Dissertation Thesis

Litter from post-consumer EEE and plastic products, and their impacts on the environment in Africa

carried out for the purpose of obtaining the degree of Doctor technicae (Dr. techn.), submitted at TU Wien, Faculty of Mechanical and Industrial Engineering

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I confirm, that going to press of this thesis needs the confirmation of the examination committee.

Affidavit

I declare in lieu of oath, that I wrote this thesis and performed the associated research myself, using only literature cited in this volume. If text passages from sources are used literally, they are marked as such.

I confirm that this work is original and has not been submitted elsewhere for any examination, nor is it currently under consideration for a thesis elsewhere.

Vienna, 26th March 2025

City and Date

Signature

Acknowledgements

I would like to express my sincerest gratitude to the Structural Polymers Group, the whole Super Group is acknowledged for their friendship and support in many difficult ways.

I would like to especially thank my thesis adviser Prof. Dr. Vasiliki-Maria Archodoulaki for her guidance, help, and constant support during the whole research work "Litter from post-consumer EEE and plastics products, and their impacts on the environment in Africa".

Great thanks go to Prof. Dr. Johann Fellner and Prof. Dr. Edwin Mbinkar Nyuysever for reviewing my doctoral thesis.

Special thanks to my wife Laurence Nguiakam and the children Ariel-Philip, Emmanuelle, Arthur Emile, Gerard Nathan, and Hortense. Without their unlimited and unconditional support, I would not be in the joy I am in now. My thanks also go to my sister Mag. Pharm. Augustine Massa. She was always there for me and contributed to raising and strengthening my inner self-confidence during my thesis.

Our thanks also go to members of the Institute of Materials Science and Technology who gave me their support at all times. THANK YOU to everyone! I also want to thank my parents, who taught me what is important in life, and all my friends and study colleagues for the beautiful time.

(*"A winner is a dreamer who never gives up."* Nelson Mandela)

SECTION I

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English Abstract

Littering is an old problem that has plagued mankind for a long time. As long as the waste was organic and biodegradable, there was no concern for living beings and the environment. Unfortunately, with the increased consumption of various products, e-waste and plastic waste have increased significantly and have become a serious threat to humans, animals, and the ecosystem due to the toxic substances they contain. Africa is the region in the world with the lowest estimated generation rate of this waste. In 2019, Africa generated an average of 2.5 kg of waste electrical and electronic equipment (WEEE) and 16 kg of plastic waste per capita, compared to 7.3 kg of WEEE and 50 kg of plastic waste globally in 2019 and 2021 respectively (and rising). The world population was estimated at 8 billion people in 2021 and around 400 million tons of plastic were produced that year. This is equivalent to the 50kg per capita worldwide mentioned above.

Waste management from obsolete products at the end of their life has become a challenge for developing countries, while developed countries are increasingly seeking and finding solutions to their waste. However, the mismanagement of this waste, its accumulation, and the exponential population growth over the years have made the problem more worrying and require a sustainable solution. African countries lack the financial resources and appropriate technology to tackle the problem.

This thesis presents the problem and proposes possible solutions for Africa based on the 'circular economy' idea. The materials contained in electrical and electronic equipment and plastic products have a value that needs to be recovered through state-of-the-art waste recycling in a context adapted to local realities. This requires the establishment of an effective, well-structured waste collection system for a recycling strategy (material recovery) to prolong the life of materials and avoid or significantly reduce the use of virgin raw materials, thus contributing to the conservation of resources, the fight against climate change and the creation of a healthy environment.

Deutsche Kurzfassung

Die weltweite Zunahme an Elektroschrott und Plastikmüll ist zu einem Problem für Mensch, Flora und Fauna sowie für die Umwelt geworden. Dieser Teil des Littering-Problems wird mit einem kontinuierlichen Wachstum vom elektrischen bzw. elektronischen sowie vom Kunststoffmüll immer größer und akuter. In Afrika werden viele organische und biologische abbaubare Abfälle produzieren, aber der Kontinent erlebt auch wie alle Teile dieser Welt ein Wachstum von Elektro- und Plastikabfälle. Der afrikanische Kontinent ist die Region der Welt mit der geringeren geschätzten Erzeugung solcher Abfälle. In 2019, wurde in Afrika im Schnitt 2,5 kg Elektro- und 16 kg Kunststoff-Abfälle pro Person erzeugt, während Weltweit lag es im Schnitt und pro Person auf rund 7,3 kg Elektro- bzw. 50 kg Kunststoff-Abfälle in 2019 bzw. 2021 (Tendenz steigend). Bei einer geschätzten Weltbevölkerung von 8 Milliarden Menschen im Jahr 2021, ca. 400 Millionen Tonnen Kunststoffe wurden im selben Jahr produziert. Dies entspricht den oben genannten 50 kg pro Kopf.

In Afrika, neben der Anhäufung dieser Abfälle und einem exponentiellen Bevölkerungswachstum macht das Fehlen einer nachhaltigen Managementstrategie diesen Abfällen, die Bedrohung noch ernster und die Suche nach einer Lösung immer notwendiger. Die Entsorgung von Abfällen aus veralteten Produkten, die giftige Substanzen enthalten und die das Ende ihrer Lebensdauer erreicht haben, ist eine große Herausforderung für Entwicklungsländer -wie die meisten afrikanischen Länder- geworden, während sich Industrieländer mit einem hohen Forschungsniveau dabei sind ständig verbesserten Lösungen für das Problem zu suchen und zu finden. Afrikanischen Ländern fehlt es sowohl an Geldmitteln als auch an geeigneten Technologien, um das Problem anzugehen.

Die vorliegende Arbeit wird das Problem im Allgemeinen darstellen und mögliche Lösungen für Afrika im Besonderen vorschlagen, basierend auf der Idee, dass die „Kreislaufwirtschaft" der in Produkten enthaltenen Materialien einen Wert hat, der durch ordnungsgemäßes Recycling von Abfällen (Elektro- und Elektronikgeräte und Kunststoffprodukte) nach dem Stand der Technik wiedergewonnen werden muss, in einem an die lokalen Gegebenheiten angepassten Kontext, wie z. B. einer effektiven, gut strukturierten Sammlung dieser Abfälle für ein Recyclingsystem (stoffliche Verwertung), das eingerichtet werden muss, um die Lebensdauer von Materialien zu verlängern und somit eine neue Erschließung von Ursprungsrohstoffen zu vermeiden oder stark zu reduzieren (Ressourcenschonung, Beitrag zum Kampf gegen den Klimawandel und Schaffung einer gesunden Umwelt).

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List of Abbreviations and Symbols

ABS .... Acrylonitrile butadiene styrene
BEV .... Battery electric vehicle
BOT .... Build Operate Transfer
BFR .... Brominated flame retardant
BMO .... Base metal operation
CFC .... Chlorofluorocarbon
Co .... Cobalt
CO_2 .... Carbon dioxide
CP .... Cellophane
CRT .... Cathode ray tube
CSR .... Corporate social responsibility
DfE .... Design for environment
EEE .... Electrical electronic equipment
EoL .... End of life
EPR .... Extended producer responsibility
EPS .... Expanded polystyrene
EU .... European Union
EV .... Electrical vehicle
EVOH .... Ethylene-vinyl alcohol
FAO .... Food and agriculture organization
FR .... Flame retardant
GDP .... Gross domestic product
GHG .... Greenhouse gas
GM .... General Motor
HDPE .... High density polyethylene
IMF .... International monetary fund
KSAH model .... Knowledge, skills, attitudes, and habits model
LCA .... Life cycle assessment
LCC .... Life cycle cost
LDPE .... Low density polyethylene
Li .... Lithium
LIB .... Lithium-Ion batterie
LLDPE .... Linear low-density polyethylene
MAPP .... Modified atmosphere plastic packaging

MSW .... Municipal solid waste
NGO .... Non-Government Organization
Ni .... Nickel
OECD .... Organization for Economic Co-operation and Development
PAH .... Polycyclic aromatic hydrocarbon
PBDD/Fs .... Polybrominated dibenzo-p-dioxins and dibenzofurans
Pd .... Palladium
PE .... Polyethylene
PES .... Polyester
PET .... Polyethylene terephthalate
PCB .... Printed circuit board
PCDD/Fs .... Polychlorinated dioxins and furans
PMO .... Precious Metal Operation
POP .... Persistent organic pollutant
POTM .... Put On The Market
PP .... Polypropylene
PRO .... Producer responsibility organization
PS .... Polystyrene.....................
PT .... Polyether
PU .... Polyurethane
PVC .... Polyvinylchloride
R&D .... Research and Development
PWB .... Printed wiring board
REE .... Rare-earth element
Ref. .... Reference
RoHS .... Restriction of hazardous substances
rPET .... Recycled PET
SHC .... Second hand clothe
UNEP .... United Nations Environment Programme
US$ .... US Dollar
WEEE .... Waste of electrical electronic equipment

1 Introduction

1.1 Introduction

The generation of waste is as old as humanity. The two are as inextricably linked as life and water. The production of EEE and plastic products continues to grow due to ever-increasing demand, including in regions like Africa. Advances in research and development (R&D) contribute to the manufacture of new products [1,2] that potentially generate even more waste.

Context: Africa's population continues to grow. The International Monetary Fund (IMF) estimates that Africa's population is currently 1.4 billion and is expected to reach 2.5 billion by 2050. In addition, the amount of product waste is increasing yearly, becoming a serious challenge to governments, communities, NGOs, industry, and the scientific community in the coming years. It is often "cheaper" for some developed countries to export their waste to Africa than to manage it domestically, as many African countries have less stringent environmental regulations and some accept waste imports for economic reasons [3]. Although the EU has a strict waste policy based on a waste hierarchy, which is supposed to be respected by all Member States, it remains a challenge to ensure strict compliance with this policy by all Member States, as some of them try to import their waste into Africa legally/illegally. The EU waste hierarchy looks as follows: avoidance/prevention, reuse, recycling, recovery, and finally disposal. In this context, 'reuse' means using an old product that is still functional without further transformation or remanufacturing. Recycling, in contrast, is the physical or chemical processing of waste products to recover materials or energy at the end of their life cycle. It involves the complete transformation of the original product so that it no longer exists in its original state. Using the best available technology, residual waste can be minimised at the end of the waste treatment process, especially when complete prevention is not achievable. The product life cycle describes the path a product takes from raw materials, through production and use, to final disposal. A modern waste management strategy focuses on implementing the waste hierarchy to protect the environment and living beings. The 9Rs theory is an approach to realizing a circular economy throughout the product life cycle. It consists of the following principles [4]:

- Rethink (making product use more extensive by sharing it)
- Reduce (increasing efficiency in product manufacture through resource preservation)
- Reuse (reusing a functioning product by another person)
- Repair (repairing and maintaining a product, conserving its original function)

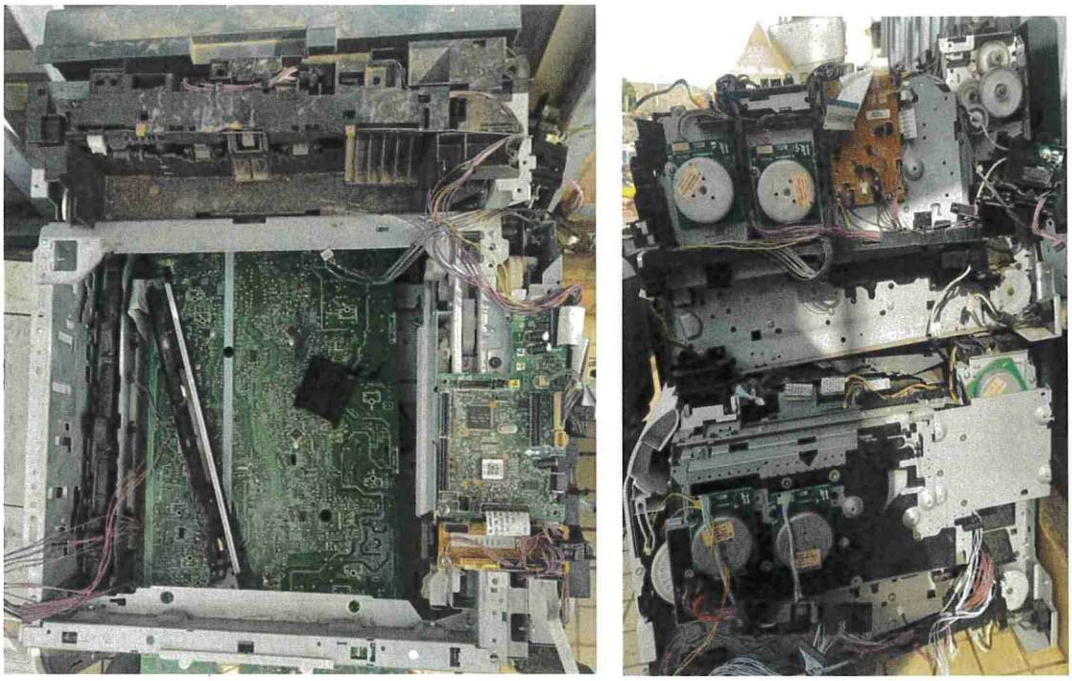
- Refurbish (restoring the old product and bringing it up to date)
- Remanufacture (using part of a discarded product in a new product with the same function)
- Repurpose (using a discarded product or part of it in a new product with a different function)
- Recycle (processing materials to obtain the same higher or lower quality)
- Recover (materials/energy recovery)

Because it is difficult to avoid waste, the 9Rs framework mentioned above is recommended to improve the sustainability of any product. The growing urban population in African countries increases waste generation and becomes a cost problem for municipalities. They often don't have enough resources. The result is a lack of interest, ineffective urban planning, and inadequate waste collection equipment. Poor municipal waste management affects the environment and contributes to the spread of diseases such as cholera. In addition, in many sub-Saharan African countries, this activity is in the hands of the informal sector, which accounts for more than half of the GDP in some countries [5] and exacerbates the situation. The amount of waste generated by electrical and electronic equipment is increasing at an alarming rate [6], contributing to global pollution problems caused by toxic substances. The rapid growth of plastic production in recent decades [7] has led to a significant increase in plastic waste, resulting in a continuous accumulation of plastic waste in the environment. Around 50% of plastic products become waste after only one use [8]. In 2019, the global e-waste generation was around 53.6 million tons, and Africa's contribution was 2.9 million tons. In addition, Africa generated 15 million tons of plastic waste in 2015, and both EEE and plastic waste are expected to increase annually. The life cycle of plastics is estimated to be several hundred years [9]. The accumulation of EEE and plastic waste in the environment constitutes a risk to the ecosystem. Poor plastic waste management on land is a major contributor to marine plastic pollution and requires urgent attention. A study shows that 80% [10] of marine plastic debris has land-based sources, including litter from beaches and rivers. Lightweight plastic debris can be carried by the wind over long distances, eventually reaching various marine and coastal environments. The plastic debris in water facilitates its transport across the ocean, where it is exposed to UV radiation and higher surface temperatures [11,12]. This exposure contributes to an increase in plastic fragmentation. Many studies have investigated the ingestion and presence of macro- and meso-plastics in aquatic and marine animals [11,12]. However, research about the effects of microplastics (small plastics) is rapidly expanding. Microplastics are a diverse mixture of particles ranging in diameter from a few microns to several millimeters. These particles come in different shapes, including completely spherical forms, elongated fibers, and many colors, such as red and blue [13]. The term "microplastics" has been widely used to describe anthropogenic debris since 2004 [13].

Research questions: The questions to be asked are: What are the potential sources of e-waste and plastic pollution in Africa? Which resources are present in the African waste stream, particularly the contribution of e-waste and plastic waste? What are the consequences and how can the problem be solved in the medium and long term?

Problem statement

Electrical and electronic devices: In 2019 [14], global e-waste generation exceeded 50 million tons and is expected to grow by another 20 million tons over the next decade. Figures 1, 2, and 3 show printers, tablets, and mobile phones that have reached the end of their life cycle. These figures highlight the materials used in these products that will end up in landfills. However, a second life for these materials is possible if individuals or companies proactively work to recover materials from these obsolete products. Short-lived items such as mobile phones - regardless of brand or market price - are a serious problem in the electrical and electronic equipment sector. Their small size contributes to littering, leading to inappropriate dumping in various locations. It appears that expensive mobile phones are not commonly found in landfills. This may be because the consumer base for these luxury devices is much smaller than for low-cost phones. However, the issue remains the same for both price ranges, as the two types of phones contain toxic substances and are short lifespan products. Even if all electrical and electronic equipment (EEE) can be repaired and reused, the issue of spare parts availability is still not fully resolved in many regions of the world. In Africa, for example, it can take a long time to order spare parts and there's no guarantee they will be delivered. Regions in other parts of the world are often given priority for deliveries. In addition, many developing countries face problems such as a lack of infrastructure in terms of quality and quantity of well-organized collection systems, few collection points, and failure in recycling facilities. Poor postal services, poorly structured administration, and corruption further complicate the situation.



b)

Fig. 1: a) Top and b) side view of an obsolete printer

b)

Fig. 2: a) Front and b) back side of an obsolete tablet

a) b)

Fig. 3: a) Front and b) back side of an obsolete mobile phone

It is a fact that developed countries generate more e-waste per capita than others and that due to the continued growth of their economies, the amount of e-waste generated annually in developing countries has increased notably.

Plastic products: The packaging waste stream represents the largest share of post-consumer waste across all sectors and is often regarded as one of the most problematic types of waste. This is due to its short lifespan, high littering potential, and noteworthy visibility to the public. As a result, policymakers are increasingly focusing on packaging waste and establishing typical recycling targets to address the issue. Low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), high-density polyethylene (HDPE), polypropylene (PP), polystyrene (PS), expanded polystyrene (EPS), polyethylene terephthalate (PET), and polyvinyl chloride (PVC) account for 99% [15] of all plastics used in packaging in Europe. Plastic packaging is a short-lived product that can generate significant waste if not managed properly at the end of its life. The accumulation of such waste without proper treatment has become a crucial problem for many countries, particularly developing countries. For example, Figure 4 illustrates the uncontrolled disposal of plastic packaging mixed with other waste in a large city in Cameroon.

Fig. 4: Mixed wild waste landfill in a city in Cameroon (inclusive all kind of plastic)

Figure 5 shows an example of a more advanced multilayer packaging material. Currently, multilayer plastics cannot be recycled into new food packaging due to immiscibility caused by the additives used as layers binding [16]. Plastic packaging films are made from blended polymers in a single form and offer gas barrier, sealing properties, printability for branding, and stability [17]. The use of composite materials presents a recycling challenge at the end of their life cycle due to the difficulty of sorting or separating the different layers. The recycling of post-consumer plastics, including composite materials, is problematic. This problem is particularly severe in Africa, where waste is often disposed of without sorting [17]. Polyethylene (PE) is often used because it is the most cost-effective option. However, when high toughness is required, packaging companies opt for polyethylene terephthalate (PET) material, especially for beverages. For protection against oxygen, the food industry typically chooses ethylene vinyl alcohol (EVOH) [16] as a barrier because it is more effective at blocking oxygen than PE, PET, and nylon. In addition, where a strong barrier is required, packaging can incorporate metalized film. When depolymerization or mechanical recycling is not viable and more robust methods are necessary, pyrolysis becomes a suitable technology. This method can effectively process highly contaminated mixtures of plastics, providing great flexibility in terms of feedstock compared to mechanical recycling. The key advantages of pyrolysis include its ability to separate different types of plastics and its economic sustainability.

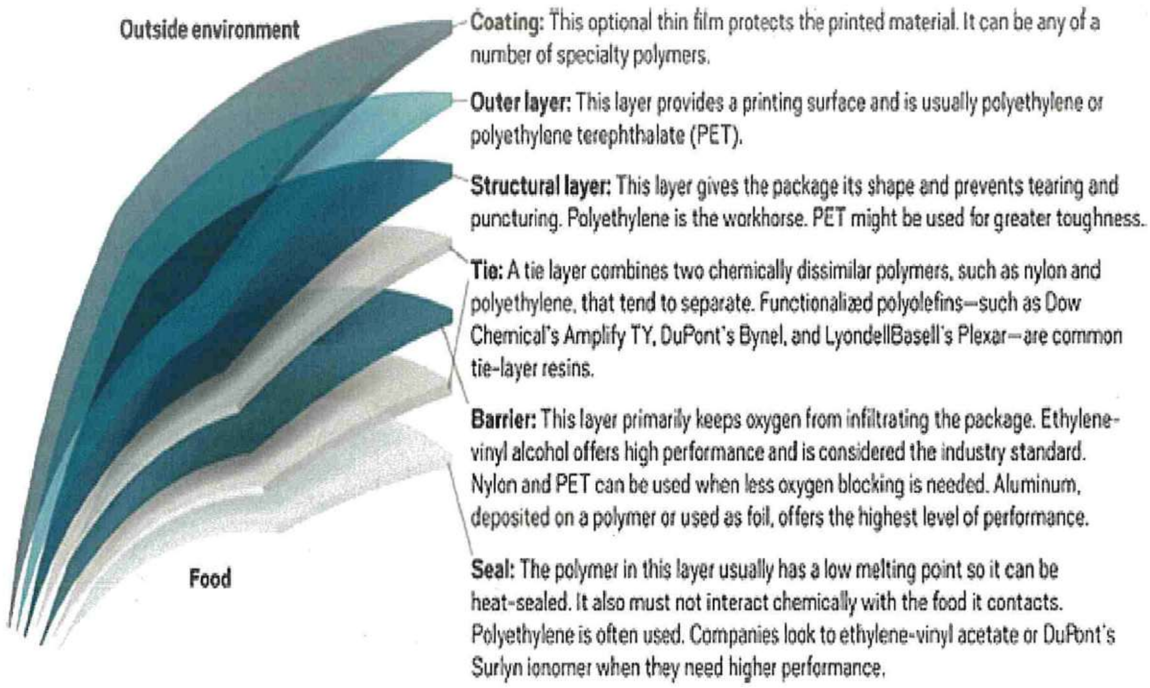


Fig. 5: Example of a modern 7-layer food packaging structure [15]

Textile imports: Clothing is a fundamental individual right and the second most basic human need [18]. Over the past two decades, the average annual textile consumption has doubled, increasing from 7 kg to 13 kg per person [18]. This rise has led to a total global consumption of 100 million tons of textiles [18]. In 2015, the global production of apparel and textiles was 95.6 million tons [18]. By 2018, this number had increased to 110 million tons, reflecting a 15.1% growth [17]. The textile and clothing industry employ approximately 60 million people worldwide and generates an annual turnover of over US$450 billion [19]. This industry consumes about 93 billion cubic meters of water annually for washing, bleaching, and dyeing. Finish products require 200 liters of water to produce just one kilogram of fabric [19]. In 2019, the textile industry demanded between 103 and 111 million tons of textile fibers [20,21]. This demand is projected to rise to approximately 130 million tons by 2025, reflecting an increase of around 400% [18,21]. Since 1970, the apparel industry accomplished an average annual growth rate of 5.6% [20]. The lifespan of textile products varies based on their intended use, but it is generally estimated to be between 1.5 and 3 years under typical conditions [22]. Textile production primarily relies on petroleum-derived virgin fibers, which account for over half of the textile fiber market [23]. The proportion of synthetic fibers used in textile applications is expected to grow from 55% in 2000 to around 68% in the future [23]. Demand for clothing in Africa and Asia is expected to triple by 2050 [19], with potentially several environmental consequences. In 2015, approximately 72 million tons of polyethylene terephthalate (PET) was produced globally. Of this, 66.7% (around 48 million tons) [19] was used for fiber production, mainly in the polyester form. In contrast, polyamide (PA) textile production accounts for about 5% of the total market, with current production levels ranging from 5 to 10 million tons. Synthetic fibers are increasingly being used, overtaking natural fibers such as wool, cotton, and cellulose. Comfort and durability are competing with recyclability. The reluctance of people in the Global North to dispose of their old clothes locally leads to their legal or illegal export to Africa and other developing countries, contributing to plastic pollution. Some unwanted second-hand clothes (SHC) imported from the United States and the United Kingdom end up in Africa [19]. In addition, SHC imports in Africa damage the local garment production market due to their low prices.

