous Waste Management Process Flow.

In summary, the first step will be to identify the source from where the hazardous waste material is being generated. This will involve determining the type of industry and nature (e-waste, radioactive waste, or medical waste) of hazardous waste produced. The municipalities will further

rate the source handling of these hazardous waste materials if it meets regulations. This will enable the city to determine the best sanctions it can place on the waste generator.

With source handling meeting regulations, the next step will be to locate appropriate treatment facilities based on the type of waste generated, and then transporting or hauling these wastes to the points of processing. This transportation of hazardous waste materials might involve the transboundary movement of hazardous waste materials, and thus must follow national guidelines. Processing options might require recycling if the waste material can be reused, or landfill operations using engineered landfills or incineration.

The model developed by [91] has been utilized in Turkey and it shows great potential for African countries if professionally integrated. The model will help reduce expenses in the overall management of hazardous waste, which will be an optimal solution for Africa. The model finds solutions to problems, such as the best location for treatment facilities, the best technologies to be adopted for the treatment of hazardous waste, where disposal facilities can be located, and routing hazardous waste from the source of generation to disposal, thus effectively reducing the cost while efficiency is increased [91]. The model suitable for African countries must revolve around cost-effectiveness, environmental sustainability, job creation, and community empowerment, based on the peculiarities of each African country. This is shown in Figure 11. Huge hazardous waste investments might not be necessary for Africa, given the present economic situation of the continent. This implies that models must be able to determine the best management outcomes with the poor economic situation of Africa.

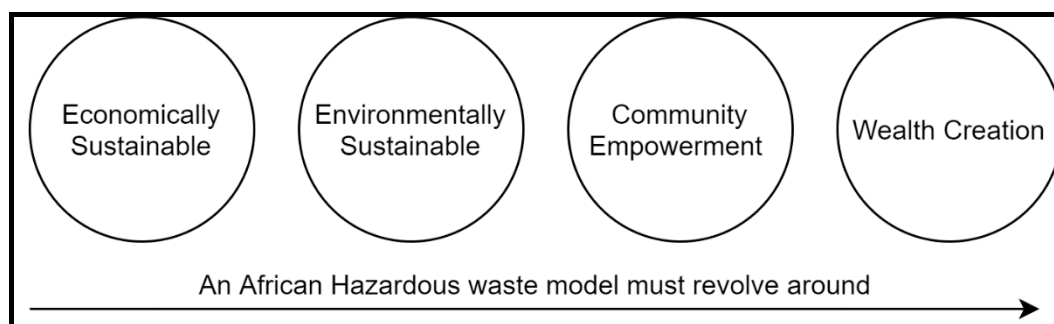


Figure 11. Critical issues that an African hazardous waste management model must tackle.

6. Some Critical Processes and Operations

6.1. Landfill Operations

Landfilling is said to be an easy and cheap method of waste disposal. Landfill, when not managed properly, can deteriorate into open dumps [98,99]. According to [40], landfills may be classified into common, approved, and secured landfills, respectively. Secured landfills that are designed explicitly for waste with hazardous contaminants are further classified into open dumps, control landfills, and closed landfills with control and closed landfills absorbing weakly toxic and highly toxic substances, respectively [40]. The lack of engineered landfills could lead to devastating effects on the environment, because a lot of toxic waste materials will end up finding its way to the environment [100]. According to [101], the major shortcoming of this method in Africa begins with sorting at the point of generation. As a result, hazardous waste materials are easily found in African landfills, which has led to groundwater contamination in some cases [101]. Furthermore, African landfills have significant shortcomings in handling hazardous waste, with ratings from low hazard to hazard being dumped in non-engineered landfills [102].

Table 5 gives a summary of landfills in Africa and their classification, based on the level of compliance with international regulations.

Table 5. A review of landfills in Africa and their ranking, based on the level of agreement to international rules [101–103].