Extreme short time plastic products (Bags/Bottle): Extreme short-life plastic packages, such as sachet water and single-use plastic bags, are commonly used for water sales for the first, to transport daily purchases, or to help preserve the freshness of food products like vegetables and meats for the second. However, these materials are highly dispersive and are more prevalent, particularly in developing countries. Food waste constitutes over 50% [24] of global municipal solid waste (MSW), making it one of the most common forms of waste. Millions of Tons of food waste are generated each year, especially from fruits and vegetables. The efficient use of plastics can extend the shelf life of certain products while reducing the amount of food waste. The shelf life of fresh produce can be extended using modified atmosphere plastic packaging (MAPP), which helps to protect food from spoilage. This technique extends the shelf life of products from 5 to 10 days and reduces food loss in stores from 16% to 4% [25]. Arturo B. Soro et al [26] mention that MAPP extends the shelf life of meat products by 7-28 days and fresh fish products by 8-56 days.

1.2 Aim of the thesis

This study examines the challenges of electronic and plastic packaging waste from several perspectives. It discusses the origins of this waste and how key industry players are dealing with it, drawing on relevant literature. The analysis also highlights recent developments in developing countries. To promote sustainability, the production and disposal of plastics and electronic equipment should be made more environmentally friendly throughout their life cycle (eco-design). This includes avoiding or minimizing waste wherever possible. Governments worldwide are recommended to enact strict regulations, that integrate recycling and all possible reuse options into their waste management strategies. This approach can help transition from the existing problems of linear overproduction and overconsumption to a more sustainable system, ultimately contributing to the global reduction of CO_2 emissions. This study aims to synthesize existing literature and provide empirical evidence to support the global sustainability challenge, particularly in Africa. It seeks to generate findings that redefine policy and industry about this matter.

2 Literature Review

Global waste generation was estimated at 1.3 billion tons in 2010 [27,28]. This is projected to increase to 2.59 billion tons by 2030 and could reach 3.4 to 3.8 billion tons by 2050 [28]. Litter is a blight on the landscape. It is caused by a lack of collection points, poor education and environmental awareness, laziness, and inappropriate penalties for those who litter. People are often responsible for littering, so it's indispensable to understand why they create waste and how to minimize it. Waste is usually made up of different materials. While plastic waste has received much attention in recent years due to its harmful effects on marine life, e-waste is the fastest-growing waste stream in the world.

2.1 Consumption behavior of Africans, packaging, and rubbish

Consumer behavior includes the mental, physical, and emotional actions of people to select, purchase, consume, and dispose of goods and services [29]. Consumer behavior is an important area of research because it allows marketers to adapt their product offerings to changing consumer needs. All business activities must end with customer satisfaction. Before purchasing a product, the consumer goes through a decision-making process. Five key personality traits (agreeableness, extraversion, openness to experience, conscientiousness, and neuroticism) influence buying behavior [30]. In Africa, many products are marketed at all times, to the delight of brands and the population. African consumers love brands. The Boston Consulting Group [31] surveyed African consumers in 2019. The result: 70-73% of respondents are sensitive to brands and find them objective and valuable. In developing countries with fast economic growth, the figure is 33.3%, compared to only 25% of people in developed countries [31]. African countries use so-called traditional retail channels, such as small traders, markets, street vendors, etc., and visit them on average four times more often [31] than modern channels (online shopping in stores is for rich people [31]). According to the same study, good old familiar brands are best for Africans, but only 38% of people outside Africa believe this [31]. For Africans, quality generally depends on the lifespan of goods. In 2023, average GDP per capita is estimated to be US$2,370 in Africa, US$8,388 (3.5 times higher than Africa) in Asia and the Pacific, US$11,351 (5 times higher than Africa) in South America, US$34,706 (14.6 times higher than Africa) in Europe and US$64,279 (25.6 times higher than Africa) in North America [32]. With this GDP per capita, Africans can't afford to buy expensive things that wear out or break down quickly. In Nigeria, as in many African countries, the population tends to use modern channels, mainly specialist retailers, to buy electronic goods (reassured by the guarantee of their products' performance), while people return to traditional channels, usually general stores/markets, to buy food, drink, and clothing. Manufacturers use packaging strategies to encourage consumers to buy from them rather than their competitors. Packaging plays a vital role in marketing strategies. The importance of good packaging is currently underestimated in Africa and reduced to its functional transport purpose. As a result, many African manufacturers focus on cost reduction, and packaging is often reduced to a suboptimal minimum. The Food and Agriculture Organization (FAO) [33] argues that poor packaging is partly responsible for food loss and waste in Africa. Packaging in Africa should therefore be more than just an economically viable investment opportunity, it is essential for food security and poverty reduction. Product packaging serves fundamental functions such as easy and convenient transport, protection from external wear, necessary and legal information on use and contents, ease of use by the consumer (microwaveable packaging), and environmental protection. Cardboard and paper packaging have a long tradition in many African countries, plastic packaging is gaining market share year after year due to its low cost, immense flexibility, and adaptability to different types of packaging. The commonly used packaging in Africa is the poor quality single-use plastic bag for fresh vegetables and perishable goods for everyday shopping [34]. On average, each customer in the market receives four product carriers per day [34]. There is a debate in African countries about the sustainability of plastic packaging due to its negative environmental impact. Many countries are trying to ban all hazardous plastic packaging as the concentration of improperly disposed plastic waste increases significantly and pollutes the environment [35]. In addition, WEEE was accumulated over the years and disposed of improperly [6]. Many African countries don't have the financial, technological, or political capacity to tackle the problem. Although African countries produce less waste per capita than other regions, the ever-growing population and improper dumping make the situation more critical and lead to more litter.

2.2 Reasons of littering

The laziness and carelessness characterizing a definite group of people created a habit of not being ashamed to litter. Negligence and lack of awareness lead people to litter everywhere without realizing the medium and long-term consequences. Most people underestimate the negative impact on the environment. As a result, people get into the habit of throwing packaging waste, cigarette butts, and other rubbish in public places. People believe that city cleaners will clean up after them. The problem is sometimes the lack of people who care about keeping public places clean. Several studies have shown a correlation between the amount of waste in a particular area and deliberate waste dumping [36,37]. The presence and concentration of waste in one place lead people to create uncontrolled dumping sites. The lack of adequate local waste management services is a key driver of illegal and uncontrolled dumping in many developing countries. In Cameroon, for example, it is estimated that on average 5.5 million tons [27] of waste is generated each year (about 15,000 tons per day), of which 5 to 8% is plastic [38]. Overflowing bins, clogged canals and drains, and piles of rubbish on the streets are commonplace. The lack of public bins and individual indifference encourage littering and expose people to health hazards, food contamination, and diseases [27]. Generally, street cleaners say that most Cameroonians still don't consider it everyone's responsibility to keep Cameroon's cities clean because littering is "a common habit" in the country [27]. Environmental experts warn of a looming disaster because of the increasing waste on the country's roads, seas, and beaches [27]. Over the years, the fishing, trading, and tourism activities along Cameroon's coast threatened the health of seabirds, reptiles, fish, marine mammals, and humans. In Cameroon, most waste is not biodegradable and is sometimes thrown into the sea from residential areas or dumped by individuals and vessels. Research suggests that littering is an individual behavior, a conscious decision to leave litter behind, or negligence in waste management [27,39,40]. Litter is generated in the country by local traders, small market vendors, fishing, tourism, factories, moving vehicles (uncovered trucks transporting goods), pedestrians consuming goods (especially single plastic bags), construction/demolition sites, households, and industries.

For example, Stanley Orock [27] mentions some reasons for littering in Cameroon. The causes of littering are manifold and littering is the result of:

- People dump rubbish on streets and roads, including drivers who throw rubbish out of car windows and open loads of unsecured items that can easily blow away

- Household waste disposal and collection: Animal scavengers and wind can move unsecured items in the corner of bins (also from overloaded bins)

- Poorly secured commercial waste, uncontrolled construction waste, and waste from workers eating lunch in an unclean environment become litter

- Many tourists or people out for fun leave rubbish on the streets, especially at night when bins don't exist. Sometimes there are bins, but people are used to littering everywhere

- Entertainment events are a source of waste that can impact neighboring areas when serious control measures are not in place

- Most people leave rubbish behind because they want to dump it illegally on public or private land. Illegal dumping attracts flies and other harmful insects, causing environmental damage and health problems

- Intentional and/or habitual littering, for other reasons such as laziness or as an act of rebellion

2.3 Consequences of littering

Poor waste management costs every taxpayer. It harms people, animals, and waterways. It costs society money and confirms a lack of environmental sensitization of the people. The damage caused by littering is environmental, health, economic, and social.

2.3.1 Environmental impacts

In today's world, the environment is changing due to human activity, including littering. Around 94% of people [27] consider littering to be a serious threat to the environment. However, people still litter, i.e. most people want a clean environment but consciously or unconsciously refuse to do the right thing to achieve it. Litter is reported from all environments, including mountains, the deep sea, and the atmosphere [41]. It occurs in subtropical gyres, submarine canyons, water columns, islands, rocky intertidal habitats, beaches, dunes, mangroves, coastal lagoons, and estuaries [41]. Littering that is dumped along roads, in stormwater systems, and into rivers, seas, oceans, and other bodies of water poses an immediate threat to wildlife, ecosystems, and biodiversity by entangling, suffocating, poisoning, and killing [27,41,42]. Metal and glass fragments in litter can cause cuts to birds and other animals. The creation of unsightly urban landscapes is also a consequence of littering.

2.3.2 Health Impacts

The global South is more affected by air, food, and waste pollution than the global North. Indeed, the deaths of more than two million people worldwide, including children, are attributed to harmful microbial and chemical contamination in food and water resulting from mismanaged waste streams [28]. Litter is a breeding ground for bacteria, rats, and other vermin, creating health hazards. People who live in clean areas with lots of green space have a better quality of life (much better mental and physical health) than those with a waste problem. Individuals living in poor-quality environments are more likely to suffer from mental health problems such as anxiety and depression, according to the same source. People living in areas with a lot of waste are more susceptible to fewer physical activities (obesity and overweight are possible consequences) [27]. This is associated with health risks such as diabetes, heart attacks, and strokes (and places a burden on local health facilities). Garbage pollutes land, air, and water with toxic substances [28,43,44], leading to diseases such as cholera, acute diarrheal disease, typhoid, etc. In addition, the presence of broken glass, bottles, syringe needles, etc. in the waste stream can cause serious health risks in public places such as beaches and parks that attract many people (tourists and locals).

2.3.3 Social impacts

Improper waste damages the image of places, especially the image of the people who live there. People should be proud of where they live. If an area has a waste problem, it reduces the pride of its residents. If there is a waste problem, people will not want to spend time there because of poor quality of life and sense of community, and people's well-being suffers (economic impacts and anti-social behavior are the consequences) [27]. It is estimated that more than 200 million people worldwide are victims of environmental pollution, including littering [41]. As rubbish attracts rubbish, such areas give the impression that the people who live there do not care about a clean environment and throw away their waste. Such areas cannot attract people who can invest and make positive changes to improve people's quality of life.

2.3.4 Economic impact

In Cameroon, for example, local authorities are the largest group of land managers. So, it is not surprising that they have to spend most of the money (taxpayers' money) on collecting rubbish and keeping cities clean. A substantial amount of money that could be invested elsewhere in the economy is spent on waste disposal. Due to a lack of transparency, the exact amount is not available. The cost of littering is higher: Australia spends US$1 billion a year on litter removal, England £850 million, and the US more than US$11.5 billion [41]. State authorities in developing countries claim that the population's lack of discipline regarding garbage makes it costly for the state budget, so the money used for this could be used for other investments to stimulate the economy, especially for drinking water supply, roads, building schools, electrification, job creation, etc. Confirmation that the economic cost of garbage disposal is high [27].

2.4 Possible solutions against littering

Using a combination of structural modifications, societal willingness, individual behavior towards waste, and turning the focus toward actors within the system (like for example park management companies, municipal councils, waste collection & street cleaner companies, and governments responsible for planning and development) to reduce substantially waste generation [39]. Waste avoidance and waste reduction remain the main priorities that need to be achieved by the whole community in the fight against littering. The ideal solution to waste problems is to take responsibility individually for properly disposing of waste. If citizens are to be encouraged not to dump their waste, local authorities/governments must provide appropriate conditions for disposal. The implementation of relevant measures by local authorities, such as more bins in different places for successful waste collection. More bins in city centers, footpaths, public spaces, markets, all neighborhoods, near bus/public transport stops, and fast food restaurants will make it possible to dispose of and collect waste. Bins need to be emptied regularly to avoid additional problems such as overfilling. It is increasingly recognized that having enough bins does not guarantee that waste will not be littered. Only strict enforcement of waste laws (prohibiting illegal dumping and illegal disposal) would encourage people to stop littering in private and public places. People think it will be hard to find them at the time of the "crime," so they leave the garbage behind. However, people who know about the fines are less likely to litter [36]. Sanctions help to reduce littering, but better education and awareness are essential to achieve sustainable results. Weekly community clean-ups can also be organized and are a good way of communicating anti-littering messages to people. The matter can also be promoted on billboards, TV shows, social media platforms, and newsletters to spread the anti-litter message widely. An anti-litter campaign poster could also be placed in high-traffic areas near public transport stops to remind people not to litter. If people's economic situation in Africa continues to improve, what will happen to the growing electronic and plastic waste?

2.5 EEE and plastic waste management

Companies use their knowledge of materials to process them into innovative, high-tech consumer goods and meet the growing demand. These products are made from materials belonging to one of the following material groups: glass, ceramics, metal, or plastic in the case of monomaterial products, or from a mixture of at least two of the above material groups in the case of polymaterial products. Figure 6 illustrates the life cycle of a product.

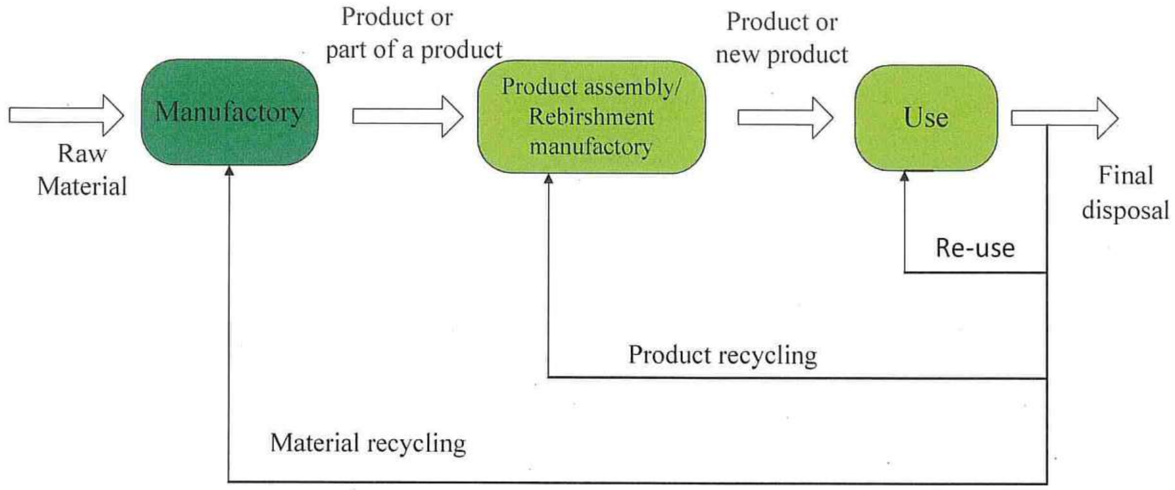


Fig. 6: In [45] modified LCA based on all steps of product development

Particular attention is paid to the product sustainability. In 1992, UNEP adopted sustainability as a policy goal for the proper development of humanity, i.e. it should be the ultimate goal of product development [46]. According to the original definition in the Bruntland Report, also called Our Common Future, sustainability consists of three components/aspects: environmental, economic, and social. The components are analyzed, evaluated, and balanced to design new products and/or improve old ones [47].

2.5.1 Materials present in obsolete EEE

Mobiles phones: The typical material composition of a mobile phone product looks as follows: acrylonitrile butadiene styrene polycarbonate (ABS-PC), ceramics, copper and compounds, silicon plastics, epoxy, other plastics, iron, and other metals. Mobile phone models vary and depend on the manufacturer. Materials used in one are not necessarily the same concerning quality and quantity as those used in the other. In 2018, Singh N. and al [48], in their study of 10 smartphones and 10 feature phones, showed that the manually disassembled parts of each end-of-life device consisted of the following by weight: 42% plastic, 23% PCB, 19% other metals, 12% screens, 2% vibrators, 2% magnets and less than 1% light-emitting diodes (LED) as presented in Figure 7. The authors also confirm that the average weight of the printed circuit board (PCB) was almost identical for mobile phones and smartphones, which means that the percentage share of precious metal content in both devices is approximately the same (same economic value for the recycler).

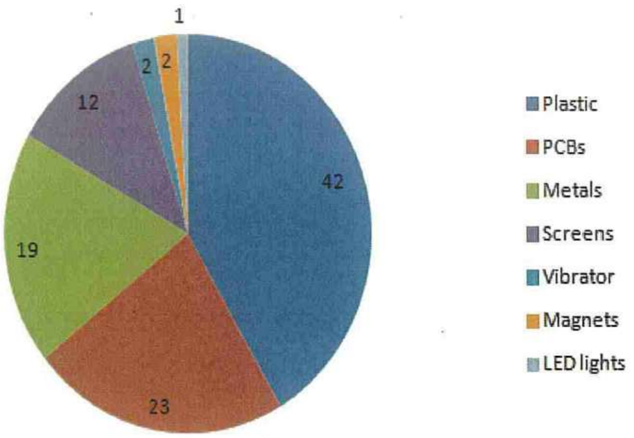
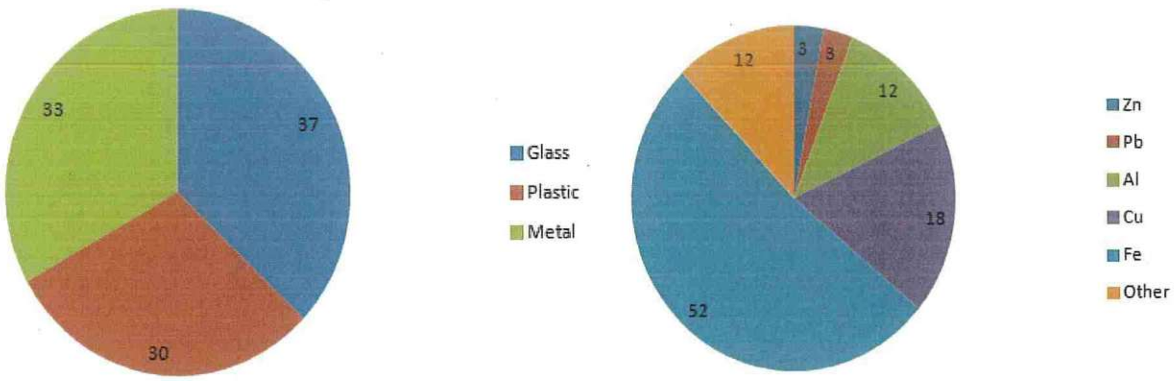


Fig. 7: Mobile phone waste composition (in wt %) by weight [48]

Desktops (personal computer): A desktop personal computer (PC) system consisting of a monitor, control unit, and keyboard. A personal computer is usually made of the following materials: steel, thermoplastics, aluminum, copper, and others [49]. They generally have the following average material composition: glass 37%, plastic 30%, and metal 33%, where the metal part is composed of zinc (Zn) 3%, lead (Pb) 3%, aluminum (Al) 12%, copper (Cu) 18%, iron (Fe) 52% and other 12% as shown in Figure 8 [50].



a) b)

Fig. 8: a) Material composition (in wt %) of computers, b) Composition of the metal part [50]

Laptops personal computer (Notebooks): A wide variety of materials are used in the manufacturing process of notebook computers: from plastics, glass, base metals such as copper, aluminum, steel, etc. to precious metals such as gold and silver, among others [51]. The average material composition of a laptop by weight is: ABS (9.87%), PC (10.74%), epoxy (6.46%), other plastics (9.08%), glass (7.94%), copper (7.15%), aluminum (13.55%), steel (23.05%), gold (9.35x10^{-3}%), silver (0. 04%), palladium (1.59x10^{-3}%), nickel (0.03x10^{-3}%), zinc (2.65x10^{-3}%), neodymium (0.53x10^{-3}%), tin (0.25%), lead (0.16%), and other (11.69%) [51]. Figure 9 shows the average material composition of a notebook computer.

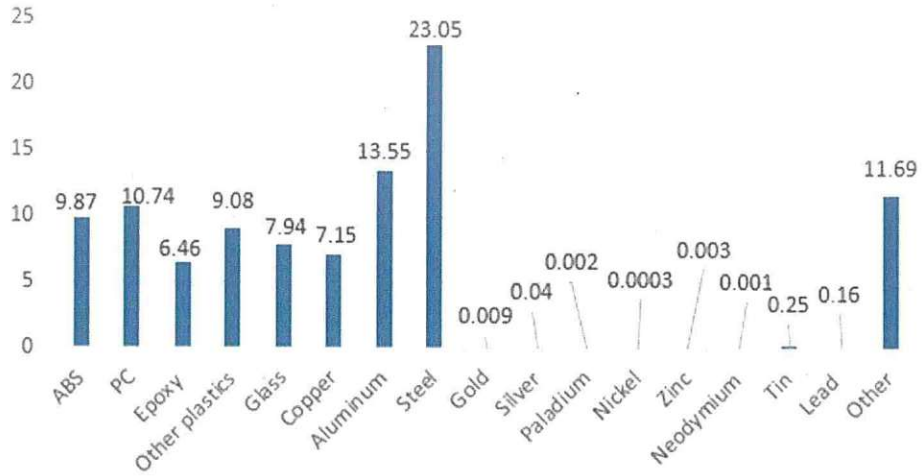


Fig 9: Average material composition (in wt %) of a notebook [51]

Televisions (TVs): As presented in Figure 10, the estimated material composition of a typical TV is 50% lead glass, 22% plastic, 11% steel, 1% ferrite, 3% copper, 5% PCB, and 8% other metals.

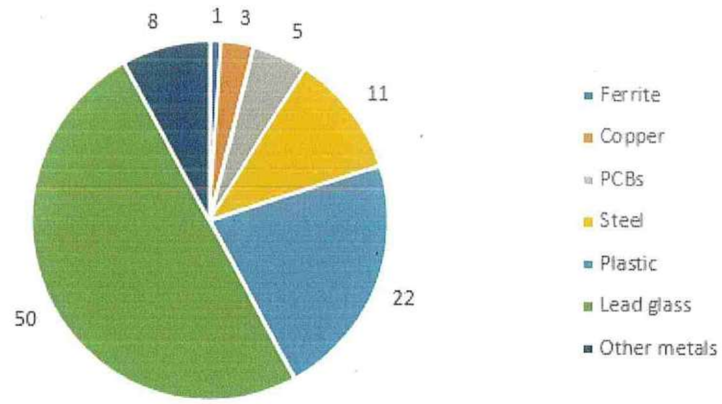


Fig. 10: Average material composition (in wt %) of a typical TV [50]

Refrigerators: Table 1 shows the typical material composition of a recycled refrigerator/freezer [52].

Table 1: Typical material composition by weight used in a refrigerator [52]

Material type		With CFCs (kg)	With CFCs (wt%)	Without CFCs (kg)	Without CFCs (wt%)
Valuable materials	Ferrous Metal	33.60	54.08	28.60	48.21
	Aluminum	1.10	1.77	0.80	1.35
	Copper	0.52	0.84	0.52	0.88

	Copper cables	0.34	0.55	0.34	0.57
	Plastics	7.70	12.39	10.20	17.19
Hazardous substances and waste	Lubricant oil	0.08	0.13	0.08	0.14
	Polyethane foam	13.70	22.04	13.70	23.09
	Blowing agent	0.69	1.11	0.69	1.16
	Refrigerant gas	0.2	0.32	0.20	0.34
	Ordinary waste	4.20	6.76	4.20	7.08
Refrigerator mass		62.13		59.33	

Refrigerators Blowing Agents (BAs) produce emissions at their end-of-life. In the USA, 70% of refrigerator materials are recycled [39]. The energy consumption and CO_2 emissions associated with recycling, such as transport, dismantling, and shredding, can be estimated.

Special case of batteries: Batteries are one of the components of the electrical and electronic devices that need one. Lithium-ion batteries are among the most commonly used cells in Europe and worldwide [53]. Due to the highly flammable, unbound electrolyte in the cell, there is a risk of fire, which is why their use on a large scale is viewed with great skepticism (thermal rupture effect) [53]. If the cells are encapsulated, the fire is extinguished in less than a minute and the thermal rupture doesn't occur [53]. The need for raw materials for batteries has increased with the increase in lithium-ion megafactories since 2016 [53] and has therefore been introduced in electric vehicles (EVs) over the last decade. This raw material demand must be met and the supply chain has to be and remain "clean" (i.e. without child labor, plundering countries, and promoting war, among others). Lithium-ion batteries (LIBs) are more attractive for use as plug-in hybrids and battery electric vehicles (BEVs) due to their lightweight, higher energy density, longer cycle life, and ability to support deep discharges [53]. It is not always easy to meet all requirements for new material extraction; battery recycling is a possible source of critical raw materials. Energy storage systems (ESS) should be able to effectively smooth fluctuations and mismatch energy production and consumption through coordinated energy supply and time shifting [54]. For example, global storage capacity was approximately 4.67 TWh in 2017 and is projected to increase to 11.89-15.72 TWh in 2030 (an increase of 154.6-234.11%) [54]. In the future, although battery energy storage systems (BESS) currently account for only a small share, the total capacity of batteries in stationary applications is predicted to grow at exceptionally high rates according to the same source. In addition, carmakers are moving aggressively towards electric products: Mercedes-Benz announced the electrification of its entire future range by 2030; Audi intends to phase out all internal combustion engines by 2033 and produce only fully electric vehicles by 2026, Ford, General Motors (GM) and Stellantis want 40 to 50 percent of their sales to be zero-emission vehicles by 2030, and Volvo intends to produce fully electric cars by 2030 [55]. In addition to all the possible e-mobility applications, the demand for raw materials such as nickel (Ni), cobalt (Co), manganese (Mn), and lithium (Li) required for battery production will increase. This will lead to increased mining and production. It will not be easy to meet the expected demand from the global supply chain [55,56]. According to Ma X. et al [55]: Given that the average lifetime of LIBs is 1-3 years for consumer electronics and 8-10 years for electric vehicles or energy storage systems, approximately 0.2 million tons of post-consumer LIBs and 0.88 million tons of end-of-life LIBs could have been generated in 2023. It is estimated that around 11 million tons of spent LIBs will be generated by 2030, indicating a large market for LIB recycling [57]. Spent LIBs have the potential to be considered as a secondary resource that can be recycled to reduce supply risks and associated negative environmental impacts [57]. Obsolete LIBs that are improperly disposed of cause health problems due to the presence of heavy metals and toxic gases such as Co, Ni, Mn, and hydrogen fluoride (HF), which can be released into the environment. In 2021 [56], 90% of primary lithium production took place in Australia (53%), Chile (32%) and China (13%), while 73% of primary cobalt production came from the Democratic Republic of Congo, which is unstable because of war since 1998. To fill the gap in raw materials (quantitatively) and to avoid environmental pollution, recycling in state-of-the-art LIBs is crucial.

Table 2 gives the estimated lifetimes and masses of some electrical and electronic products. The lifetime of mobile phones, PCs, and kettles is between 1 and 3 years, a relatively short lifetime before disposal compared to other products in the table.

Table 2: Mass and lifespan of some EEE products [58]

Item	Item mass (kg)	Estimated life (years)
Personal computer	25	3
Fax machine	3	5
High-fidelity system	10	10
Cell phone	0.1	2
Electronic games	3	5
Photocopier	60	8
Radio	2	10
Television (TV)	30	5
Video recorder/DVD	5	5
Air-conditioner	55	12
Dish washer	50	10
Electric cooker	60	10
Food mixer	1	5
Freezer	35	10
Hair-dryer	1	10
Iron	1	10
Kettle	1	3
Microwave	15	7
Refrigerator	35	10
Telephone	1	5
Toaster	1	5
Tumble dryer	35	10
Vacuum cleaner	10	10
Washing machine	65	8

2.5.2 Life cycle cost

Life Cycle Cost (LCC) [59] is the sum of the estimated costs from conception to disposal of a good, determined by the estimate of the total costs incurred during its lifetime. The main objective of LCC analysis is to select the most cost-effective approach from a range of alternatives to achieve the lowest long-term cost of ownership. LCC analysis provides the framework for specifying the estimated total incremental costs of developing, producing, using, and disposing of a particular item [60]. The LCC of a product includes three types of costs: those of the producer, those of the user, and those of society. This is shown in Table 3. In the table, only the design phase has no social costs because it is a time of conception, planning, market availability, and investment. This is also the right time to design the product with few or no social costs. There are several social costs, namely packaging, waste, pollution, disposal, and health costs.

Table 3: Product life cycle phases and costs [60]

	Company cost	Users cost	Society cost
Design	Market recognition Research and development		
Production	Materials Energy Facilities Wages, salaries Taxes, etc.		Waste Pollution Health damages
Usage	Transport Storage Waste Breakage Warranty service	Transport Storage Energy Materials Maintenance	Packaging Waste Pollution Health damages
Disposal/Recycling		Disposal/Recycling Dues	Waste Disposal Pollution Health damages

2.5.3 WEEE

In 2021, approximately 54.8 million tons [61,62] of e-waste were generated worldwide, and in the following year, 61.9 million tons [63]. This trend did not correspond to the desired goal of preventing and/or reducing WEEE and needs to be addressed urgently. Ideally, this growing trend in e-waste should be halted or at least significantly reduced to an absolute minimum.

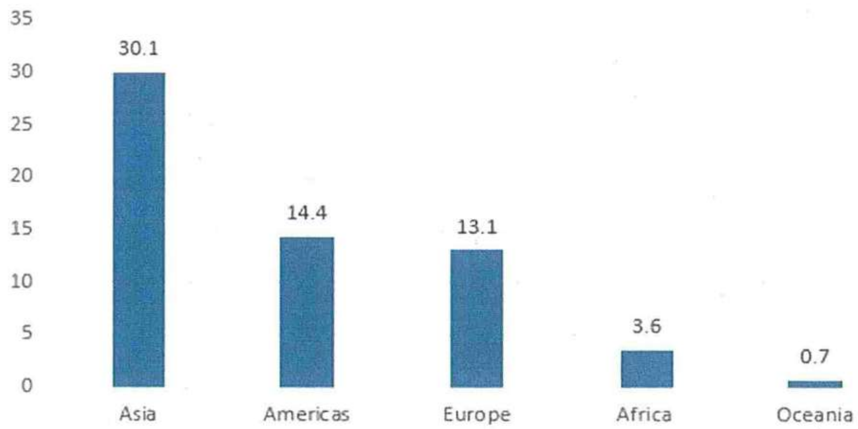


Fig. 11: Global e-waste generated per region in million tons in 2022 (Mt) [63]

The forecast for 2030 is 74.7 million tons globally according to the Global E-waste Monitor 2020 [62], representing a 20.7% increase in e-waste compared to 2022. The estimated amount of e-waste generated in Africa will increase to 4 million tons by 2030 if no waste management measures are taken. The material composition of e-waste is shown in Figure 12

[39].

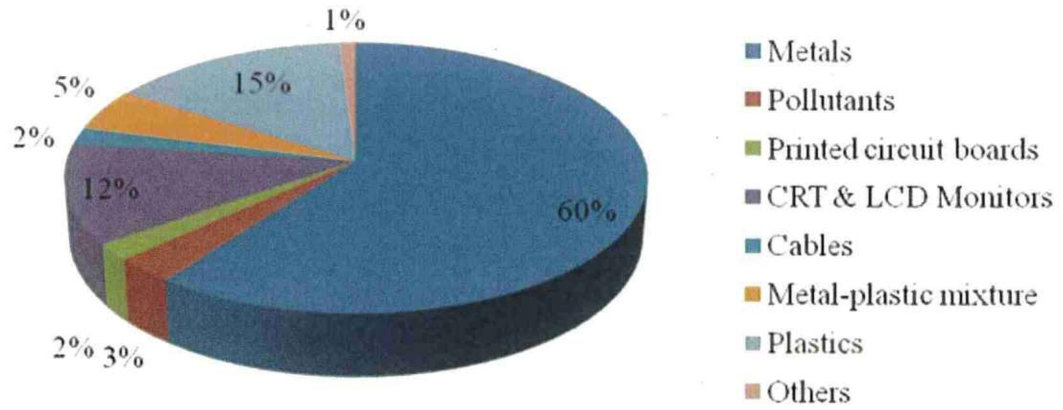


Fig. 12: Material composition (in wt %) of e-waste [43]

Rare earth elements (REEs) are widely used in digital technologies such as disc drives and communication systems, but also in batteries and fuel cells for hydrogen storage, catalysts, light emitting diodes (LEDs), and fluorescent lighting [64]. As photovoltaic modules contain less than 1% [65] of silver in their composition, it may become economically viable to be recycled due to the large number of obsolete items. One of the challenges of e-waste management is that the long-term deposition of rare earth elements in such waste can have toxic effects on human health and the environment. Many obsolete REEs need to be disposed of properly.

2.5.4 Challenges of EEE waste

Products or parts of products that need to be removed from the waste stream because they contain pollutants and therefore pose a risk to human health, animals, and the ecosystem include batteries, mercury lamps, color toners, plastics containing brominated flame retardants (BFRs), CRT glass, PWBs, and PCBs [66], to name but a few. After incineration, approximately 30% [67] of air pollutants persist in landfills such as fly ash, bottom ash, boiler ash, slag, and sewage sludge, poisoning soil and groundwater. In addition, although today's advanced pollution control equipment cannot eliminate all toxins, it is better to continue to find ways through R&D to eliminate all hazardous substances for a healthy environment. This means that waste incineration for energy recovery is polluting, exacerbates climate change, and undermines sustainability. The presence of toxic substances in e-waste makes it dangerous for developing countries that don't have the technical and financial capacity to landfill and/or treat sustainably this waste. Over time, the main objective of solid waste management has shifted from landfill or semi-solid waste disposal to material and energy recovery as secondary resources. Material flows are closed through recycling discarded products and the urban recovery of current and future waste streams (circular economy). Secondary resources are materials produced by processing waste materials instead of primary materials. Resource recovery through secondary raw materials enables the conservation of primary ores. It also reduces the carbon and environmental footprint. For example, recycling aluminum (Al) and copper (Cu) saves up to 95% and 85% energy, respectively, compared to production from primary ores, and 50% of copper semi-finished products are currently made from recycled materials [62]. In addition to all the hazardous substances contained in electronic waste, the production of mobile phones and PCs consumes a significant proportion of the gold (Au), silver (Ag), and palladium (Pd) mined worldwide each year. The electronics industry is the third largest consumer of gold (12% of total gold demand). More than one million people in 26 countries [62] in Africa, Asia, and South America work in gold mining, mainly in critical, unregistered, and substandard conditions, motivated by the demand for this precious metal in electronics. All this makes e-waste recycling an economically and environmentally interesting way to a circular economy while minimizing landfills. Figure 13 shows the informal treatment of electronic waste in Agbogbloshie, a suburb of Accra, Ghana.

Fig. 13: Picture of informal e-waste treatment in Agbogbloshie – Ghana (Source: the newspaper "Liberation" of January, 9th 2019, photo of Cristina Aldehuela – AFP)

2.5.5 Recycling of electrical and electronic waste

After dismantling, the collected WEEE has to be separated into six components before further processing. The dismantled WEEE is shredded in a 4-shaft shredder machine with a capacity of 3,000 kg/h [68] and passes through a magnetic separation of iron. At the same time, non-magnetic metals are separated by hand from the moving machine. The collected plastic components are sold to authorized buyers. Components like printed circuit boards (PCBs) are directly treated for precious metal recovery using pyro/hydrometallurgical processing routes. Activities such as cutting, shredding, shadow mask removal, crushing, washing, and re-melting of the shredded/molten glass (cullet) are part of the recycling of cathode ray tubes (CRTs) [68]. Generally, most African countries can't manage solid waste and are forced now to solve the WEEE problem without accurate data and regulation. Therefore, a global solution to this problem may be the best option for Africa. Our proposal is a strict global regulation for the collection and treatment of e-waste under the supervision of an international agency with the following functions:

- To ensure that (at least a maximum number of) worldwide obsolete electronic devices are collected and properly documented
- To monitor and report on the transboundary movement of these devices, thus ensuring that data on this matter is always available and accessible to everyone (transparency improvement)
- To use all modern communication channels and instruments to raise global awareness of the dangers of e-waste
- To be a real mentor, concerning the country's reality, for regions that don't have the know-how to manage the collection of e-waste at the three levels (municipalities, cities, whole country) and to sanction countries that don't respect the agreement
- To advise countries or regions on ways to use incentives to bring e-waste treatment out of the informal sector and into the formal sector, where it can be a source of income without risks to workers' health
- To coordinate and monitor the effectiveness of a global take-back system for obsolete and dangerous electronic products
- To find potential investors to finance the construction of e-waste treatment plants in developing countries using Build-Operate-Transfer (BOT) mechanism

At the end of this process, the amount of e-waste generated each year will be known, and the next steps in the management process will be the rational and sustainable design and construction of facilities.

The best-of-two-world philosophy [69], can be a part of this global solution for e-waste treatment in the short and medium term: local pre-processing of domestically generated e-waste by manual dismantling in developing countries and delivery of critical fractions to state-of-the-art end-processing facilities in developed countries. Manual dismantling is maintained locally in developing countries under better safety and working conditions, as it produces fine materials with low technical requirements. At the same time, hazardous fractions are sent to state-of-the-art facilities in a sustainable, eco-regulated international market, so that the detoxification and recovery of valuable materials at the end of the process is optimized. The global sharing of existing waste treatment infrastructure with manual dismantling facilities in developing countries will be economically attractive and avoid high investments, i.e. positive revenues with low environmental impact. The positive social aspects of this action are: the improvement of e-waste treatment in developing countries, avoidance of negative environmental impacts (safety, health, and environmental standards), creation of new jobs in the formal sector, and improvement of working conditions. The long-term strategies consist of the transformation of the Basel Convention into an international law that effectively controls the shipment of e-waste from OECD to non-OECD countries, from developed to developing countries, the creation of state-of-the-art treatment facilities for the final processing of e-waste in some countries, financed and managed directly or indirectly by the international institution, focusing more attention on research and development in biotechnology (bioprocessing/bioleaching) for economic and environmental sustainability in material recovery (eco-efficiency) and, more importantly, designing products with recycling in mind in the choice of materials and their assembly, so that the recycling process becomes easy to realize and implement. Mechanical shredding and sequential sorting are the most commonly used automated pre-processing methods, while manual human labor is widely used for non-destructive disassembly. In 2019, the worldwide value of the raw materials contained in WEEE was estimated at US$10 billion [61]. Figure 14 presents an example of a WEEE recycling system.

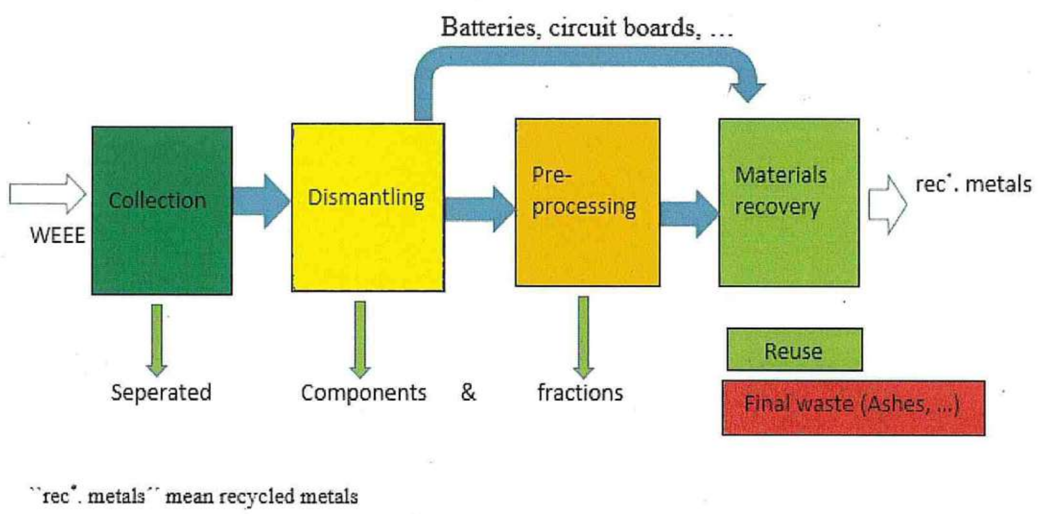


Fig. 14: An example of a WEEE recycling chain

2.5.6 Example of a practical recycling plant

In Hoboken (Belgium) [70], Umicore's integrated metals smelter and refinery treated the first PCBs in an IsaSmelt furnace to recover precious metals, as shown in Figure 15. They are then refined by hydrometallurgical processes and electrolysis in Outotec's Ausmelt TSL reactor (Espoo, Finland). It was taken over by the new owner Metso in 2020 [71]. WEEE is processed in copper/lead/zinc smelters in a combined process to recover Zn, Cu, Au, Ag, Indium (In), Pb, Cadmium (Cd), and Germanium (Ge) [70]. Umicore Recycling Solutions uses a specially developed Val Eas process with an annual capacity of more than 4,000 tons [72] for an environmentally friendly treatment of Ni-metal hydride, Li-ion batteries, electronic appliances, hybrid, and electric vehicles. In this metallurgical process, the principal metals cobalt (Co), nickel (Ni), copper (Cu), and iron (Fe) are first separated from the other battery materials at the smelter in Hofors, Sweden. A post-combustion technology (based on a plasma gun) ensures that all organic compounds are decomposed and that no harmful dioxins or volatile organic compounds are produced. The resulting alloy is further refined in a hydrometallurgical process in Olen, Belgium, to produce high-purity cobalt oxide and nickel salts, the raw materials for battery cathode material. The final conversion into active cathode material for lithium-ion cells occurs at Umicore's Cheonan plant in South Korea. For nickel-metal hydride batteries, the Ni compound is converted into nickel hydroxide at Umicore's plant in Jiangmen, China. Used batteries are processed into new materials for new battery products, thus closing the material loop.

A typical aluminum smelter in Europe requires a minimum input of 50 thousand tons of aluminum scrap per year and an investment cost of about €25 million to run a plant [73]. Only a few companies in the world, such as Aurubis AG in Germany, Boliden in Sweden, DOWA in Japan, Umicore in Belgium, and Xstrata in Canada, are equipped with the technical know-how, sophisticated flow sheets, and sufficient economy of scale for the precious metal refinery to fulfill technical and environmental requirements. The integrated smelter-refinery of Umicore Precious Metal Refining in Belgium can produce 2400 tons of silver, 100 tons of gold, 25 tons of palladium, and 25 tons of platinum per year at an investment cost of more than €500 million [73].

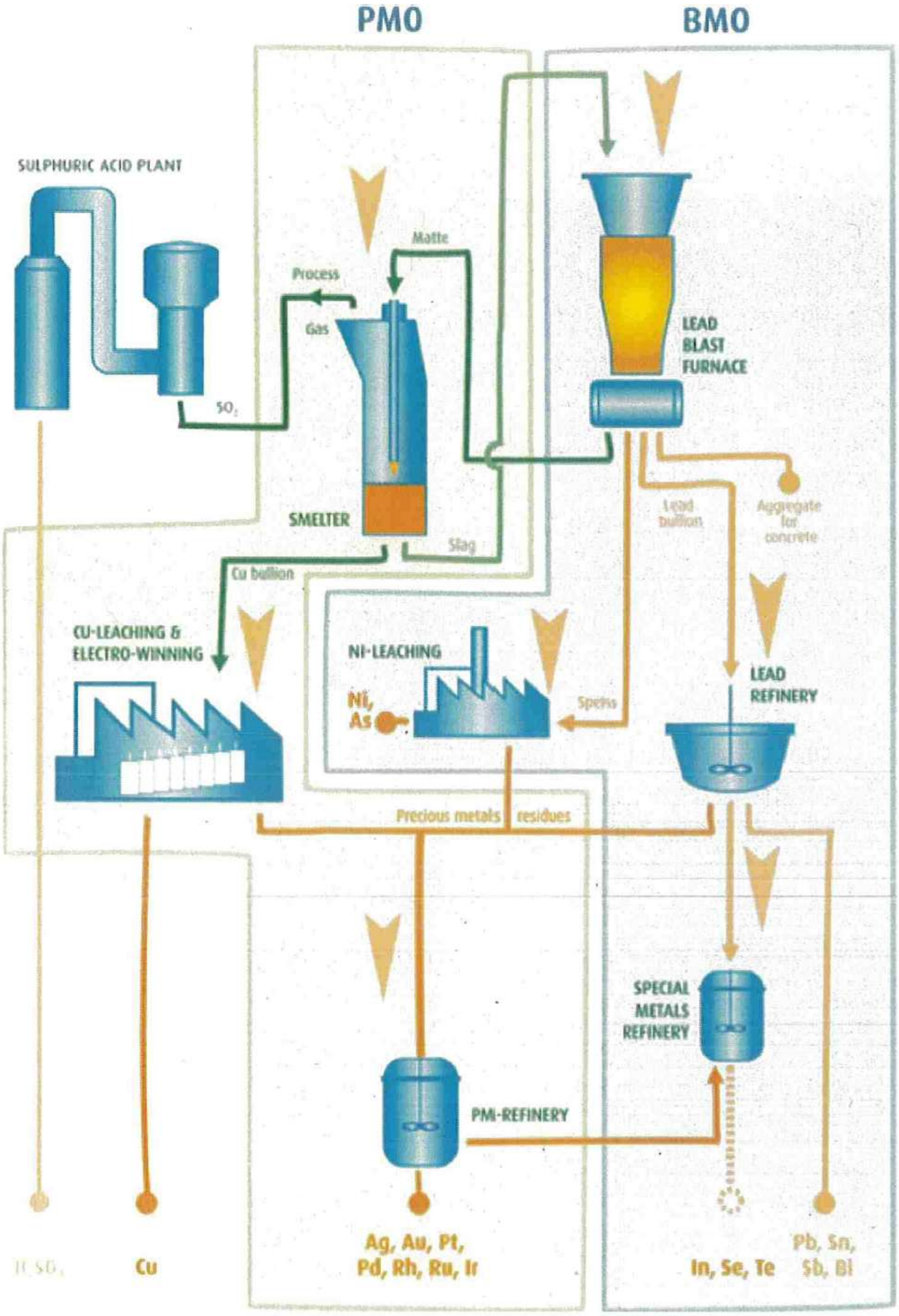


Fig. 15: Process scheme of the Umicore IsaSmelt e-waste recycling facility in Hoboken (Belgium). PMO: Precious Metal Operation; BMO: Base Metal Operation [70]

BASF's chemical recycling plant in Korea converts plastic waste into materials that can be reused [74].