S/N	Level of Landfill Control	Rating	Landfills	Characteristics
1	No level of control	0	<ul style="list-style-type: none"> • Mbellewa (Cameroon) • Antula (Guinea Bissau), • Igbatoro (Nigeria) • Awotan (Nigeria) • Lapite (Nigeria), • Eneka (Nigeria), • Ajankanga (Nigeria), • Aba-Eku (Nigeria), • Unguwan (Nigeria), • Wakaliga (Uganda), • Bakoteh (Gambia), • Kadhodeki (Kenya), • Gachororo (Kenya), • Koshe (Ethiopia) 	Controlled Functions are limited, No leachate collection system, Open dumping, and uncontrolled burning. NB: Not capable of Handling Hazardous Waste
2	Semi-controlled Landfill	5	<ul style="list-style-type: none"> • Solous (Nigeria) • Musaka (Cameroon) • Mpape (Nigeria) • Epe (Nigeria) • Kiteezi (Uganda) • Granville (Sierra Leone) • Kingtom (Sierra Leone) • Garankuwa (South Africa) • Nduba (Rwanda) • Hatherley (South Africa) • Vingunguti (Tanzania) 	Absence of leachate collection facilities, unsorted waste materials NB: Not capable of Handling Hazardous Waste
3	Medium or Controlled Landfill	10	<ul style="list-style-type: none"> • Olusosun (Nigeria) • Dompooase (Ghana) 	A degree of the trained workforce who follow a set of instructions in daily operations, Facilities are available to capture particulates; equipment may be managed appropriately. NB: Not capable of Handling Hazardous Waste
4	Engineered Landfill (Medium to High)	15	<ul style="list-style-type: none"> • Coastal Park (South Africa) • Bellville South (South Africa) • Robinson Deep (South Africa), • Gamodubu (Botswana) 	A high level of planning is taken in the location, daily operation, and emission control. Daily cover materials are utilized, leachate collection systems are available to a certain degree, and method for gas collection is put in place. NB: Capable of Handling Hazardous Waste
5	State of the art Landfill (Highly Controlled)	20	N/A	These are state of the art facilities, and they operate in compliance with international regulations and standards. Efficient Hazardous waste management potential, leachate, and gas harnessing are sustainable; plans are put in place for post-closure. NB: Capable of Handling Hazardous Waste

From Table 5, most identified landfills in Africa fall within the zero-rating level, which signifies a no level of control or supervision of disposal into these dumps [103]. These landfills can be categorized as open dumps and cannot handle hazardous waste materials. For example, the Lapite landfill in Oyo state Nigeria has no form of leachate collection, cover materials, with studies showing groundwater contamination as a result of toxic substances from unsorted waste. There is also a high presence of Zn and Mn; levels which are unacceptable according to WHO and the Nigerian environmental regulatory body NESREA [101,104]. Similarly, in Port Harcourt Nigeria, the Eneka landfill shows a higher degree of groundwater contamination, due to higher levels of rainfall in the area. It could require quick rehabilitation to protect public health [105].

Furthermore, the semi-controlled landfills in Africa show similar characteristics to landfills, without any level of control. These types of landfills may possess some equipment or unskilled staff force who oversee the daily operation of the landfill [103]. For example, the Solous landfill in Lagos handles over 820,000 tons of municipal solid waste, with occasional compaction and staff put in place [101]. This landfill lacks a leachate collection system, and thus frequent groundwater pollution is recorded [106]. This is similar to the Granville Brooke and Garankuwa landfills in Sierra Leone and South Africa, respectively [101,107].

Medium or controlled landfills in Africa, such as the Olusosun and Dompase in Lagos Nigeria and Kumasi Ghana, do conform to some international regulations and possess an adequate leachate collection system. Nevertheless, they still fall short in areas of proper monitoring and the control of waste that is being disposed of. If well-coordinated, a controlled landfill could be able to handle some hazardous waste [101,108].

Studies have shown that only South Africa and Botswana can boast of engineered landfills in Africa, as shown in Table 5. These landfills can handle some hazardous waste materials if sorted adequately, due to their efficient liner and leachate collection system with groundwater monitoring facilities. For example, the Robinson deep in South Africa is equipped with a bentonite modified coating that protects groundwater from leachate infiltration. The Bellville south and Coastal Park in South Africa both possess groundwater monitoring systems [109,110].

Governments and investors should pay more attention to developing engineered landfills and state of the Art facilities for waste management, with the high consideration of hazardous waste management. This will help protect public health among its citizens.

6.2. Recycling

Another management technique is the recycling of hazardous waste materials. Most waste has become regarded as having typical value and could be recovered and reused for valuable goods [28]. This involves the reprocessing of hazardous waste materials as raw materials for technical procedures or a substitute for a marketable product, which in turn is economically optimal and advantageous to public health [87]. Recycling could have potential positives to a nation's economy. For example, studies have shown that recycling 10 kg of aluminum not only provides a 90% energy saving, but also averts the formation of 13 kg of bauxite residue, 20 kg of CO₂ gas, and 0.11 kg of SO₂ gas [38,111]. Likewise, recycling iron and steel offers 74% of energy saving, a 86% decrease in air pollution, 40% decrease in water use, 76% in decline in water contamination, 97% decrease in mining wastes, and a 90% saving in virgin materials use [38,112]. Notably, [111] reports that, for every 10,000 tons of materials disposed of annually, computer reuse creates 296 more jobs.

Resources obtained from the United Nations Statistics Division show some data on hazardous waste materials that have been landfilled, recycled, and incinerated. These statistics, as depicted in Table 6, represent data collected from national statistical offices and ministries of the environment of the choice nations.