2.5.7 WEEE legislation, e.g. EU WEEE-Directive

The main objectives of the EU WEEE Directive are [75]:

- To reduce the disposal of WEEE to landfill
- To provide a free of charge take-back system by the producers for the EoL

product of consumers

- To improve the design of products with a view to both preventing the generation of WEEE and increasing their recoverability, re-usability, and recyclability to achieve the targets for the recovery, re-use and recycling of the different classes of WEEE
- Provide for the establishment of collection facilities and separate collection systems for WEEE from private households, requiring producers to set up and finance systems for treating WEEE, including provisions on financial guarantees for new products put on the market

For environmental and recycling reasons, the European Union (EU) sets a minimum standard to be achieved by each Member State. In the WEEE Directive [75] there are ten (10) product categories:

- Large household appliances (refrigerators, washing machines, stoves)
- Small household appliances (vacuum cleaner, toasters, hair dryers)
- Information and telecommunications equipment (computer and peripherals, cell phones, calculators)
- Consumer equipment (radios, TVs, stereos, photovoltaic panels)
- Lighting (fluorescent lamps, sodium lamps)
- Electrical and electronic tools (drills, saws, sewing machines)
- Toys, leisure, and sports equipment (electric trains, video games)
- Medical devices (ventilators, cardiology, and radiology equipment)
- Monitoring and control instruments (smoke detectors, thermostats, control panels)
- Automatic dispensers (appliances that deliver hot drinks etc.)

The six (6) product stream categories are [75]:

- Temperature Exchange Equipment
- Screens and Monitors (with a surface greater than 100 cm^2)
- Large Equipment
- Small Equipment
- Small ICT (no external dimension more than 50 cm)
- Lamps

In 2015, all targets were increased by 5%. Since 2016, all EU Member States must achieve a 5% reuse target separately. WEEE collection was changed from a minimum of 4 kg per capita to 45% on the Put On The Market (POTM) in 2016. It changed to 65% POTM or 85% of generated WEEE in 2019 [75]. Table 4 shows the evolution of the quantitative recovery and recycling targets for all EU Member States between 13/08/2012 and 15/08/2018.

Table 4: Minimum recycling and recovery targets for the EU Member States [75]

Product category	Recovery target in % 13/08/2012 to 14/08/2015	Recovery target in % 15/08/2015 to 14/08/2018	Recovery target in % since 15/08/2018	Recycling target in % 13/08/2012 to 14/08/2015	Recycling target in % 15/08/2015 to 14/08/2018	Recycling target in % since 15/08/2018
Large household appliances	80	85	85	75	80	80
Small household appliances	70	75	80	50	55	70
Information and telecommunication equipment	75	80	80	65	70	80
Consumer equipment	75	80	85	65	70	80
Lighting	70	75	75	50	55	55
Tools	70	75	75	50	55	55

In the case of gas discharge lamps, 80% must be recycled.

Despite EU legislation on collection and recycling, it is estimated that only one-third of WEEE is reported to be separately collected and adequately treated. The other two-thirds are dumped in landfills, inadequate treatment facilities, and/or illegally exported from the EU. In addition to the EU and some US states, countries such as Canada, China, South Africa, Mexico, Argentina, Chile, Colombia, Ecuador, Morocco, Algeria, Tunisia, Turkey, Saudi Arabia, Australia, New Zealand, Vietnam, Thailand, and Indonesia have similar legislation on e-waste or substance restrictions in force or at various stages of implementation [61]. However, legislation alone does not necessarily lead to successful and sustainable e-waste management systems, and the types of e-waste covered by legislation vary considerably between countries. As a result, it is still difficult to coordinate the quantities of e-waste collected and recycled. An appropriate solution is to set up an institution with a global view of e-waste flows, similar to (or within) UNEP, to maintain overall control and ultimately be responsible for the appropriate e-waste management system worldwide. In 2017, about 4.8 billion people (66% of the world's population) from 67 countries were covered by national legislation, compared to 2014, when only 44% (61 countries) were covered [61]. Furthermore, adopted national legislation in many African countries, is not always translated into concrete and effective action. Table 5 shows the percentage of the population covered by legislation by subregion in 2014 and 2017.

Table 5: Per sub-region, population covered by the legislation in 2014 and 2017 [61]

	2014	2017
World	44%	66%
East Africa	10%	31%
Middle Africa	14%	15%
Northern Africa	0%	0%
Southern Africa	0%	0%
Western Africa	49%	53%
Caribbean	12%	12%
Central America	74%	76%
Nothern America	98%	100%
South America	29%	30%
Central Asia	0%	0%
Easter Asia	99%	100%
South-Eastern Asia	14%	17%
Southern Asia	0%	73%
Western Asia	37%	38%
Eastern Europe	46%	99%
Northern Europe	99%	100%
Southern Europe	100%	100%
Western Europe	99%	100%
Australian & New Zealand	81%	85%
Melanesia	0%	0%
Micronesia	0%	0%
Polynesia	0%	0%

According to the table above, Europe has the most developed e-waste legislation and is the region in the world with the highest documented quantities of e-waste collected and recycled. North America, East Asia, and South Asia are the other regions where legislation is developing. Regions without national e-waste legislation are Africa, the Caribbean, Central Asia, Melanesia, Polynesia, and Micronesia. These countries are more exposed and vulnerable to the negative impacts of e-waste problems.

2.5.8 Plastic waste management

Plastic/textile waste: The development of synthetic polymers in the mid-20th century led to a significant increase in the global production of plastics. Globally, the growth in plastic production over the last few decades has led to a massive increase in plastic waste and the continued accumulation of plastic debris in the environment. Annual global plastic production is estimated to increase from around 300 million tons in 2014 to 454 million tons in 2018 [76,77] and reach 1,800 million tons by 2050. Fihlo L. et al [78] define textile recycling as a way to implement the circular economy (a closed-loop production system) and thus as a solution that helps companies to promote sustainable business development. According to the authors, textile recycling helps to reduce production costs for manufacturers, as recyclable materials are a cost-effective and efficient alternative with a low environmental impact. It is also reported that recycling used clothing could reduce greenhouse gas emissions by 53%, pollution from chemical processing by 45% and water eutrophication by 95% [79]. Each stage of the textile waste recycling lifecycle (i.e. collection, sorting, transport, recycling) creates jobs and opportunities for small or family businesses. Total greenhouse gas (GHG) emissions from the apparel industry are 1,200 million tons. The apparel industry uses 93 billion cubic meters of water, 8 million tons of fertilizer, 200,000 tons of pesticides for cotton, 42 million tons of chemicals, and 1 million tons of dyes [79]. In addition, greenhouse gas emissions are estimated at 4.7 kg $CO_{2e/kg}$ for cotton production, 11.9 kg $CO_{2e/kg}$ for plastic-based fiber production, and 9.6 kg $CO_{2e/kg}$ for yarn and fabric production (including dyeing) [79]. Estimates for water use are 4,600 L/kg for cotton production, 38 L/kg for plastic-based fiber production, and 88 L/kg for textile dyeing [79]. Despite the difficulties in accessing data on plastic waste from African countries, we use the 2010 available data.

Table 6: Plastic waste data for 2010 from some African countries [80]

Countries	Generated plastic waste per capita & per day (in kg)	Generated plastic waste per country (in million tons)	Plastic waste mismanagement per country in %	Population (in million) *
Nigeria	0.1	5.96	81	200.96
Egypt	0.18	5.46	67	99.21
South Africa	0.24	4.47	54	58.82
Algeria	0.14	1.9	58	43.41
Sudan	0.1	1.29	80	43.22
Democratic Rep. of Congo	0.04	1.06	85	97.88
Morocco	0.07	0.86	66	35.59

Côte d'Ivoire	0.1	0.77	82	26.28
Tunisia	0.14	0.56	60	11.78
Angola	0.06	0.53	71	30.13
Senegal	0.1	0.49	82	16.77
Kenya	0.03	0.41	83	49.36
Tanzania	0.02	0.39	84	56.32
Ghana	0.04	0.36	81	30.17
Cameroon	0.05	0.34	81	25.51
Libya	0.14	0.32	23	6.59
Somalia	0.05	0.24	85	n.a.
Togo	0.06	0.14	84	8.21
Benin	0.04	0.14	83	11.81
Mozambique	0.01	0.13	84	31.16
Madagascar	0.02	0.12	84	27.11
Liberia	0.08	0.12	84	4.59
Guinea	0.03	0.12	84	13.63
Namibia	0.14	0.11	66	2.46
Congo	0.07	0.11	77	4.57

*Ref. International Monetary Fund (IMF), February 2020: https://www.imf.org/en/Countries

n.a. not available

2.5.9 Plastic leakage (Microplastic)

The life cycle of plastics is estimated to be several hundred years [11]. Poor management of land-based plastic waste is one of the serious issues in marine plastic pollution. According to a study, around 80% [10] of marine plastic waste is thought to originate from land-based sources, including beach litter. Reducing the amount of plastic waste in the oceans depends, on the one hand, a significant reduction of plastic on land in general, and in particular, a reduction of plastic packaging, such as lightweight single-use carrier bags as well as heavy-duty carrier bags, on the other hand, the ability of the scientific community to develop technologies (best available technology) that enable high recycling rates, very low environmental impact (zero environmental and human impact are the main goal to achieve) to affordable costs. Polyethylene (PE) is one of the most widely used synthetic polymers in the whole world. There are many types of PE, but the most commonly used types are LDPE and HDPE, which accounted for around 17.5% and 12.1% respectively [10] of European plastic production in 2015, according to Plastics Europe. Polyethylene is found in 79% [10] of marine litter. The density of LDPE and HDPE is less than that of water (1 g/cm3). The list of plastics used for the classification of the parent materials of microplastics includes PE, PS, PP, PES (polyester), PVC, PA, AC (acrylic polymers), PT (polyether), CP (cellophane), and PU (polyurethane) [11]. Lightweight plastic debris can be transported with the wind over a radius of several kilometers and reach different marine and coastal environments. The ability of plastic waste to float in water increases its transport across the ocean, exposing it to UV radiation and higher temperatures at the water's surface, thereby increasing fragmentation [11]. Figure 16 confirms that the most global use of plastics in the consumer goods sector is in products (31%) and consumer packaging (46%). According to the Waste Partnership Working Group (UNEP, CHW, PWPWG.1/INF/1), packaging accounts for 36% of the world's annual resin production [81].

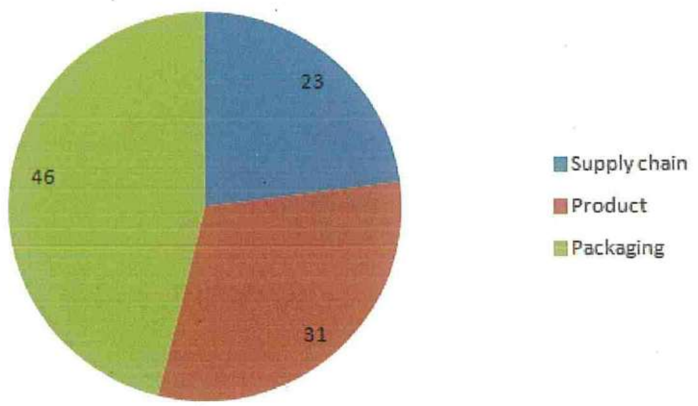


Fig. 16: Worldwide plastic demand (in wt%) for all consumer goods sectors [82]

While many studies have investigated the uptake and accumulation of macro- and meso-plastics in aquatic animals and marine biota, the effects of microplastics (small-sized plastics) are currently an expanding area of research. Microplastics can be defined as a collective term to describe an exact heterogeneous mixture of particles with diameters ranging from a few microns to many millimeters, including particles of different shapes, from completely spherical to elongated fibers of various colors (e.g. red and blue) [13]. Microplastics have been widely used in anthropogenic debris since 2004 when Thompson et al. used the term to illustrate and describe microscopic pieces (~ 50μm) of plastic in marine sediments and the water column of European waters. In 2009, Arthur et al. proposed that microplastics should include all fragments < 5 mm [26]. Microplastics have a variety of sources, but can be broadly categorized as (i) primary sources as a direct release of small particles (release of pellets or powder) and (ii) secondary sources as a result of fragmentation of larger plastic products [13,83,84,85]. The presence of plastic materials in the marine environment is undeniable and calls for urgent action to reduce this serious threat to the ecosystem and human health. It is estimated that 4% of the world's oil production is processed into plastics and 1.4% of the world's plastic production lands in the marine environment [86]. Approximately 150 million tons of plastic entered the world's oceans, with an additional 9 million tons entering each year. Sixty to 80% of marine litter is plastic debris, and about fifty percent (50%) of the world's annual plastic production is discarded after a single use [85]. The longevity of plastic makes this debris dangerous to marine life and freshwater. For this reason, marine plastic pollution is becoming a major concern for NGOs, the public, scientists and governments. Entanglement in marine debris can cause starvation, suffocation, laceration, infection, reduced reproductive success, and mortality in species (e.g. Antarctic fur seals). Recent studies suggest that the risks posed by microplastics (including fragmentation and degradation of macroplastics, microbeads, and microplastic fibers) in the marine environment may be greater than those posed by macroplastics, but research and policies to reduce pollution from these sources are scarce [85]. Microbeads are usually white or opaque in color and research shows that many surface feeding fish species often mistake microbeads for plankton. For aquatic organisms, the ingestion of plastics is one of the most dangerous adverse environmental impacts on the marine environment. Due to their small size and presence in pelagic and benthic ecosystems, associated microplastic contaminants are potentially bioavailable to many organisms [85]. Table 7 shows the rate of microplastics, products/typical origin and density per polymer type.

Table 7: Percentage of microplastics, products / typical origin, and density per polymer in plastic waste from different studies [84,87,88,89,90].

Polymer type	Portion of microplastics (%) ***	Products and typical origin	Polymer density (g/cm³)
Polyethylene *(LD-, LLD-, MD-, HD_PE)	36-78	Bottles, netting, drinking straws, milk and juice jugs Plastic bags, six-park rings, storage containers	0.91 - 0.97
Polypropylene (PP)	20-100	Rope, bottle caps, gear, strapping, netting	0.9 - 0.92
Polystyrene (PS)	6-80	Plastic utensils, food containers	1.04 - 1.1
Foamed polystyrene		Floats, bait boxes, foam cups	
Polyamide (PA, nylon)	3-20	Netting and traps	1.02 - 1.14
Polyester (PES)	60-96	Textiles, boats	1.24 - 2.3
Acrylic **PC, PC-Bisphenol A	-	-	1.09 - 1.20
Polyoxymethylene (POM)	-	-	1.41 - 1.61
Polyvinyl alcohol (PVOH)	-	-	1.19 - 1.31
Polyvinyl chloride (PVC)	12-19	Film pipe, containers	1.16 - 1.58
Polymethylacrylate (PMA)	-	-	1.17 – 1.20
Polyethylene terephthalate (PET)	7	Plastic beverage bottles	1.34 – 1.45
Polyurethane (PUR)	<10	Plastic film, bottles, cups	1.24 – 2.10
Cellulose Acetate (CA)	-	Cigarette filters	1.22 – 1.24

*LDPE = Low-density polyethylene, LLDPE = linear low-density polyethylene, MDPE = middle-density polyethylene, HDPE = high-density polyethylene; ** PC = polycarbonate; *** Values range depending on literatures and from different sampling places

Microbeads are increasingly being manufactured (to replace natural exfoliants such as pumice, oatmeal, and nut shells) for single-use cosmetics, such as abrasive scrubbing cleansers and toothpaste [85]. Some cosmetic products contain almost as much plastic by weight as the plastic packaging container. The microbeads are designed to be removed by wastewater treatment infrastructure, wastewater treatment facilities are not generally designed to remove manufactured microplastic particles, so they are released into aquatic ecosystems. It is estimated that 8 trillion microbeads [85] are released daily from wastewater treatment plants into the marine environment, with all the associated environmental and public health consequences. Trucost [82] estimates that the damage caused to the oceans by plastic waste (including macroplastics, microplastics and nanoplastic) is US$5 billion under current status quo policies and US$7 billion if alternatives to plastic are used. A growing concern about microplastics is their potential to enter the human food chain through fish, shellfish, and filter-feeding bivalve mollusks consumption, causing potential human health problems. The presence of microplastics in the tissues of filter-feeding bivalve mollusks has been confirmed, but their toxicity risks are poorly understood and represent a field for further research. The presence of microplastics in many animals used in the human food chain, such as fish, shellfish, and crustaceans, is now undisputed. The water and sediments of many estuaries and coastal lagoons expose farmed shellfish to ingestion of microplastics. In addition, fish and other animal feed (fishmeal) used in aquaculture to feed fish, shrimp, and other species can be contaminated by microplastics in these products. In 2018, Carlos de Sá et al [11] identified 59 publications dealing with the interactive effects of other environmental contaminants with microplastics: 63% was carried out on fish, 19% on mollusks, 14% on crustaceans, and 19% on annelids. Regarding the group of organisms studied, the authors identified fish as the first with 14%, followed by a mixture of large and small crustaceans with 21%, mollusks with 14%, annelids with 6%, and relatively few publications on other organisms [11]. PE was often reported in studies on fish (34 publications or 12% of the total number of studies identified), 12 publications on mollusks, 7 on small crustaceans, and 4 on annelids [11]. Microplastics are detected in seafood sold for human consumption, and in both (fish and shellfish) purchased from markets. This fact raises concerns about human ingestion of microplastics through the contaminated consumption of marine species as food and the possible adverse effects on human health. Accurate information on the impact of microplastics on human health through the consumption of fish and shellfish is still in its infancy and needs to be studied and investigated. However, the presence of microplastics in the human food chain is a fact. Motivated by the environmental situation of simultaneous exposure of organisms to multiple contaminants, many publications were produced on the combined effects of microplastics and other environmental toxins, with the main aim of investigating whether there is a positive or negative interaction between microplastics and the toxicological effects of these contaminants. It is possible that microplastics and other pollutants may have synergistic effects on the health of organisms, or that microplastics may act as transport vectors of other contaminants [11]. Trucost [82] estimated that the damage caused by plastic waste (including macroplastics, microplastics, and nanoplastics) to human health and ecosystems is US$63 billion under current status quo policies and US$343 billion if alternatives are used. Therefore, while the use of plastics is economically more advantageous than alternatives, improvements in design and material selection need to be made to optimize the efficiency and durability of plastic materials. How dangerous is the presence of microplastics in our food chain, or when will it become risky for people to eat food contaminated with microplastics? More research is needed to answer these questions. There is also no information on the fate of microplastics in the human body after ingestion.

2.5.10 Plastic recycling

Good management of waste prevents microplastic marine pollution. From a circular economy perspective, there are two types of material recycling [91]: (i) Closed-loop recycling, defined as the use of recycled plastics to make the same product as the original product. The new product is made entirely from recycled plastics or a mixture of recycled plastics and its original counterpart. (ii) The use of recycled plastic in a product other than that from which it was from the original recovered is defined as open-loop recycling. This does not necessarily mean that the new product is a lower-value product (e.g. the production of textiles using fibers from PET bottles) [91]. There are four types of recycling of plastic waste, namely: (i) primary recycling is defined as the material recycling of production waste, (ii) secondary recycling is defined as the recycling of old product parts, (iii) tertiary recycling is defined as the decomposition of the polymer into its monomers (raw material recycling) and (iv) quaternary recycling is defined as the thermal recycling of material waste (incineration for energy recovery). Table 8 shows a typical composition by weight of a sample of post-consumer plastic packaging waste (PC-PPW).

Table 8: Typical weight composition of a post-consumer plastic packaging waste sample [92]

Waste	% Weight
PET	26.80
PVC	24.90
Rubber	3.10
PS/ABS	9.60
PA/PBT and other polymers	5.40
PE/PP (added)	11.90
PE/PP	5.50
PAPER/FIBRE	4.20
METAL/INERTS	8.60

Energy recovery from solid plastic waste uses combustion processes to produce heat, steam, and/or electricity. The high calorific value of some plastics makes them a convenient potential energy source. The typical calorific value for commonly constructed MSW incinerators is between 9 and 13 MJ Kg^-1 [93]. Due to its crude oil origin, PSW has a higher calorific value than other materials compared to gas oil, heavy oil, and other crude oil derivatives, as shown in Table 9. However, it is a fact that a 1% increase in plastic content increases greenhouse gas emissions by about 12.1 kg CO_2 equivalent per ton of MSW [17,94]. In Africa, very dirty plastics and multi-layer plastic packaging are mixed in the waste stream, and are open incinerated with negative environmental consequences to reduce the waste quantity. Refuse-derived fuel (RDF) is an alternative fuel source derived from municipal solid waste (MSW) with calorific values between 10-12 [95]. It is used in the cement industry. Egypt processes 4.25 million tons of municipal solid waste (MSW) to produce about 722,000 tons of RDF, using 31 treatment lines that process 320 tons of waste per day in two shifts [95]. Numerous references confirm the presence of toxic substances such as polycyclic aromatic hydrocarbons (PAHs) and persistent organic pollutants (POPs) such as brominated flame retardants (BFRs), pesticides, dioxins, furans (PCDD/Fs and PBDD/Fs) in recycled plastics [96,97,98,99,100].

The EU's 2019 Single-Use Plastics Directive (SUPD) will boost chemical recycling [101]. Chemical recycling is the process of converting plastic products back into the original raw material through depolymerization [102], better, it is a process of changing the chemical structure by converting polymer waste and turning it into potential raw materials for plastics production or other products [103]. Common processing approaches include solvolysis (using solvents to break down plastic waste into low molecular weight products), pyrolysis (using an inert atmosphere to break down the polymer chain), and gasification (using air or steam in a partial oxidation process to convert plastic waste into gases) [8].

Table 9: Comparison of the calorific value of some of the plastics currently in use with that of conventional fuels [93]

Item	Calorific value (MJkg^-1)
Polyethylene	43.3-46.5
Polypropylene	46.50
Polystyrene	41.90
Kerosene	46.50
Gas oil	45.20
Heavy oil	42.50
Petroleum	42.3
Household PSW mixture	31.8

The destruction of foams and granules in the energy recovery process resulting from WIP also destroys chlorofluorocarbons (CFCs) and some other hazardous blowing agents present, the presence of flame retardants (FRs) in some products is currently a big concern with this technical approach. More than 100 fluidized bed incinerators have been installed worldwide (e.g. in Madrid, such a plant absorbs 10% of the city's waste, including 9% of PSW in the mix) for electricity generation [93]. The physical quantity of plastic waste in Africa is relatively small due to the disposal method of mixing all waste [17]. This fact makes it difficult to find plastic recycling facilities with energy recovery on the continent. Despite the difficult financial situation in many countries, knowledge of the energy potential of plastic waste in Africa could be useful in planning or implementing a thermo-chemical treatment system for energy recovery [17]. Although PET bottles packaging (generally a mono-material product) was recycled for two decades and PET bottles with up to 100% recycled content are on the market, considerable amounts of post-consumer PET waste are still not recycled into new packaging materials [104]. In Africa, the first bottle-to-bottle PET recycling plant (a $6 million facility) was opened in South Africa [104]. The plant has a production capacity of 1,800 kg/h and supplies 14,000 tons/year of recycled PET (rPET) in the PET packaging industry in South Africa and neighboring countries [105]. A closed-loop food-to-food application in packaging is currently only possible with PET bottles. Figure 17 shows a typical plastic life cycle.

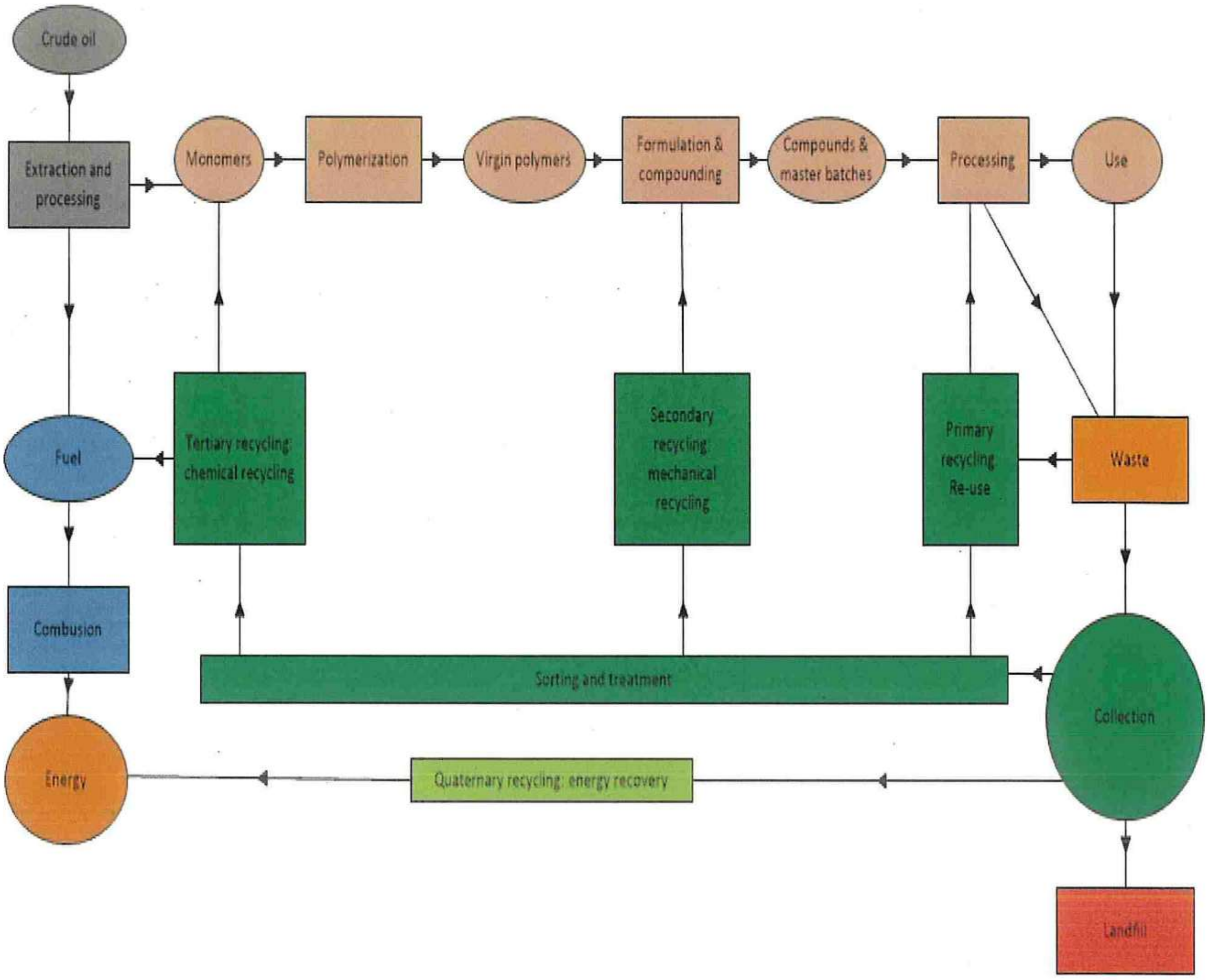


Fig. 17: Typical lifecycle of plastic [92]

There are a few publications in the economic literature, that focus exclusively on plastic waste management. Figure 18 below shows the global plastic packaging waste stream in 2015. This figure confirms that the disposal of plastic packaging remains a global problem that requires a worldwide solution. It also shows that only 28% of plastic packaging was treated in 2015, of which 14% was recycled for material recovery (2% effectively recycled, 8% low-value recycled, and 4% recycled with in-process losses). The remaining plastic packaging (86%) was disposed of as follows: 40% was landfilled, 32% leaked, and 14% incinerated.

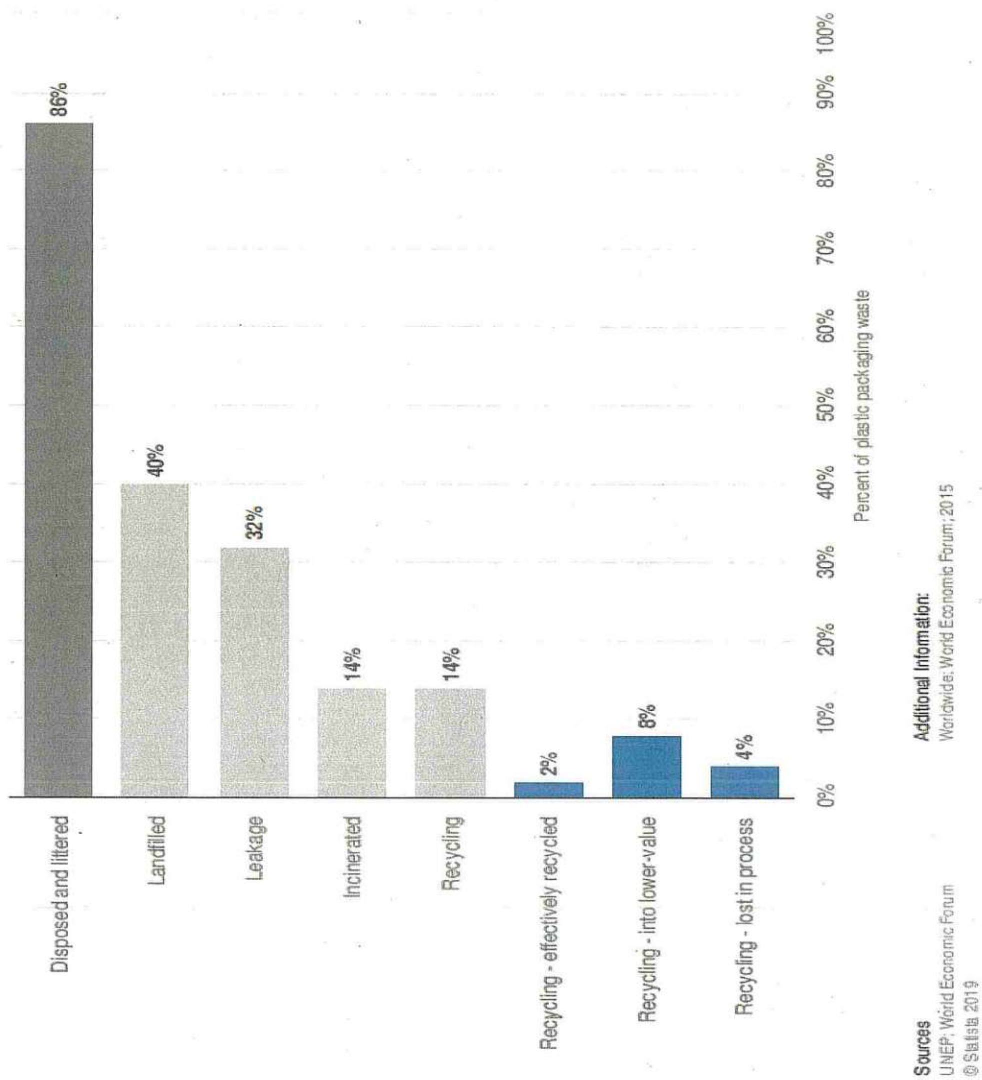


Fig. 18: Plastic packaging waste flow worldwide in 2015 [106]

The market value of plastics recycling was estimated to be around US$31.5 billion globally in 2015. It is estimated to be around US$56.8 billion in 2024, as illustrated in Figure 19 [106].

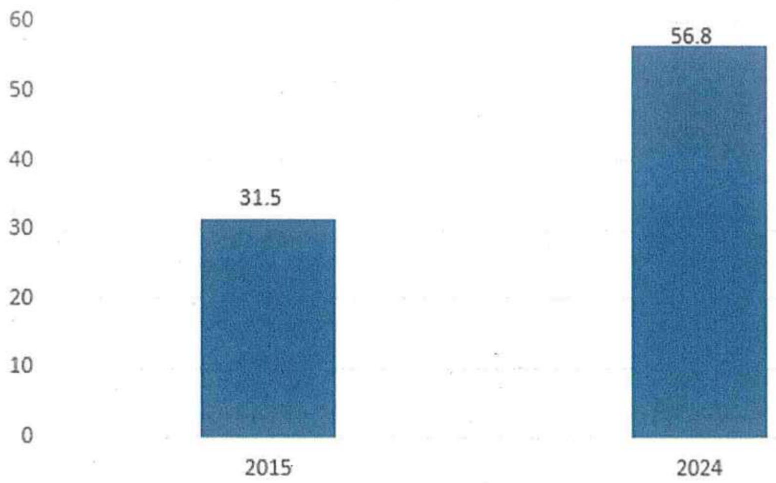


Fig. 19: Global plastics recycling market value (US$ billion) in 2015 and forecast for 2024 [106]

A global alternative strategy is to use international legislation to require the plastic packaging industry to produce only biodegradable plastics. Figure 20 shows the market in billions of dollars for 2018 and the estimate for 2023 and 2027.

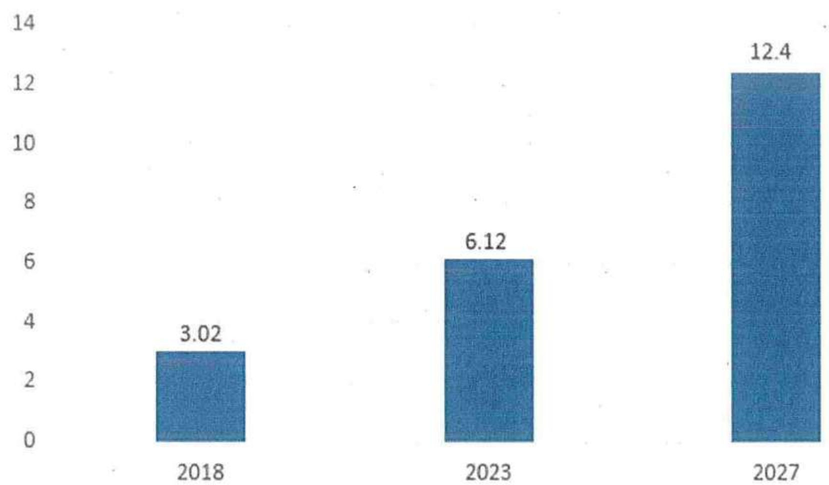


Fig. 20: World biodegradable plastics market (billion US dollars) in 2018, with forecasts for 2023 and 2027 [106]

2.6 Governance and waste

To tackle the local increase in waste electrical and electronic equipment (WEEE) and plastics, many countries are introducing producer take-back and/or recycling schemes. Extended producer responsibility (EPR) requires the producers of EEE to take back and recycle their obsolete products. The best solution to the problem is to do this at national level under the supervision and control of the United Nations Environment Programme (UNEP) or another new international body. EPR will force producers to invest more in innovation to develop appropriate product designs that minimize the environmental costs and make them responsible for EEE and plastic waste treatment costs. In practice, this means that each producer bears only the recycling costs associated with its product (individual producer responsibility) or shares all the costs of the final product (collective producer responsibility). The recycling chain is best financed by an efficient model that regulates the financing and cost calculation for different product categories. Different producers participating in the same collection system and producing different EEE need to know their financial shares. The most efficient product collection system must be achieved at the end of life (EoL), when many producers share the same collection system and the associated costs. This is typically realized in Europe through the creation of Producer Responsibility Organizations (PROs), as mentioned above by Pia Tanskanen [107].

All stakeholders play a key role in the recycling process, from the collection of end-of-life products to final disposal of non-recyclable components in landfills. Their involvement in e-waste management is crucial to follow a strategy that can optimize collection efficiency, maximize the recovery of the valuable materials, and minimize the amount of material to be disposed of. In addition, the stakeholders in this case consisted of producers, retailers, vendors, government and local authorities, consumers (individually or collectively organized NGOs), and the recycling industry. All of them are people who act and influence the effectiveness of the recycling process. As a sustainable solution, all relevant stakeholders must agree to provide funding and share costs. In other words, they must all contribute to ensuring that the recycling of electrical and electronic equipment and plastic waste is efficient, cost-effective, accessible, and economically viable.

For African countries, peace and political stability are the first conditions that will facilitate the establishment of a medium- and long-term waste management policy. A political will of leaders to make sustainable waste management a principal priority in their development policies follows. To this end, a strategic plan with a precise timetable will be drawn up. It will be respected by all those who come to power through democratic and credible elections that reflect the will of the grand majority of the people. The authorities must listen to the public and promote national social cohesion. This makes it easier for them to raise awareness of waste prevention measures, ensure high collection rates, and transport waste to appropriate collection points. It also facilitates awareness campaigns and compliance with national waste legislation.

3 Methodology

To address our topic, we have consulted numerous useful sources and databases such as International Scientific Publications, reports from organizations, websites, and policy documents. Over 500 articles were reviewed using keywords like "waste management in Africa," "e-waste in Africa," "e-waste management in Africa," "e-waste toxic substances," "In Africa generated e-waste," "e-waste valorisation," "waste and Africa population," "e-waste management in Austria," "Repair services for EEE devices as a source of clean jobs creation," "negative impacts of e-waste of the environment," "e-waste treatment plants in Africa," "plastic production in Africa," "Africa plastic import," "second-hand clothes trade," "second-hand clothes waste in Africa," "plastic waste management in Africa," "plastic recycling in Africa," "plastic waste treatment plants in the world," "micro-fibres in African wastewater," "micro-plastic in African aquatic environment," to name a few.

We used Design for Environment (DfE) guidelines [108] and sustainable product design metrics [109] to highlight the problem in Africa, in particular the permanent increase in the EEE waste amount if the current business-as-usual model continues. Even the coronavirus pandemic hasn't stopped this trend. The mobile phone market in Africa grew during this turbulent period, confirming its resilience and the increasing potential for waste generation. Manual dismantling of WEEE provides the best recovery rate of original components and materials without damaging them. This facilitates sorting and improves reuse. To achieve this, we use the 76 Design for Environment (DfE) guidelines defined by Telenko C. et al [108] and select those that ensure that all EEE sold on the African market meet the desired design. And use the metric for measuring sustainable product design concepts by Han J. et al [109] to confirm the sustainability of the selection, particularly measuring material, production, use, and end-of-life. The methodology can be applied to all electrical and electronic equipment to improve the sustainability of all products. The mismanagement of plastic waste in Africa is studied, its sources are presented, analyzed, and discussed to propose appropriate solutions.

Finding the best solution to waste problems requires implementing state-of-the-art recycling processes that avoid negative impacts on living organisms. However, this requires a certain level of expertise and investment. Effective electronic and plastic waste management relies on several key components: the conception and realization of environmentally friendly product designs, efficient waste collection systems, safe material recovery methods, proper disposal techniques, and a ban on the shipment of non-functioning electronic equipment to developing countries. It is also important to raise public awareness of the negative impact of WEEE and plastic waste on the environment and living organisms. The fulfillment of effective waste management (recycling) strategies is vital.

We used relevant literature, sorted the information, analyzed the relationships between them, and structured this thesis as follows: After the above literature review and the current chapter, the chapter "Results and Discussion" follows and ends with "Conclusion and Perspectives" as the last section.

4 Results and Discussion

4.1 Result/Summary of research papers

As part of this thesis, we published two major review papers. The first paper gives an overview of the problems of WEEE management in Africa and proposes an approach to address the treatment deficits. It presents the environmental impact assessment of WEEE and the 'circular economy' approach to recover materials contained in EEE products at the end of their use life through recycling. This has to be done according to the state of the art and adapted to local realities. Secondary raw materials are materials produced by processing waste materials to replace the use of primary materials. The circularity enables the conservation of primary ores and significantly reduces the carbon and environmental footprint. Standard electronic products and their components, such as batteries, switches, relays, and printed circuit boards, contain antimony, barium, beryllium, cadmium, copper, gold, lead, lithium, mercury, nickel, silver, palladium, and zinc [110,111,112]. In addition, electronic products contain various organic chemicals and rare earth metals. The health effects of rare earth elements (REEs) have not been adequately studied. The manufacture of mobile phones and personal computers consumes enough gold (Au), silver (Ag), and palladium (Pd) mined worldwide each year. The electronics industry is the third largest consumer of gold, accounting for 12% of total gold demand [61]. In 2019, the US EEE manufacturing industry used 9% of total aluminum, 21% of beryllium, 19% of copper, 40% of gold, and 26% of silver. Rare earth elements (REEs) are widely used in digital technologies compartments such as disc drives and communication systems, batteries and fuel cells for hydrogen storage, catalysts, light-emitting diodes (LEDs), and fluorescent lighting [64].

Han J. et al. [109] determined the value of the negative environmental impact caused at the design stage, with a result that could reflect the level of sustainability in a simple but effective way, using the measurement scales of low (0), medium (1), and high (2) to indicate sustainability attributes. The authors have clearly defined the conditions under which each metric category (material, production, use, and end-of-life) can be calculated to support decision-making. Based on the Design for Environment (DfE) guidelines and metrics for sustainable product design, the international community can establish criteria for placing products on the global market and significantly reduce the environmental problems associated with WEEE. If these criteria are applied to produce appliances, Africa will also benefit. The following equations are used for $\text{Metric}_{Material}$, $\text{Metric}_{Production}$, Metric_{Use}, and Metric_{EOL} [109]:

$$Metric_{Material} = \frac{9 \times \left(\frac{\sum_{i=1}^{N} (M_1+M_2) \times M_3}{N} \right)}{8} + 1 \quad (1)$$

$$Metric_{Production} = \frac{9 \times (P_1 \times P_2 + P_3) \times P_4}{12} + 1 \quad (2)$$

$$Metric_{Use} = \frac{9 \times U_1 \times (U_2 + U_3)}{8} + 1 \quad (3)$$

$$Metric_{EOL} = \frac{9 \times (E_1 + E_2 + E_3) \times E_4}{12} + 1 \quad (4)$$

We evaluate each metric (material (M), production (P), usage (U), and EoL (E)) related to a mobile phone Table 10.

Table 10: Evaluation of each metric measurement

Metrics	Attributes	Business as Usual Production	Under Selected DfE Conditions Production
Material	Material origin (M_1)	• Stainless steel (1), screen (1), plastic (1), battery (0), ceramic as composite (0)	• Only recy. stainless steel (2), only recy. * LCD screen (2), recy. PC-plastic (2), recy. battery (1), natural ceramic (1)
	Material property (M_2)	• Stainless steel (1), screen (1), plastic (1), battery (0), ceramic as composite (0)	• Only recy. stainless steel (2), only recy. LCD screen (2), recy. PC-plastic (2), recy. battery (1), natural ceramic (1)
	Use material quantity (M_3)	• Stainless steel (1), screen (1), plastic (1), battery (0), ceramic as composite (0)	• Only recy. stainless steel (2), only recy. LCD screen (2), recy. PC-plastic (2), recy. battery (1), natural ceramic (1)
	Use of material type (N)	5	5
	$Metric_{Material}$	2.4	7.3
Production	Balance between the number of parts and complexity (P_1)	Currently design standard with a mass production (2)	The same design standard with a few more steps like the production of recycled components (1)
	Parts standardisation (P_2)	Battery and some components can benefit from standard component (2)	Some components require customisation (0)
	Parts design for assembly (P_3)	Good potential for assembly (2)	Good potential for assembly (2)
	Suitable fabrication method (P_4)	Currently valid operations are needed (2)	Relative more operations are needed (1)
	$Metric_{Production}$	10	2.5
Use	Product use time/lifetime (U_1)	The design time needs to be closer to its use time (1)	The design time needs to be closer to its use time (2)
	Energy consumption during use (U_2)	Needs battery to power (1)	Needs also recy. battery to power (2)
	Robustness, reliability, and maintenance (U_3)	Internal components for the base will require a fair amount of resource to maintain/service (1)	Internal components for the base will require a fair amount of resource to maintain/service (1)
	$Metric_{Use}$	3.3	7.8

Metrics	Attributes	Business as Usual Production	Under Selected DfE Conditions Production
	Reuse (E_1)	Battery and some components have fair potential to be reused (1)	Battery and some components have great potential to be reused (2)
	Recycling, remanufacturing, and repair (E_2)	All material involved can be recycled or not (1)	Almost all material involved can be recycled (2)
	Disposal (E_3)	Blender base that contains battery and some components will not be easy to disassemble (1)	Battery and some components cause a very slight negative impact due to disposal (1)
	Ease of disassembly (E_4)	Blender base that contains battery and some components will not be easy to disassemble (1)	Blender base that contains battery and some components will be easier to disassemble/landfill (2)
End of life	$Metric_{EOL}$	2.5	8.5

The authors used a scaling process to ensure that the final value of each metric fell between 1 and 10, where 1 represents poor sustainability and 10 excellent sustainability, to produce an easily understandable result. Table 11 shows the results of each metric measurement.

Table 11: Result of each metric measurement

	Business as usual production	Production using DfE guidelines
Material	2.4	7.3
Production	10	2.4
Use	3.3	7.8
End of life (EoL)	2.5	8.5
Average value	4.6	6.5

The table shows that production based on current practices receives the highest score of 10. This is simply because we assume that companies find the current production process comfortable (i.e. profitable) despite the low score value (2.5) EoL metric measurement. However, we do not share this view. The alternative approach shows that all other scores (material, use, and end of life) are above 7 and above average, reflecting good environmental performance. Although the cost of this alternative has not been assessed, we believe it is the way forward given the threat of climate change and its disastrous consequences for people and the environment. Applying this method to all other electronic and electrical equipment (EEE) can help designers make environmental choices at the design stage. Modern e-waste management requires more investment in advanced technologies to recover valuable metals. However, this is not currently the case in developing countries and needs to be improved. E-waste management in Africa is still in informal hands, which is dangerous for the environment and living beings.