Table 6. Summary of Hazardous Waste Landfilled, Recycled, and Incinerated in Some Selected African Countries [2].

Country	Hazardous Waste Landfilled (Tons)	Hazardous Waste Recycled (Tons)	Hazardous Waste Incinerated (Tons)
Benin	0	0	1698
Cameroon	47,316	1788	2686
Madagascar	33,812	0	12,145
Mauritius	0	4194	14,460
Morocco	58,810	55,144	0
Niger	1,057,000	0	0
Nigeria	0	0	0
Reunion	1614	4938	1698
South Africa	38,445,876	10,589,308	4,184,581
Tanzania	0	12	389
Tunisia	0	40,000	0
Zambia	0	35,000	0
Zimbabwe	0	0	181

The data cover the period 1990–2015. Only African nations were selected for this analysis, with a notable exemption of Nigeria, whose information is not currently available on the United Nations Statistics Division portal. Results from South Africa over the 25 years were the most impressive of all African countries represented. Hazardous waste landfilled in South Africa over this time frame was about 38,445,876 tons, with Niger following at about 1,057,000 tons. In the case of recycling, South Africa reportedly recycled about 10,589,308 tons of hazardous waste, with Morocco following far behind at about 55,144 tons. Lastly, for incineration, South Africa had reportedly 4,184,581 tons and Mauritius followed at 14,460 tons.

7. Conclusions and Recommendation

The management of hazardous waste materials is highly crucial to the sustenance of an environment and preservation of sound health practices amongst humans. Developed and developing countries have a significant role to play in hazardous waste management. These roles will range from sound regulatory practices by government institutions to technological advancements in the areas of recycling and reuse, energy recovery, and much more. Responsibilities could be placed on the producers of hazardous waste such as paints and toxic chemicals, on the post monitoring of their products after it leaves their shelves. Similarly, a national recall program can be put in place to recall all unused drugs, electronic wastes, and many other expired products to foster proper management [86]. Furthermore, an emphasis should be placed on data collection and storage on the present nature of waste in African countries, as African countries suffer from data needs.

The involvement of all stakeholders, such as producers, managers, decision-makers, waste processors, and the formal and informal sectors at large, will go a long way in the development of a suitable and sustainable waste management plan. Table 7 gives a summary of the challenges faced by most African Nations in hazardous waste management and a possible way forward for decision-makers.

Hazardous waste management, although challenging in Africa, can be tackled with effective measures considering the peculiar nature of each African country, and not just a copy and paste approach. Wealth creation must be at the center of the African hazardous waste management industry, to maximize economic benefits.

Table 7. Challenges and solutions for decision making [113–115].

Challenge	Solution
1. Lack of Data	i. Comprehensive Inventory of Waste Generators by Govt. Agencies ii. Tracking and monitoring at the community level. Helps identify informal sectors iii. Inventory at national borders on all potentially harmful products and destination of the product.
2. Little or no Infrastructure	i. Collaboration with international experts, researchers on the development of safe handling and treatment facilities maximizing local workforce and technology ii. Emphasis should be placed on Reduce, Recycle, and Reuse (3R's)
3. Poverty	i. Collaboration with NGOs and international organizations to help tackle waste management thus reducing the pressure on governments. ii. Emphasis must be placed on economic returns like in the USA thus creating a lucrative market for hazardous waste management. iii. Local institutions and individuals must go through formal training on hazardous waste management thus creating a labor force competent on managing HW
4. Lack of Awareness	i. Capacity building for locals ii. Campaigns and ads on hazardous waste management at the household level
5. Poor enforcement of laws	i. Strengthening of existing hazardous waste management laws ii. Overlapping objectives must be solved by merging two similar agencies in a nation. iii. Tracking should be done at the community level iv. Tough punishments to offenders and illegal traders of hazardous waste.

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Abbreviations

BAN	Basel Action Network
CFR	Code of Federal Regulations
CO ₂	Carbon dioxide
E-waste	Electronic waste
EEAA	Egyptian Environmental Affairs Agency
ECZ	The Environmental Council of Zambia
EPA	Environmental Protection Agency
HW	Hazardous Waste
HHW	Household Hazardous Waste
HIV	Human Immunodeficiency Virus
Hg	Mercury
IHW	Industrial Hazardous Waste
Mn	Manganese

MT	Metric tons
NEMA	National Environmental Management Authority
NESREA	National Environmental Standards and Regulations Enforcement Agency
NGO	Non-Governmental Organization
OECD	Organization for Economic Cooperation and Development
PC	Personal computer
PCB	Polychrome biphenyl
SO ₂	Sulfur dioxide
UNEP	United Nations Environmental Protection
USEPA	United States Environmental Protection Agency
WHO	World Health Organization
Zn	Zinc

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