The second paper analyses and discusses the sources and reasons for plastic mismanagement in Africa. Africa produces very little plastic and uses it sparingly for essential purposes such as water storage. But Africa has become a dumping ground for plastic waste from the northern hemisphere (i.e. Europe and the US) in the form of so-called "recycled" plastic and clothing feedstock. Globally, only 9% of plastic waste is recycled, while 22% is mismanaged. In 2015, it was reported that 12% of plastic waste was incinerated, while 79% ended up in landfills or leaked into the environment [112,113]. Single-use plastic packaging is the largest segment of plastic produced globally [114]. After Asia, the African continent is where the mismanagement of plastic waste is most widespread and visible [115]. Thirty-three African countries imported about 126 million tons (Mt) of polymers in primary form and 46 Mt of plastic products between 1990 and 2017 [116], which means that all these countries imported about 172 Mt of plastic materials and polymers during this period [117], with an estimated value of US$285 billion [118,119]. The paper focuses on African countries, which have received little attention to date, and takes an approach to assessing the impact of plastic production and waste management in Africa. The situation is critical [120] and needs to be addressed. This study attempts to synthesize the existing literature and provide empirical support for the underlying issue of sustainability in Africa, to produce results that will redefine policy and industry on this issue. Africa produces 5% (19,535 kilotons in 2021) and consumes 4% of the world's plastics [121,122,123]. Plastics are used daily for various purposes, such as packaging goods, beverages, and food for easier transport, shoes, clothing, telecommunications, transportation, etc. [119]. Egypt, with 2,329 kilotons (kt), South Africa, with 1,410 kt, and Nigeria, with 513 kt, were among the biggest African plastics producers in 2020 [122]. Imports of plastic raw materials from some African countries have increased significantly in recent years. It is hard to have statistics on all African countries for the same year. Therefore, we used different references for different years. For example, between 2007 and 2020, Algeria's imports will increase from 304 to 931 kt (+108%), Morocco's from 374 to 659 kt (+76%), Tunisia's from 209 to 326 kt (+56%), Nigeria's from 513 to 848 kt (65%) and Ethiopia's from 54 to 224 kt (+315%) [124]. Egypt and South Africa imported 896 kt and 539 kt of plastic raw materials in 2020 [124]. Lightweight, elasticity, and low cost make plastic more attractive for designing products. Most of the packaging used in Africa is poor quality single-use plastic bags (designed to be used once and discarded) [125] for fresh vegetables and perishable goods for daily shopping. Egypt, Nigeria, and South Africa are the largest producers and importers of plastic polymers and products (including imported packaging). In Ghana [118], 150,000 sachet water bags are produced daily by large companies and 45,000 bags by small companies (85% of the plastic waste generated in Ghana). In addition, over 60 million sachets are consumed daily, with around 1,500 sachet water factories in Lagos (Nigeria) alone [118]. In 2015, Africa generated 19 million tons of plastic waste, of which 17 million tons (90%) was mismanaged [115,126], compared to 60-99 million tons (15.8-26.1%) of mismanaged plastic waste globally in the same year. Only a few African countries have small-scale recycling facilities with a total capacity of 78,980 tons per year [127], while the EU-27+3 (the current EU-27, Norway, Switzerland, and the United Kingdom combined) have recycling facilities with a capacity of over ten million tons per year. In general, municipal solid waste (MSW) contains about 8-12% plastics [128], which can release toxic gases into the atmosphere if incinerated improperly [129]. Toxic substances have been confirmed in recycled plastic waste [96,98]. Concentrations of PAHs and polychlorinated biphenyls (PCBs) have been detected in sediment cores from the Lagos (Nigeria) lagoon system, which may pose a significant ecotoxicological risk to estuarine organisms [130]. Due to the mismanagement of plastic waste on land, about 80% of all plastic waste in Ghana (similar to most African countries) comes from land-based sources, while 20% comes from marine sources [131]. The World Wildlife Fund (WWF) [115] has reported that four major African rivers (Congo, Niger, Nile, and Zambezi) are among 14 major rivers around the world that have been identified as hotspots for plastic leakage from land-based sources, close to urban centers with high waste generation but poor waste management systems. The presence of microplastics such as polystyrene (PE), polypropylene (PP), polyvinyl chloride (PVC), polyamide (PA), polystyrene (PS), polyurethane (PU), ethylene vinyl acetate (EVA), acrylonitrile butadiene styrene (ABS), polyethylene terephthalate (PET) and a mixture of PE and PP in epipsammic sediments has been documented in Nigeria [132]. Microplastics and other contaminants may have a synergistic consequence on the health of organisms or act as vectors for the transport of other contaminants [11,133,134]. Numerous studies report the presence of microplastics in fish, salt, drinking water, rice, etc. Globally (including Africa), an average of 22 million tons of macro- and microplastics will enter the environment in 2019 [135]. To reduce the problem of plastic pollution, many African countries have banned single-use plastic bags, but enforcement and implementation remain a challenge [113]. In Rwanda, a combination of strong legislation, enforcement, and arguably successful policy was implemented to reduce plastic pollution [136]. The lack of monitoring and data management systems limits the government's ability to quantitatively measure and evaluate the actual impact of plastic policies, which is necessary to design, improve, and implement sustainable plastic waste policies [137]. Recycling with material recovery is an appropriate solution to plastic waste pollution.

Recycling used clothing reduces greenhouse gas emissions by 53%, pollution from chemical processing by 45%, and water eutrophication by 95% [78], contributing to sustainable resource management. Each stage of the textile waste recycling chain (i.e. collection, sorting, transport, and recycling) creates jobs and provides new opportunities for small and/or family businesses. The immense quantities of textile waste generated by the secondhand trade (legal and/or illegal) are a potential source of income for African countries if a chemical recycling process is established.

4.2 Discussion

The value of the raw materials in e-waste worldwide is estimated to be US$10 billion in 2019 [61]. This means that Africa needs to recognize that urban mining is not only a way to manage sustainably its raw material resources (resource conservation) but also a way to significantly increase income if done according to the state of the art. In addition, improving repair services in the formal sector through appropriate training can be a source of wealth creation. Although the African population lives slightly below the poverty line, they contribute to conservation, consciously or unconsciously, simply by preserving their products for as long as possible. Energy savings are high when recycled materials are used instead of raw materials in electrical and electronic equipment.

In Africa, it is essential to improve plastic waste management through a better collection system, a ban on improper dumping, the reuse of plastic products, and the improvement of plastic recycling. We believe that awareness campaigns to improve individual consumption of plastic products are very important. All stakeholders need to be involved in the early stages of plastic waste prevention measures. To show their willingness to take responsibility for actions, to increase commitment, and to agree with all measures to be implemented at the end of the process (Corporate Social Responsibility (CSR): Multinationals are recommended to participate in the social and environmental standards enhancement in the world) [138]. The logistical organization of waste collection plays a key role in its subsequent treatment. Communities in Indonesia have set up places where villagers can dispose of their waste instead of burning it or dumping it in nature or rivers. Since 2008, local households organized themselves into groups and set up a 'waste bank', which is not a bank in the traditional sense [139]. In theory, it works like a classical bank. The only difference is that people save the monetary value of their waste instead of money. Each customer receives up to A$2.50 (2.50

Australian dollars) per month [139]. Approximately 11,532 waste banks are registered in 362 Indonesian municipalities/districts and operate smoothly without financial difficulties. Many of these banks are run or owned by women [139,140]. The Indonesia National Plastic Action Partnership (NPAP) is a multi-stakeholder platform that brings together government, academia, researchers, experts, industry, financial institutions, the private sector, and civil society organizations to address plastic pollution and achieve a 70% reduction in marine plastic litter by 2025 [140,141]. Waste banks have become an important tool to achieve this goal. Huge investments are planned for waste management and recycling between 2017 and 2040, around US$18 billion [140]. African countries can use this cheaper and more cost-effective tool (waste bank) to collect their EEE and plastic waste.

The operating costs for a pyrolysis plant with a capacity of 30,000 tons per year are as follows: over US$100/ton for plastic waste, US$196/ton for pyrolysis costs, US$5 for disposal/transport in the USA, France, Singapore, and China [142]. Together over US$300/ton is the price for such an operating pyrolysis plant. The construction of a facility is very costly for many African countries, which are already struggling with education and health problems (lack of adequate infrastructure). A feasibility study is required before building a recycling plant in Africa. This will help to know the amount of generated waste, its quality, the estimated cost, and the best location for the project. Pyrolysis of plastics is a promising technology for converting plastic waste into valuable products. However, it faces technology barriers like efficiency, scalability, and maintenance. Pyrolysis plants require a high initial investment. In Africa, external financial support is needed and it is a challenge for African governments to enforce and comply with legislation [143]. BASF in Korea uses chemical recycling to convert plastic waste into new materials with the same properties as those made from fossil raw materials [74]. According to PlasticEurope, 44 plastics and recycling projects are planned in 13 EU countries to promote chemical recycling. Conversion to feedstock technologies using pyrolysis and/or gasification will account for 80% of the planned capacity [144].

Large quantities of unwanted used clothing from the USA (about 500,000 tons exported per year) and the UK (about 319,998 tons per year) end up in Africa [19,145]. Kenya was Africa's leading importer of used clothing in 2021 (184,000 tons) [146]. Ghana, Benin, Tanzania, Kenya, and Uganda received between 2% and 4% of the world's exported SHC [147]. Recycling used clothing can reduce greenhouse gas emissions by 53%, pollution from chemical processing by 45%, and water eutrophication by 95% [78], contributing to sustainable resource management and the well-being of people in Africa. The results of a study [148] about textile waste into energy conversion attest that cotton briquettes made from textile waste have a calorific value of 16.80 MJ/kg and a cost of 0.006 EUR/kWh when used as fuel. This represents an annual fuel cost reduction of 80% and 75% compared to fuel oil and wood pellets respectively [148].

5 Conclusion and Perspectives

Conclusion/Remarks

Therefore, without an effective environmental policy, poor quality plastic products and "pseudo-products that are de facto waste" will increase in Africa and lead to a critical situation for people's lives. In the short term, the illegal/legal trade of unwanted used clothing, unusable plastic waste, and e-waste from developed countries to Africa and between African countries must be banned. Energy recovery is currently not widely used in Africa. It is time to move away from the open burning of plastic as a waste reduction method to sustainable and environmentally friendly solutions for waste management. The best way to reduce textile waste is to reduce the production of new clothes and increase the quality and life of these new products, as suggested by the European Commission's Waste Hierarchy (2018) [145]. In the medium term, African countries need to implement a strategy through legislation for a well-organized and selective collection system for plastic and electronic waste. This will maximize the collection rate of all these wastes and protect the environment. Within this timeframe, it is also hoped that industry will use clean and sustainable technologies to develop products that meet environmental standards and are easily recyclable, in the spirit of a circular economy (material recovery). In addition, secure incineration facilities to treat proper plastic and obsolete SH clothing is a viable medium-term solution that transforms waste into energy production while minimizing environmental impact. The 9Rs concept mentioned in the introduction must also be part of Africa's waste management strategy for the future. In the long term, Africa needs to improve its waste management by raising public awareness through campaigns and education systems to reduce waste generation. In addition, political stability, government commitment, and good economic data can enable African countries to access innovative, clean technologies for advanced recycling of post-consumer EEE and chemical treatment of end-of-life plastic products.

Proposed regulations should require companies to produce sustainable and repairable products, with ample influence on their product design. Producers, importers, and consumers should address a hierarchy of measures and key considerations:

- Evaluate the need to use the material
- Implement strategies to minimize the amount of material used
- Choose materials that are easy to recycle
- Design products for easy disassembly at the end of their life cycle

Perspectives

The effectiveness of the organization of a solution-oriented society is determined by the progress of its capacity for technological innovation to meet people's needs (including the protection of the environment). In addition, governments need to enforce and respect rules. Concepts such as self-development in the socio-cultural field, self-governance in the socio-political field, and self-sufficiency in the technical-economic field are principal instruments of designing a system tailored to people's needs [149]: (i) The Knowledge, Skills, Attitudes, and Habits (KSAH) model [150] highlights the components to improve self-awareness and put the foundation for continuous development that ultimately leads to self-satisfaction, performance, and success. Constant self-questioning of adopted principles, values, and goals is the right attitude (self-development in sustainability) to observe. A good equilibrium is required between independent values and goals, long-term infrastructures (recycling plants), and the ability to respond to short-term trends. In this context, the local adaptation of the implementation and use of the best available technologies should be a societal goal. When the results of technological development are integrated into economic and social processes, they also bring about changes in the organizational structures concerned and an adjustment of values in these new structures. Taking this into account throughout the life cycle enables appropriate holistic technology development to improve the quality of life. (ii) Self-determination is linked to human autonomy, meaning individuals can choose, change, and influence all aspects of their lives (empowerment in sustainability) [151]. Structures in a self-governing society can be created through deliberately chosen technical and economic infrastructures. All these elements can be very well developed in universities and research institutions, tested, and optimized in some cases for public use within internal (self-)governance. Unfortunately, politicians/authorities in Africa tend to use regulations and punitive measures to enforce rules without a sensitization phase.

A future-oriented global plastics industry, consistently oriented towards the circular economy, is committed to mechanical recycling and design for recycling. This should play a central role in the public debate and the investment decisions of all stakeholders. A comprehensive investment and technology offensive for reduction, reuse, and recycling is lacking in many chemical companies. Instead, it is always emphasized that chemical recycling should be used where mechanical recycling is not sufficient. This may be true, but who in the plastics industry has tried to back up this claim with practical experience? The question is if we have exhausted all the possibilities for environmentally friendly mechanical recycling. Massive investment in chemical recycling does not seem justified at present. The fact is that there is little interest in the serious recycling of plastics, which was not part of the training of chemical and plastics engineers. Chemical and plastics engineers have been taught to think "linear". Circular thinking has been encouraged and supported in universities only in recent years. We are still at the very beginning of plastic circularity. If the alignment of existing industrial value models with a sustainable carbon cycle succeeds, then the future of plastics can be promising. Africa must create incentives to move e-waste processing from the informal sector into the formal sector. This will generate income without risk for workers' health. In the future, this means setting up state-of-the-art, clean recycling facilities with the latest technology to treat this e-waste and recover precious metals for sale on the metals market to conserve resources and create a healthy environment for living beings. All stakeholders are required to work together to achieve the "greening" of the electronics industry.

This may sound utopian in 2025 when oil is plentiful and recycling technologies are unprofitable. But imagine if all the oil wells suddenly dried up human ingenuity would quickly find ways to use the carbon trapped in landfills. Today's technologies and markets are advancing, and materials considered "non-recyclable" in 2025 could be "highly recyclable" by 2050. We could extract valuable carbon from waste and use it in manufacturing. Even crude oil was once used as a light bulb or lubricant until ingenuity and engineering turned it into one of the most valuable commodities.

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SECTION II

Peers-reviewed papers

environments

MDPI

Review

Electrical and Electronic Waste Management Problems in Africa: Deficits and Solution Approach

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Abstract: The lack of proper waste management in developing countries results in environmental pollution and human illness. This review presents the available data on the electronic and electrical waste generated and/or transported in Africa. Particular attention is given to waste treatment and the recycling sector, as well as methods for recovering metals from e-waste. The roles and responsibilities of stakeholders and institutions involved in Africa are discussed. Design for Environment guidelines and Sustainable Product Design Concepts are illustrated to find proper strategies for managing e-waste in general, and for Africa in particular. Raising awareness among national and international institutions is necessary to improve e-scraps management in Africa. Measures should be taken to facilitate the transition of e-waste management from the informal to the formal sector, which will create decent jobs and corresponding incomes.

Keywords: recycling; Design for Environment (DfE); sustainability metric measurement; e-waste valorization; hazardous substances; Africa; urban mining; Perceived Behavioral Control (PBC); Theory of Planned Behavior (TPB)

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Citation: Moyen Massa, G.; Archodoulaki, V.-M. Electrical and Electronic Waste Management Problems in Africa: Deficits and Solution Approach. *Environments* **2023**, *10*, 44. https://doi.org/10.3390/environments10030044

Academic Editor: Manuel Duarte Pinheiro

Received: 20 January 2023
Revised: 17 February 2023
Accepted: 23 February 2023
Published: 5 March 2023

1. Introduction

Littering has concerned humanity for decades [1]. Organic and biodegradable waste has not always been an urgent concern for humans and the environment. However, as the world population grows, so too does the production of goods to meet demand [2]. Unfortunately, the increased consumption of various goods has led to a substantial increase in electrical and electronic waste, which has become a serious threat to humans, animals, and the ecosystem due to the toxic substances contained within them [3]. The management of municipal solid waste (MSW) is a major problem worldwide, especially in developing countries [4]. Due to a lack of funding, interest in solutions, efficient urban planning, poor equipment for waste collection, and increasing city populations, waste management has become a serious health and environmental issue in developing country municipalities. At the end of their life cycle (EoL), goods need to be either disposed of or appropriately processed with material and/or energy recovery [5]. This step is crucial to avoid negative impacts on the Earth and marine pollution, which can have serious consequences for the environment and people. Admittedly, Africa has the lowest per capita generated e-waste rate in the world. The predominance of the informal sector in many African countries (accounting for more than half of the GDP in many of these countries [6]) has led to a deterioration of the situation in the case of waste of electrical and electronic equipment (WEEE). Design for Environment (DfE) [7] guidelines, along with sustainable product design measurement metrics [8], can be used to find suitable solutions to the problem in Africa. This work presents a solution approach based on the idea of a "circular economy" with the aim of recovering materials contained in products after their use time through proper recycling of e-waste according to the state-of-the-art and adapted to local realities.

2. E-Scraps Generated

It is generally known that, in the case of reuse, the owner of a functioning device hands it to a third party by sale or donation (second-hand user) after some service life. The devices are only tested and cosmetically cleaned without further disassembly or replacement of parts. Repair is a necessity linked to a defective product after some service life. In the case of Repair-and-Reuse, the owner of a product no longer covered by a guarantee can either repair it for self-reuse or sell it to a third party that, depending on economic conditions favorable to the buyer, can repair, upgrade, or refurbish it before putting it back on the market [9]. The repair phase is the last step before entry into a recycling process. The difference between them is that by recycling, the original product will completely disappear (be discarded) to obtain some components/materials or/and energy recovery (suitable disposal), while by repair, the device still exists. Refurbishment can be defined as repairing an old product by upgrading it and making it a new product different from the old one. Recycling describes the physical and/or chemical processing of collected product waste with the main aim of recovering materials and/or energy contained in the products at the end of life [10]. The best available technology should be used to quantitatively and qualitatively minimize the residues obtained at the end of the waste treatment process, if this cannot be completely avoided. The life cycle (LC) of a product begins with raw materials extraction, followed by production in factories, the consumer use phase, the waste management phase, and the final waste disposal at the end of life (EoL) of the product [11]. Encouraging both "Reuse" and "Repair-and-reuse" to keep electrical and electronic products alive for as long as possible before bringing them into the recycling process extends the lifespan of products. This is especially important since the consumer use phase, in many cases, is very short.

E-waste [12] covers a large spectrum of valuable electrical and electronic products incorporating non-precious metals (iron, steel, copper, aluminum, etc.), precious metals (gold, silver, palladium, platinum, etc.), plastics, and hazardous substances (e.g., lead-containing glass, mercury, cadmium, batteries, flame retardants, chlorofluorocarbons, and other coolants with the potential to greatly impact the environment). In fact, the outputs of e-waste after treatment generally look, by weight, as follows: 38.1% ferrous metals, 16.5% non-ferrous metals, 26.5% plastic, and 18.9% other [13]. Figure 1 shows the worldwide generated e-waste per region and per waste stream in 2019 (53.6 Mt e-waste was generated in total). It is worth mentioning that since 2014, only the screens and monitors category has decreased (-1%), while the other five stream categories have increased in quantity between 2% and 7%. Secondary raw materials are materials that have been generated from the processing of waste materials to substitute the use of primary materials. Resource recovery from the use of secondary raw materials makes the conservation of primary ores possible, significantly reducing the carbon and ecological footprints. Much of the literature has focused on the LC of daily products like mobile phones, notebooks, desktops, televisions (TVs), and refrigerators/washing machines [14–21]. In the USA, 9% of all aluminum, 21% of beryllium, 19% of copper, 40% of gold, and 26% of silver were used in the EEE manufacturing industry in 2019 [22]. Rare-earth elements (REEs) are commonly used in digital technologies such as disk drives and communication systems, but also in batteries and fuel cells for hydrogen storage, catalysts, light-emitting diodes (LEDs), and fluorescent lighting [23]. In 2018, the recycling rate of REEs was around 1% [24] due to their relatively low prices, but the demand for some REEs surpassed their supply and continues to increase, making their recycling and/or seeking of alternatives an important matter. The concentration of REEs greatly varies depending on the type of e-waste [25]. The unique magnetic and electronic properties of REEs make them abundant in computer hard disk drives, phones, and iPods. Hard disk drives have the highest content of any sample, including neodymium (Nd) > lanthanum (La) > praseodymium (Pr) > dysprosium (Dy) > gadolinium (Gd), with each element ranging from 0.01-0.2% [25]. Erbium (Er) and Thulium (Tm) are the rarest detectable REEs in e-waste samples [25]. Table 1 presents some products with their average weight and estimated lifespan. After their LC, all these devices become obsolete and are considered electrical and electronic waste.

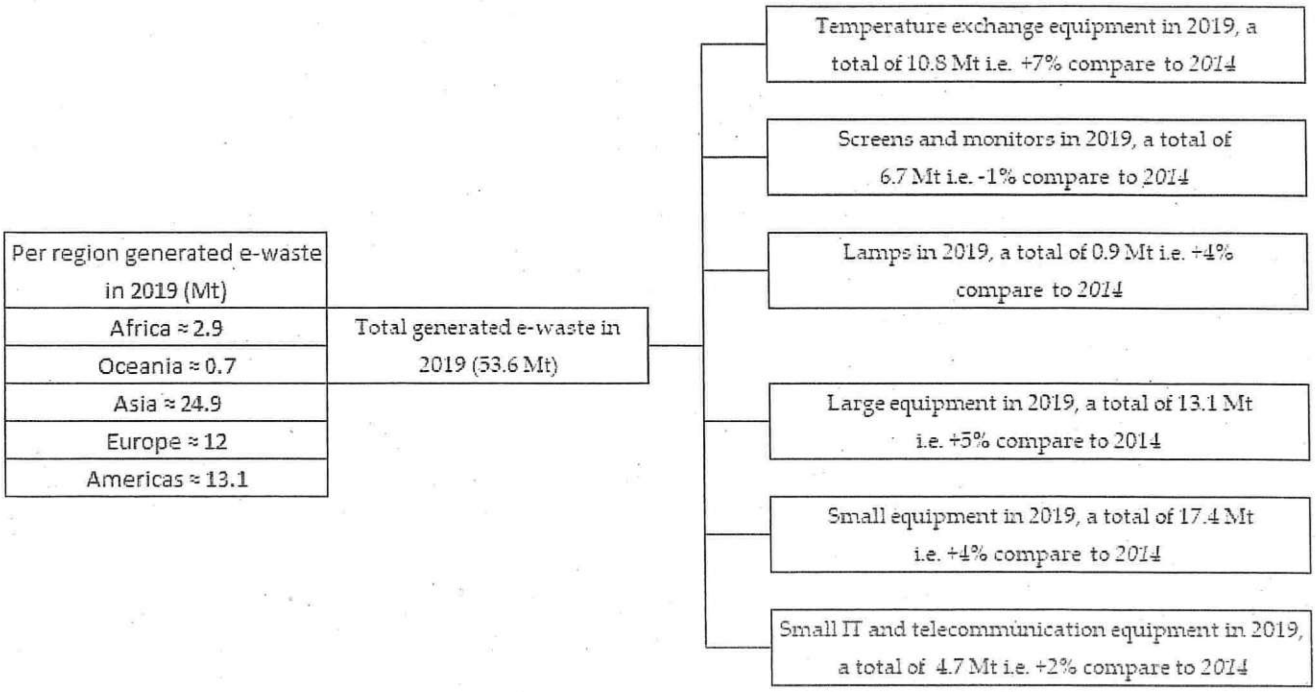

Figure 1. E-waste generated worldwide in 2019 by region and waste stream category [26].

Table 1. Average weight and estimated lifespan of devices mentioned above [21].

Item	Average Item Mass (kg)	Estimated Lifespan (years)
Cell/Mobile phone	0.1	2
Notebook *	2.3	4
Desktop computer	25	5
Television	30	5
Refrigerator	35	10
Battery *	0.055	3.5

* Estimation by measurement.

3. Special Case of Batteries

Batteries are one of the most important and critical components of electrical and electronic equipment (EEE). Lithium-ion (Li-ion) batteries are one of the most used cells in Europe and, more broadly, the world. Currently, three different Li-ion cell types exist, namely cylindrical, prismatic, and pouch cells [27]. They can be found in various applications, such as mobile/cell phones, laptops, tablets, and in the automotive sector, such as e-mobility, electric vehicles (EV), hybrid electric vehicles (HEV), and plug-in hybrid electric vehicles (PHEV). Additionally, the world of batteries comprises non-rechargeable (also called primary batteries, such as Zinc Carbon "ZnC", Alkaline Manganese "AlMn", Zinc Air "ZnAir", Silver Oxide "AgO", and Lithium Manganese Dioxide "$LiMnO_2$" batteries) and rechargeable (also called secondary batteries, such as Nickel Cadmium "NiCd", Lead-Acid, Nickel Metal Hydride "NiMH", lithium-ion "LiB", and Li-ion-polymer "Li-Po" batteries) [27]. Lead, manganese, nickel, cadmium, lithium, to name a few, can cause health problems. The batteries, which can sometimes be very small, are dispersed and can be found everywhere. Children can encounter these substances and contract diseases [28]. Common electronic items and their components, such as batteries, switches, relays, and printed circuit boards, may contain antimony, barium, beryllium, cadmium, copper, gold, lead, lithium, mercury, nickel, silver, palladium, and zinc [29–31]. Items are also known to contain a variety of organic chemicals and rare earth metals, the health effects of which have not been studied. Cobalt, nickel, manganese, and lithium are important materials that can be recovered through battery waste recycling. Australia, with 44.8%, and Chile, with 33.3%, produce about 78% of the global lithium supply [27], including electrical and electronic devices, but also hybrid and electric vehicles. Furthermore, 98% of the world's cobalt supply is mined as a byproduct of 61% copper and 37% nickel production, mostly in the Democratic Republic of Congo in Africa [27]. In an environmentally friendly way, Umicore Recycling Solutions operates using a special in-house developed Val Eas process with an annual capacity of more than 4000 tons [32] to treat Ni-metal hydride and Li-ion batteries (battery applications dominate, with 39% of the global lithium markets, followed by ceramic and glass applications).

4. E-Waste Valorization and Toxic Substances

In addition to all the hazardous substances present in e-waste, the manufacturing of mobile phones and personal computers consumes significant amounts of gold (Au), silver (Ag), and palladium (Pd) annually mined worldwide. The electronics industry is the third-largest consumer of gold, accounting for 12% of the total gold demand [33]. Table 2 presents a summary of typical pyrometallurgical and hydrometallurgical methods for the recovery of metals from e-waste, as well as some associated toxic substances and diseases. In 2019, 17.4% of e-waste was documented to be collected and recycled, with a potential raw material value of US$10 billion [26]. It was estimated that 4 million tons of secondary raw materials could have been obtained through recycling in 2019. By solely focusing on iron, aluminum, and copper, and comparing emissions resulting from their use as virgin raw materials or secondary raw materials, recycling these materials has helped save 15 million tons of CO_2 equivalent emissions in the same year [26]. Photovoltaic modules contain a high percentage by weight of a single element aluminum, while PCBs (Print Circuit Boards) are composed of a mixture of different metals, principally copper, iron, aluminum, tin, and nickel (with an average of 18 elements from the periodic table). Hard disk magnets, while they may contain high amounts of iron, also contain significant amounts of rare-earth elements, particularly neodymium, praseodymium, and dysprosium. For example, since photovoltaic modules contain less than 1% [22] of silver in their composition, it can become economically profitable to recycle them. According to the "Global Alliance for Incinerator Alternatives (GAIA)" [34], after incineration, about 30% of air pollutants still remain deposited in landfill as fly ash, bottom ash, boiler ash, slag, and wastewater treatment sludge, affecting future generations.

Table 2. Typical hydrometallurgical/pyrometallurgical processes for recovery of valuable metals from e-waste and associated toxic substances [35–45].

Industrial Processes	Metals Recovered	Main process Features	Main Metallurgical Process	Toxic Substances	Exposure Route	Average Estimated Concentration in e-Waste (mg/kg) *	Health Effects (a Few Diseases)
Noranda process at Quebec, Canada	Cu, Au, Ag, Pt, Pd, Se, Te, and Ni	Smelting of e-waste and Cu concentrate (14% of the total throughput). Electrorefining for metal recovery	Pyrometallurgy	**Persistent organic contaminants**			
				Brominated flame retardants	Air, dust, food, water, and soil		Thyroid problem, impaired development of the nervous system etc.
Boliden Rönnkär Smelter	Cu, Ag, Au, Pd, Ni, Se, Zn, and Pb	Smelting in Kaldo reactor, upgrading in Cu and high Precious Metals recovery by copper refining. Total feed 100,000 tons every year	Pyrometallurgy	Polybrominated diphenyl ethers (PBDEs)			Reproductive neurobehavioral development, thyroid function. Hormonal
				Polybrominated biphenyl (PBBs)			
Test at Boliden Rönnkär Smelter	Copper and precious metals (PMs)	PC scrap feeding to a zinc Fuming process (1:1 mixture with crushed revert slag); Plastics were tested as reducing agent and fuel; Copper and precious metals following the cop per collector to be recovered to the copper smelter	Pyrometallurgy	Polychlorinated biphenyl (PCBs)	Air, dust, food, and soil (bio-accumulative in fish and seafood)		Carcinogenicity, on multiple targets such as liver, thyroid, immune function, repro duction, and neurobehavioral development.
Umicore´s Precious metal refinery at Hoboken, Belgium	Au, Ag, Pd, Pt, Se, Ir, Ru, Rh, Cu, Ni, Pb, In, Bi, Sn, and Sb As,	IsaSmelt, copper leaching, and electrowinning and precious metal refining for Precious Metal Operation (PMO); E-waste cover up to 10% of the feed (250,000 tons of different wastes per annum); Plastic partially substitutes the coke as reducing agent and fuel in IsaSmelt; existence of Offgas emission control system	Combination of pyrometallurgy and hydrometallurgy	**Dioxins**			
				Polychlorinated dibenzodioxins (PCDDs) and dibenzofurans (PCDFs)	Air, dust, food, water, soil, and vapour		Reproductive, neurobehavioral and immune development
				Polyaromatic hydrocarbons (PAHs)	Released as combustion byproduct: air, dust, soil, and food (bio accumulative in fish and seafood)		Carcinogenicity, mutagenicity, and teratogenicity

Table 2. *Cont.*

Industrial Processes	Metals Recovered	Main process Features	Main Metallurgical Process	Toxic Substances	Exposure Route	Average Estimated Concentration in e-Waste (mg/kg) *	Health Effects (a Few Diseases)
				Heavy metals			
Umicore's trial	Au, Ag, Pd, Pt, Se, Ir, Ru, Rh, Cu, Ni, Pb, In, Bi, Sn, As, and Sb	Plastics-rich material from WEEE were tested to replace coke as a reducing agent and energy source for the IsaSmelet	Combination of pyrometallurgy and hydrometallurgy	Lead (Pb)	Air, dust, food, water, and soil	1782.4	Neurobehavioral development of children. Anemia. Kidney damage. Chronic neurotoxicity
				Chromium (Cr) or hexavalent chromium	Air, dust, food, water, and soil	75.5	Carcinogenicity, Reproductive functions.
				Cadmium (Cd)	Air, dust, food, water, and soil (specially rice and vegetables)	39	Endocrine function. Ovotoxicity
Dunn's patent for gold refining	Au	Gold scrap reacted with chlorine at 300 °C to 700 °C; Hydrochloric acid to dissolve the impurity-metal chlorides; Ammonium hydroxide and nitric acid washing respectively to dissolve the silver chloride; Samples should contain more than 80% of gold	Combination of pyrometallurgy and hydrometallurgy	Mercury (Hg)	Air, dust, food, water, and soil (bio accumulative in fish)	1.2	Neurobehavioral development of children (especially methylmercury). Anemia. Kidney damage
Outotec's Ausmelt TSL and Kaldo Furnaces	Zn, Cu, Au, Ag, In, Pb, Cd, and Ge	Copper scrap and e-waste recycling with many refining steps downstream	Pyrometallurgy	Zinc	Air, dust, food, water, and soil	1561.1	Increased risk of Cu deficiency (Anemia, neurological abnormalities)
				Nickel (Ni)	Air, water, soil, and food (plants)	65.8	Carcinogenic, lung embolism, respiratory failure
				Lithium (Li)	Air, water, soil, and food (plants)	44.3	Burning sensation, Cough. Labooured breathing
				Barium (Ba)	Air, dust, and water	626	Increased blood pressure, stomach irritation, nerve

Table 2. *Cont.*

Industrial Processes	Metals Recovered	Main process Features	Main Metallurgical Process	Toxic Substances	Exposure Route	Average Estimated Concentration in e-Waste (mg/kg) *	Health Effects (a Few Diseases)
Dowa mining Kosaka Japan	Cu, Au, and Ag	E-waste TSL, smelting in a secondary copper process	Hydrometallurgy	Beryllium (Be)	Air, water, and food	0.014	Pneumonia. Berylliosis a persistent and lung problem
				Aluminum (Al)	Air, dust, water, and soil	9510	Skeletal development and metabolism, neurotoxicity, fetal toxicity
				Antimony (Sb)	Air, water, and soil	180	Damage lung, heart, liver, and kidney, eye irritation, etc.
				Arsenic (As)	Air, soil, water, and food	0.47	Skin alterations. Decreased nerve, diabetes, cancer
				Bismuth (Bi)	Air, water, and soil	2.7	Kidney damage, serious ulceration stomatitis, albumin, etc.
I.S-Nikko's recycling facility, Korea	Au, Ag, and Platinum Group Metals	Recycling in TSL, smelting followed by electrolytic refining	Pyrometallurgy	Cobalt (Co)	Air, dust, water, soil, and food	8.3	Discomfort of bodies, albumin, diarrhea, etc.
				Copper (Cu)	Air, dust, water, and soil	115.5	Asthma, pneumonia, nausea, vision and heart problem, etc.
Day's Patent	Pt, Pd, and Precious Metals	Smelting in plasma arc furnace at 1400 °C. PMs collected in Basis Metal (BM). Ag and Cu used to collect metal	Combination of pyrometallurgy and hydrometallurgy	Gallium (Ga)	Air, water, and fume	2.43	Irritation of the nose, mouth, and eyes, headache, diarrhea
				Germanium (Ge)	Air and dust	1.9	Abdominal cramps, burning sensation, red skin and eyes
				Indium (In)	Air, dust, water, and soil	4.6	Damage the heart, kidney and liver, etc.
				Molybdenum (Mo)	Air, dust, water, and soil	1.2	Liver disfunction with hyperbilirubinemia, pain in knees, etc.
				Selenium (Se)	Air, dust, water, and soil	12.67	Hair loss, cardiovascular, renal, and neurological problem

Table 2. *Cont.*

Industrial Processes	Metals Recovered	Main process Features	Main Metallurgical Process	Toxic Substances	Exposure Route	Average Estimated Concentration in e-Waste (mg/kg) *	Health Effects (a Few Diseases)
Aleksandrovich Patent	Au and Platinum Group Metals	Scrap combustion in a BM with carbon reduction	Pyrometallurgy	Silver (Ag)	Water and soil	49	Allergic dermatitis, inhalation hazards
				Tin (Sn)	Air, dust, water, and soil	1716.4	Eye and skin irritation, headache, stomach ache, etc.
				Vanadium (V)	Air, dust, water, and soil	66	Severe eye, nose, and throat irritation
Aurubis recycling Germany	Cu, Pd, Zn, Sn, and Precious Metals	Smelting of Cu and e-waste in TLS, black Cu processing and electrorefining	Hydrometallurgy	Yttrium (Y)	Air, dust, water, and soil	1.99	Lung embolisms, cancer with humans
				Iron (Fe)	Air, dust, water, and soil	91.1	Liver damage

* Values from different sources and areas.

5. E-Waste Recycling Process

After size reduction/comminution, the following types of separation technologies can be implemented [13]: corona-electrostatic and eddy-current separation, based on the difference in the electrical conductivity of the materials; magnetic separation, consisting of separating metals based on their magnetic properties; gravity separation (also called density-based separation), which depends on the density and particle size; and optical separation, all with the aim of refining and detoxifying the various outputs of the pre-processing. The following metallurgical processes for recycling exist: hydrometallurgical, pyrometallurgical, and bio-metallurgical processes, as well as combinations of these. They can all be used to process the output of preprocessing WEEE. The first two processes [13,46] are currently the major routes for e-waste processing with materials recovery, and there are only a few laboratory studies for e-waste treatment through bio-metallurgical processes. However, bioleaching of metals from e-waste has the potential for further improvement. Hydrometallurgical recovery processes of metals involve oxidative leaching for metals extraction, followed by separation and purification. Its advantages over thermal treatment/pyrometallurgy include lower toxic residues, lower emissions, and higher energy efficiency. Hydrometallurgical processes are based on traditional hydrometallurgical technology for metals extraction from primary ores [46]. Due to its cost-effectiveness and environmental efficiency, biotechnology [12] will play a significant role in the future of e-waste treatment and material recovery.

To improve material recovery rates without negatively impacting the environment, more investment in advanced technologies, especially in metal recovery, is required for the state-of-the-art end-processing of e-waste. However, this is not currently a realistic solution for developing countries like many African countries that lack the financial resources or management necessary for development. For example [12], a typical aluminum smelter in Europe requires a minimum input of 50 thousand tons of aluminum scrap per year and an investment cost of about €25 million to run a plant. Only a few companies in the world, such as Aurubis AG in Germany, Boliden in Sweden, DOWA in Japan, Umicore in Belgium, and Xstrata in Canada, are equipped with the technical know-how, sophisticated flow sheets, and sufficient economy of scale for precious metal refinery to fulfill technical and environmental requirements. The integrated smelter-refinery of Umicore Precious Metal Refining in Belgium has the capacity to produce 2400 tons of silver, 100 tons of gold, 25 tons of palladium, and 25 tons of platinum per year at an investment cost of more than €500 million [12]. About 25% of the annual production of silver (Ag) and gold (Au), and 65% of Palladium (Pd) and Platinum (Pt), come from e-waste and end-of-life catalysts [33]. In addition, the recovery of metals from electrical and electronic equipment mitigates the high CO_2 emissions associated with primary metal production. The CO_2 emissions of the Umicore process [32], when recovering 75,000 tons of metal from 300,000 tons of valuable materials and smelting byproducts, are only 3.73 tons of CO_2/ton of metal compared to 17.1 tons of CO_2/ton of metal using a primary production route. The continuous improvement of these measures leads to very low emissions and prevents the loss of precious metal dust. Recycling of e-waste needs to be encouraged worldwide because of the significant energy savings from using recycled materials compared to using virgin materials, as presented in Table 3.

Table 3. Energy saved by using recycled materials over virgin materials [47].

Material	Energy Savings (%)
Aluminum	95
Copper	85
Iron and steel	74
Lead	65
Zinc	60

Table 3. *Cont.*

Material	Energy Savings (%)
Paper	64
Plastic	>80

6. Strategies for Africa

The African continent, with its 54 countries [48], is one of the largest (30.37 million km^2 [48]) and most populous (1.4 billion [49] inhabitants estimated in 2021) continents on Earth. Africa [48] represents around 6% of the Earth's total surface area, 20% of its land area, and 18% of the global population. The average annual population growth rate is more than 2% [50], and the average population density is 46.1 inhabitants per km^2 [48]. The illegal trade in waste electrical and electronic equipment is also a significant worldwide transcontinental concern. Ghana and Nigeria in Africa are among the biggest recipients of e-waste from developed countries. It is estimated that around 500 containers [51] of electrical and electronic equipment enter Nigeria every month. According to the same source, approximately 400,000 used computers are imported every month, of which only around 50% still function (45% of the equipment comes from Europe, 55% from the US, and 10% from Asia). The same source mentions that approximately 300 containers of used and/or waste electrical and electronic equipment arrive at the ports of Tema in Ghana every month, and that on average, 75–80% of the imported used and/or waste electrical and electronic equipment cannot be reused. South Africa, which is one of the emerging African economies in the world and a member of the BRICS (Brazil, Russia, India, China, and South Africa) group, is facing a significant e-waste problem (5.4 kg/per inhabitant) [52] in terms of massive generation and inadequate management mechanisms, with enormous environmental challenges. In Ghana (Agbogbloshie) and Nigeria (Alaba), crude methods such as burning are used to retrieve precious metals and reusable components [51]. There is no formal legislation to manage and enforce WEEE management in Egypt. Electronic waste is mainly dealt with by the informal sector, and after extracting the recyclable streams, it is generally either burned or thrown into landfills/dump sites in slums such as Manshiet Nasser [53]. Rwanda is a country in East Africa with well-structured e-waste management in Africa. Rwanda has a law based on licenses (license 1 for collection and transportation service, license 2 for dismantling and refurbishment service, and license 3 for recycling service) for any person or group of persons who wants to do business in this domain. There are also considerable fines for those who do not respect the legislation [54]. In 2021, the African population was estimated to be 1.4 billion, a number that is predicted to grow to approximately 1.7 billion by 2030, associated with a population growth of 21.4% from 2021 to 2030. In 2021, approximately 54.8 million tons (an average of 52.2 and 57.4 tons) [26,33,55] of e-waste was supposed to be generated worldwide. The worldwide prediction for 2030 according to "The Global E-waste Monitor 2020" [26] is 74.7 million tons, which means an increase in the quantity of e-waste of 36.3%. Assuming that the ratio of the amount of worldwide generated e-waste over the amount of generated e-waste in Africa in 2021 remains equal to the ratio of the predicted values in 2030, then the estimated amount of generated e-waste in Africa for 2021 is 3 million tons, increasing to 4 million tons in 2030, as shown in Table 4.

Table 4. In 2019, the world generated millions of tons of e-waste. Comparative values for Africa are reported as estimated values for 2021 und predicted values for 2030 [26,33,55].

	2019	2021	2030
Worldwide	53.6	54.8	74.7
Africa	2.9	3	4

The predicted 4 million tons for 2030 have to be considered with a large estimation error (underestimation); nevertheless, it still corresponds to an e-waste growth rate of 33.3%

for the considered period (2021–2030). This means that e-waste generation is growing at least 1.5 times faster than the African population over the same period, despite low accuracy estimations for electronic waste in 2030. In Africa, an average of 2.5 kg [26] of e-waste per capita and a total of 2.9 Mt of e-waste were generated in 2019. According to Table 4, around 3 Mt of e-waste was generated in Africa in 2021. If we assume that the quotient of total generated e-waste and the amount of per capita generated e-waste in 2019 in Africa is slightly equal to the same quotient in 2021, then per capita generated e-waste in 2021 will be equal to 2.6 kg. Figure 2 shows the generated e-waste in some countries in each African subregion and per inhabitant in the same year.

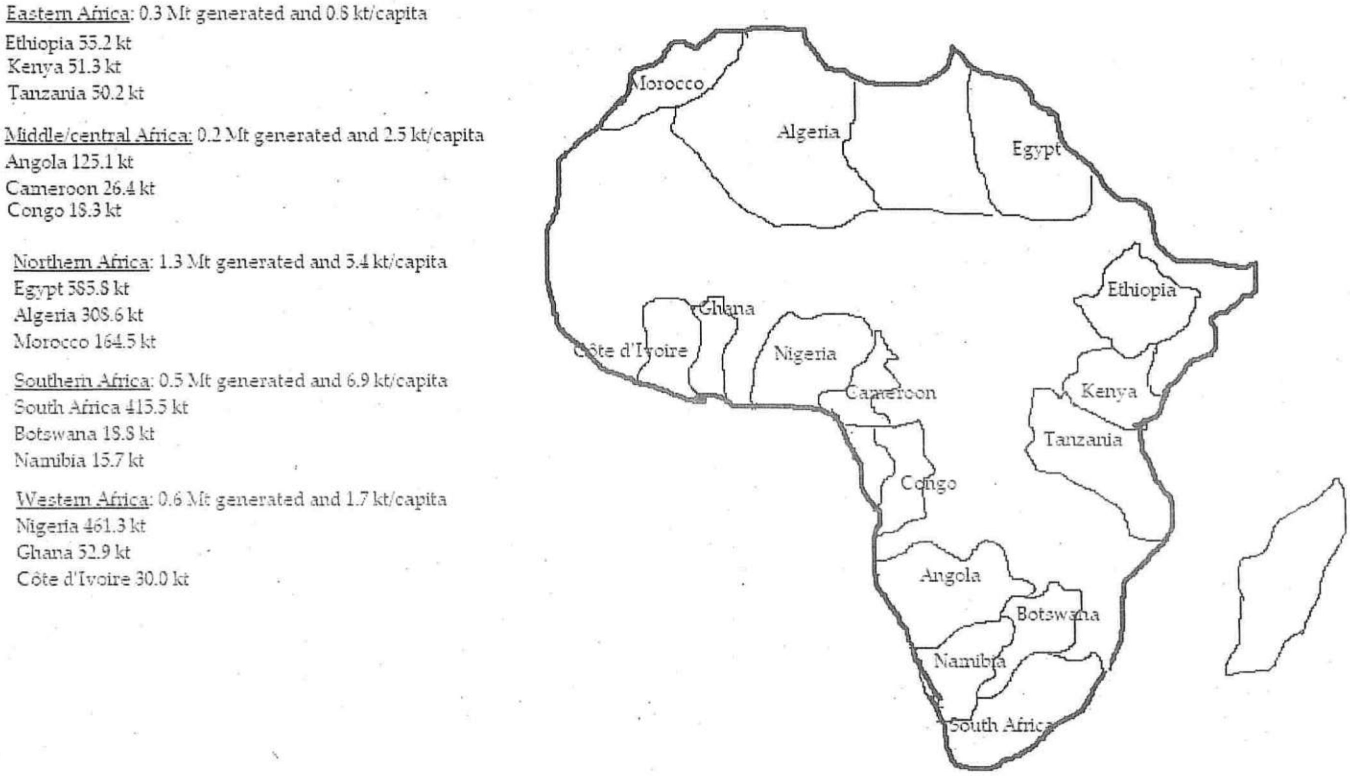

Figure 2. E-waste generated in 2019 by sub-region/inhabitant in Africa [26].

The implication of e-waste management for a country or region is the need to establish well-organized logistics and a database to address the rising e-waste in the area. There are currently two useful e-waste collection systems in developed countries [56]: (1) a collective system, usually founded as a nonprofit and nongovernmental organization by trade associations, which focuses on some product categories to efficiently find a market for their reuse; and (2) a clearing house system where producers, recyclers, waste businesses, and others compete to provide services. There are three commonly used channels for e-waste logistics [56]: (1) municipal collection sites, where citizens can deposit any amount of waste at no cost; (2) in-store retailer take-back schemes, which may be free or depend on repeat purchases; and (3) direct producer take-back, which is usually for business customers and may require a replacement purchase.

Currently, data on e-waste recycling companies in Africa are old and rare, which can be explained by the lack of transparency of actors in the sector and a sign that the sector is still informal in many countries. In Africa, it is documented that only 0.9% of the 2.9 Mt of generated e-waste [26] was collected in 2019, and it was estimated [26] that, in the same year, 55.2 kt e-waste was generated in Ethiopia, 51.3 kt in Kenya, 50.2 kt in Tanzania (in the east), 125.1 kt in Angola, 26.4 kt in Cameroon, 18.3 kt in Congo (in central), 585.8 kt in Egypt, 308.6 kt in Algeria, 164.5 kt in Morocco (in the north), 415.5 kt in South Africa, 18.8

kt in Botswana, 15.7 kt in Namibia (in the south), 461.3 kt in Nigeria, 52.9 kt in Ghana, and 30.0 kt in Côte d'Ivoire (in the west), among other relevant countries.

In 2017, Nigeria generated about 288,000 tons of e-waste [57], and in Ghana, about 15% of the imported electrical and electronic devices in 2009 were not functioning. Four companies were found to be mainly involved in metal recycling, namely Atlantic Recycling (which operates on repair and re-use activities), City Waste Recycling, FIDEV Recycling (which operates on dismantling and trading of scrap metals), and Blancomet Recycling (which operates on dismantling and trading of scrap metals). However, there is no information concerning the quantity of treated waste [57].

In 2015, approximately 17,733 tons of WEEE were collected and recycled across 27 recycling companies in South Africa [57]. Of these companies, 79% were comprised of ICT and consumer electronics. In 2018, 45.6 million mobile subscribers were identified in Kenya, and recycling was carried out from both dumpsites and primary collection sites [57]. In 2016, 97.8 million mobile subscribers were identified in Egypt [57]. The international Technology Group, Recycle Bekia, and Eco Integrated Industrial Systems can be seen as emerging companies in recycling here, but the informal sector is dominant. In Africa, all these companies are active in recycling for the winning of metal.

Particularly, the transboundary movement of old devices from developed to developing countries needs to be addressed. It is estimated that 16 to 38% of WEEE collected in the EU and 80% in the U.S. are sent "legally and/or illegally" to developing countries in the form of reused or discarded devices [13]. At least one-third of the 2.2 Mt [33] of African e-waste quantity on average was estimated to have been illegally imported in 2016. It is necessary to fight dispersion, contamination, and the loss of target materials to undesirable streams [13]. Manual disassembly provides the best recovery rate of original components and materials without damaging them, making it easier to sort and improve their reuse. To achieve this, we need to follow the 76 Design for Environment (DfE) guidelines defined by Telenko C. et al. [7], and select those that ensure that all EEE sold in the African market fulfill the desired design. Then, use the metric for Sustainable Product Design Concepts measuring of Han J. et al. [8] to confirm the sustainability of the choice, specifically measuring the material, production, use, and end of life. The mobile phone is chosen for the calculation because the African mobile phone market has shown resilience to the COVID-19 pandemic, it initially declined in the first quarter of 2020 but remained stable in the second, with delivery of 20.1 million smartphones in both quarters. The third quarter showed a resurgence of activity with an increase of 2.8 million units, and in the first quarter of 2021, there were 23.4 million smartphones shipped [58]. In 2017, Nigeria welcomed the continent's first smartphone assembly unit. AfriOne, located in the free zone, produces 120,000 units per month marketed between $92 and $108 to middle-income class consumers, a large part of the tens of millions of consumers in Nigeria [59]. The majority of smartphones sold on the African continent come from abroad, and consequently, the quantity of obsolete mobile phones will continuously increase in the future. Han J. et al. determined the actual value of the negative environmental impacts caused at the conceptual design stage, with a result that could reflect the level of sustainability in a simple but effective manner using the measurement scales low (0), medium (1), and high (2) to indicate sustainability attributes. All parameters used in the equations are defined in Table 5. The authors clearly defined in their work under which conditions each metric category (material, production, use, and end of life) could be calculated to aid decision-making. Based on Design for Environment (DfE) guidelines and sustainable product design measurement metrics, the international community can define criteria that a product must satisfy before entering the international market, thereby solving the environmental problem related to WEEE, or at least substantially reducing it. As some quantities of this e-waste end up in Africa, the continent can apply those criteria to protect their market and the environment. The $Metric_{Material}$, $Metric_{Production}$, $Metric_{Use}$, and $Metric_{EOL}$ are given by the following equations:

$$Metric_{Material} = \frac{9 \times \left(\frac{\sum_{i=1}^{N} (M_1 + M_2) \times M_3}{N} \right)}{8} + 1 \tag{1}$$

$$Metric_{Production} = \frac{9 \times (P_1 \times P_2 + P_3) \times P_4}{12} + 1 \tag{2}$$

$$Metric_{Use} = \frac{9 \times U_1 \times (U_2 + U_3)}{8} + 1 \tag{3}$$

$$Metric_{EOL} = \frac{9 \times (E_1 + E_2 + E_3) \times E_4}{12} + 1 \tag{4}$$

Table 5. Evaluation of each metric measurement relating to mobile phones.

Metrics	Attributes	Business as Usual Production	Under Selected DfE Conditions Production
Material	Material origin (M_1)	• Stainless steel (1), screen (1), plastic (1), battery (0), ceramic as composite (0)	• Only recy. stainless steel (2), only recy. * LCD screen (2), recy. PC-plastic (2), recy. battery (1), natural ceramic (1)
	Material property (M_2)	• Stainless steel (1), screen (1), plastic (1), battery (0), ceramic as composite (0)	• Only recy. stainless steel (2), only recy. LCD screen (2), recy. PC-plastic (2), recy. battery (1), natural ceramic (1)
	Use material quantity (M_3)	• Stainless steel (1), screen (1), plastic (1), battery (0), ceramic as composite (0)	• Only recy. stainless steel (2), only recy. LCD screen (2), recy. PC-plastic (2), recy. battery (1), natural ceramic (1)
	Use of material type (N)	5	5
	$Metric_{Material}$	2.4	7.3
Production	Balance between the number of parts and complexity (P_1)	Currently design standard with a mass production (2)	The same design standard with a few more steps like the production of recycled components (1)
	Parts standardisation (P_2)	Battery and some components can benefit from standard component (2)	Some components require customisation (0)
	Parts design for assembly (P_3)	Good potential for assembly (2)	Good potential for assembly (2)
	Suitable fabrication method (P_4)	Currently valid operations are needed (2)	Relative more operations are needed (1)
	$Metric_{Production}$	10	2.5
Use	Product use time/lifetime (U_1)	The design time needs to be closer to its use time (1)	The design time needs to be closer to its use time (2)
	Energy consumption during use (U_2)	Needs battery to power (1)	Needs also recy. battery to power (2)
	Robustness, reliability, and maintenance (U_3)	Internal components for the base will require a fair amount of resource to maintain/service (1)	Internal components for the base will require a fair amount of resource to maintain/service (1)
	$Metric_{Use}$	3.3	7.8

Table 5. *Cont.*

Metrics	Attributes	Business as Usual Production	Under Selected DfE Conditions Production
	Reuse (E_1)	Battery and some components have fair potential to be reused (1)	Battery and some components have great potential to be reused (2)
	Recycling, remanufacturing, and repair (E_2)	All material involved can be recycled or not (1)	Almost all material involved can be recycled (2)
	Disposal (E_3)	Blender base that contains battery and some components will not be easy to disassemble (1)	Battery and some components cause a very slight negative impact due to disposal (1)
	Ease of disassembly (E_4)	Blender base that contains battery and some components will not be easy to disassemble (1)	Blender base that contains battery and some components will be easier to disassemble/landfill (2)
End of life	$Metric_{EOL}$	2.5	8.5

* recyclable.

To produce a readily understandable outcome, the authors conducted a scaling process, ensuring that the final value of each metric falls between 1 and 10, where 1 signifies poor and 10 signifies excellent sustainability [8]. The evaluation for mobile phones is presented in Table 5. An overview of each metric category's sustainability for mobile phones is provided in Figure 3.

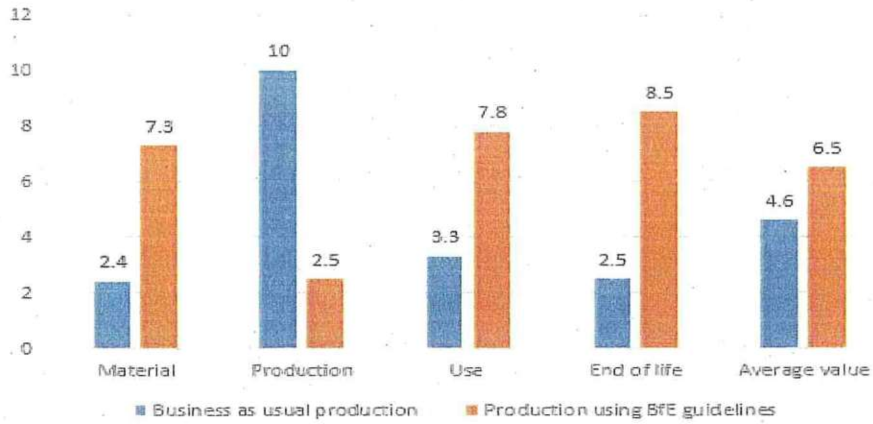

Figure 3. Overview of each metric category with respect to sustainability for a mobile phone.

Figure 3 shows that production, based on current practices, receives the highest score of 10. This is simply because we assume that firms find the current production process satisfactory (i.e., profitable) and that the alternative eco-design (DfE) has a low score of 2.5. However, we do not agree with this assessment since, for the alternative approach, all other scores (material, use, and end of life) are greater than 7 and even exceed the average value, resulting in a good environmental rating. Although the financial cost of this alternative has not been evaluated, we believe that given the threat of climate change and its disastrous consequences for humans and the environment, such efforts are worthwhile. This method can be applied to other electronic and electrical equipment (EEE) devices to help designers make environmentally sound decisions at the design stage, considering recycling in material selection to minimize the negative impact of obsolete products on the environment and living beings. Measures and strategies should also be developed to deal with existing electronic scrap. Additionally, Figure 4 presents another way to organize and manage WEEE in Africa by improving current practices. Many EEE companies are beginning to prioritize environmental protection in relation to the products they bring to market, as evidenced by their websites. For example, HP publishes a recycling vendor list to promote transparency and progress in raising social and environmental standards in the electronics industry supply chain. HP also publishes recycling volumes for their products in various countries and provides take-back services for a broad scope of products [60]. Lenovo offers Asset Recovery Services (ARS) to business customers to manage their IT assets and data center infrastructure, including equipment take-back, data destruction, refurbishment, and recycling services [61]. Dell has recovered over 2.5 billion pounds (1.1 billion kg) of used electronic equipment since 2007, as they encourage people to bring back their old products [62]. Samsung aims to achieve net-zero CO_2 emissions, use 100% renewable energy, develop environmentally friendly technologies, conserve and reuse resources, save water, and treat pollutants by 2030 [63]. Huawei is committed to minimizing its environmental impact through recycling and reuse to conserve resources and prevent waste. Electronic waste is recovered by dissolving raw materials such as copper, iron, aluminum, cobalt, etc., to introduce them into the recycling process [64]. However, groundbreaking technologies and marketing strategies are not apparent when looking at all EEE company homepages.

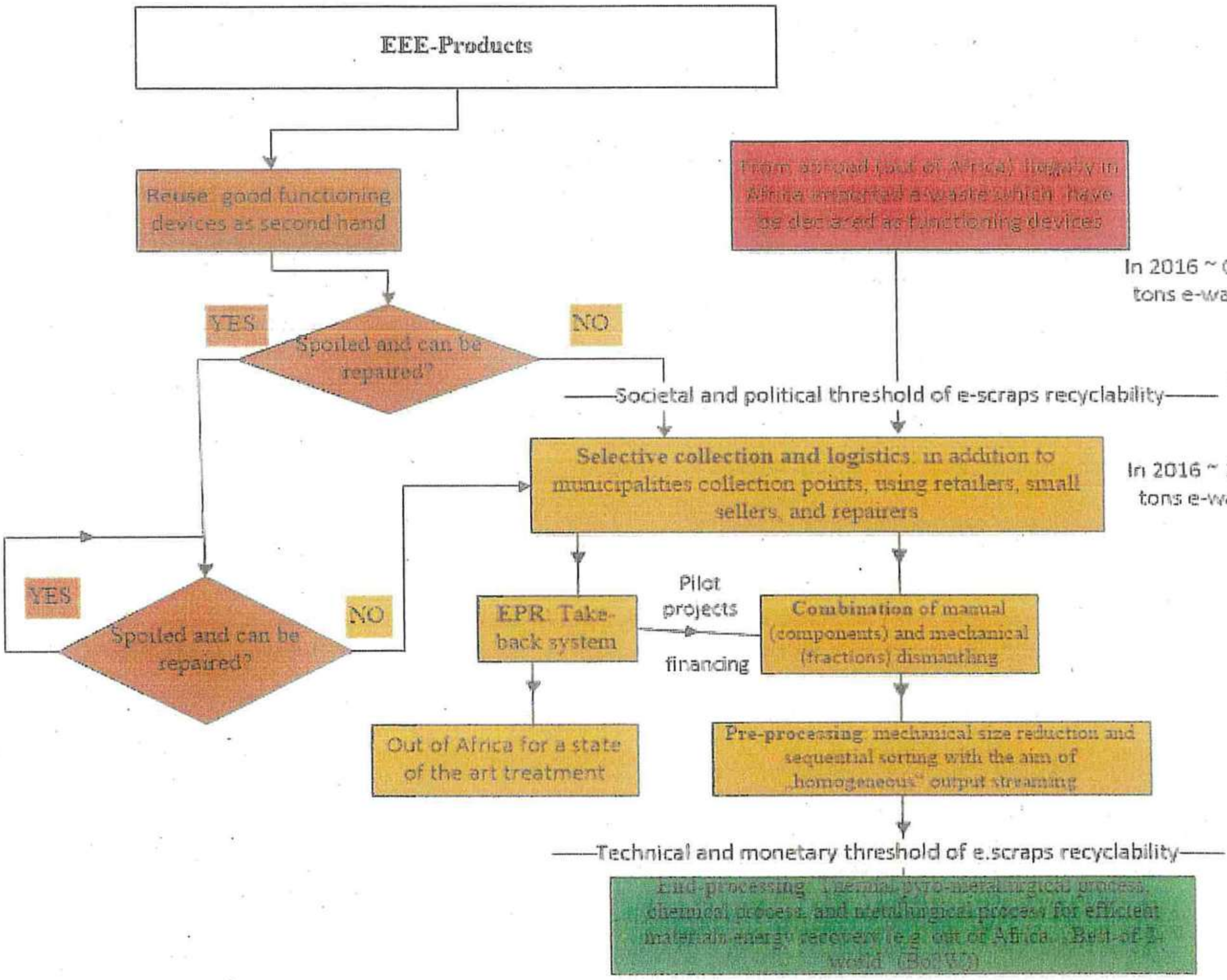

Figure 4. E-waste management strategy for Africa (improvement on current practice). Source for * [33] and for ** we assume that around 1/3 of the 2.2 Mt e-waste in Africa in 2016 was illegal importation.

Table 6 below presents some appropriate measures, which need to be put in place now, in short-, middle-, and long-term to solve the problem of e-waste in Africa.

Table 6. Current, short-, middle-, and long-term solutions of e-waste problem.

Appropriate Measures to Be Put in Place
Based on current practice in African countries, a significant portion of e-waste is illegally imported, causing significant harm to the population and the environment. In the short term, this activity needs to be effectively and completely banned, monitored, and sanctioned by national and international law.
Short-term strategy (within 5 years) should focus on improving the current situation by implementing a comprehensive and efficient collection and logistics strategy that involves all stakeholders. This should be accompanied by monitoring and raising awareness among all actors involved in the process to ensure proper handling of the waste and promote health and environmental safety. Additionally, motivated by the need to minimize the environmental impact of e-waste, several technological changes have been made. These include: • The replacement of CRT screens with LCD screens (eliminating Pb but introducing Hg) • The introduction of optical fibres (Cu eliminated from the cabling, but F, Pb, Y and Zr introduced) • The introduction of rechargeable batteries (Ni, Cd reduced, but Li increased), and so on. All this changes and their consequences need to be considered during the improvement. A well-organized and structured manual disassembly process for products that are not taken back will also be a part of a sustainable African e-scrap recycling strategy.
Meddle-term strategy (from 6 to 30 years) involves gradually organizing e-waste preprocessing up to recycling. This includes reducing landfill, organizing waste handling and utilization services by waste companies country-wide, improving hazardous waste collection, ensuring that hazardous waste packaging and labeling comply with special legislation, transporting hazardous waste only to landfills that can treat them, treating specific types of hazardous waste in Africa, stabilizing waste quantities using charges/taxes, and further reducing waste. An effective take-back system (EPR) or a combination of manual and mechanical disassembly, mechanical size reduction, and sequential sorting systems should be used to obtain homogeneous output streams at the end of the process. With photovoltaic technology being part of the solution for renewable energy, its recycling will become a challenge in 15 years due to the large amount of obsolete solar panels. Pilot projects in cooperation with producers (EPR) and the Climate Change Action Plan (2021–2025) from the World Bank Group (WBG) should be implemented [65]. Financial possibilities should be utilized to set up a policy and transitional legislation that considers e-waste management problems for sustainable development in Africa. The educational system should be reformed starting with a proper program on waste management, and encourage reduce, reuse, repair, and recycling to increase the lifespan of products and save resources.
The long-term strategy (from 31 to 50 years) consists of end processing, which is a technical and economic challenge in e-waste treatment. Various processes, such as thermal pyro metallurgical, chemical, and metallurgical, are used for efficient materials and/or energy recovery. Umicore Precious Metal Refining in Belgium has the capacity to produce 2400 tons of silver, 100 tons of gold, 25 tons of palladium, and 25 tons of platinum per year, and the investment cost for the metallurgical processes is more than €500 million. Technical know-how and large investments are necessary to achieve this step, and many individual African countries do not have the capacity to do it alone. The "Best of Two Worlds (Bo2W)" philosophy can be a solution approach for African countries, or many countries can come together and construct the plant corresponding to their needs. "Best of two worlds (Bo2W)" philosophy [12] suggests a pragmatic network solution for e-waste management in emerging economies, which seek technical and logistical integration of "best" manual e-scrap disassembly based preprocessing in developing countries and "best" end processing treatment of hazardous and complex fractions in dedicated facilities in developed countries. Existing technologies should be used to recycle the minimized waste, which occurs when EEE products reach the end of their life cycle. The goal is to gradually and significantly reduce this waste by improving its landfill and take the treatment of electrical and electronic waste in Africa out of its embryonic state.

7. Discussion

To highlight the disparity in e-waste management between developed and developing countries, we conducted interviews and surveys with stakeholders in Vienna (Austria) and Douala/Yaoundé (Cameroon), in addition to reviewing relevant literature. The summarized results of the survey and research can be found in Table 7.

Table 7. Overview of the survey and the research [26,66–68].

	Austria	Cameroon
Population (in million)	8.9	26.6
Considered big cities and its popuulation (in milion)	Vienna ≈ 1.9	Douala (Dla) ≈ 3.5 Yaounde (Yde) ≈ 4.1
Municipal Solid Waste (MSW) quantity per year	Vienna ≈ 1,024, 407 tons, 549 kg/capita	Dla ≈ 694,483 tons, Yde ≈ 2/3 of Dla quantity, 226.3 kg/capita for both cities

Table 7. Cont.

	Austria	Cameroon
Considered plastic and EEE waste quantity per year in those cities	Plastic ≈ 8195 tons EEE ≈ 8333 tons (from DRZ-Vienna)	Plastic ≈ 20,884 (3% of 694,483) tons for Dla and 13,890 tons for Yde EEE ≈ 2/3 of 26.4 kt for both cities
Existence of well organized waste selection and collection	Yes	No
EEE devices disassembly time	1–3 h depending on devices	Bad dissassembly activity, dangerous burning to gain copper for example
EEE repair time of devices	1–3 h depending on devices	It depends on when spare parts are available
EEE repair costs (in €)	20–150 and sometimes more, Vienna provincial government supports with a sum of 100 maximum the repair costs	3–50 and sometimes more. No official financial support (informal activity in precarious conditions in Dla and Yde)
Availability of EEE spare parts	Yes (Ebay, Amazon, www.ifixit.com, etc.)	Yes, but it takes long time until reception of spare parts, with consequences on the repair time
EEE spare parts market	National and international	International
EEE spare parts warranty time (in year)	2–3 (a national law)	Non existant/applicable
Labor cost per hour (in €)	15 without overhead by DRZ and more by some SMEs	0.3–0.6 (informal activity)

In view of the above, we conclude that in Austria, plastic, electrical, and electronic waste is already sorted in households, collected, and used to give a second life to either the products or the materials contained in the product. It is also noteworthy that great economic activity occurs in this sector (formal). On the other hand, for a country like Cameroon, like many African countries, very little has been done in this domain, which is still informal. The accumulation of e-waste will become a serious environmental and public health problem in the medium and long term. The questionnaire used in Cameroon shows that there is a huge gap in waste treatment between many African countries and developed countries (e.g., Austria). Africa needs to find measures that can incentivize people to bring their obsolete devices back to collection points and maximize collection. However, most activities in e-waste management in Africa are still informal and thus dangerous for the environment and humans. The value of raw materials presented in electrical and electronic waste worldwide was estimated at US$10 Billion in 2019 [26]. This means that Africa needs to realize that urban mining is not only a way of managing their mining resources in a sustainable manner (resource preservation) but also a way of considerably increasing income when it is done according to the state of the art. In addition, the improvement of repair services in the formal sector through adequate formation can be a source of wealth creation (for example, there were 340 SMEs in the repair business in Austria in 2016, which employed around 1259 people and had an estimated turnover of €113,494,000 [69]). Oluyinka et al. [70] suggests that people who intend to prevent litter are also more likely to factually engage with litter prevention (TPB "Theory of Planned Behavior"), and also that Perceived Behavioral Control (PBC) seems to have a significant impact on the intention to avoid littering. The goal of studies using this theory is to help waste managers formulate policies and interventions that target perceived behavioral intentions in the promotion of waste prevention. Oluyinka et al.'s study demonstrates two things: first, that the intention to prevent waste plays a key role in waste prevention behavior as indicated by TPB, and second, that potential interventions should primarily target people's perception of behavioral control over litter. In addition, environmental managers, applied social and environmental psychologists, and/or social scientists should be involved in designing behavior change programs. According to M. Park et al. [71], e-waste recycling is shifting from the industrialized to the low-cost base of the developing world, where e-waste recycling if often undertaken in hazardous conditions by a growing informal sector (developing countries offer lower labor costs but inconsistent regulatory enforcement). In the opinion of the authors, designers need to understand how their products end up in waste flows to the developing world and design accordingly for end-of-life. This not only entails the elimination of primary toxic substances within products (as mandated through emerging e-waste regulatory initiatives) but also design for disassembly strategies to eliminate the need for toxic processing and emissions to liberate the valuable recyclates. It would also be interesting to conduct in-depth, concrete, and more representative studies on the African continent over generations to highlight the e-waste management stance.

8. Conclusions

African populations, for the most part, live slightly below the poverty line and, consciously or unconsciously, contribute to the protection of the environment simply by preserving their products for as long as possible due to low incomes that prevent them from regularly buying new products. Accustomed to biodegradable organic waste, the African population is not aware of the threat that electronic and electrical waste poses. This means that increased awareness is needed using all necessary means, including the education system, media, social media, workshops, and door-to-door and face-to-face information, to convince the population to behave differently with regard to e-waste. Improved governance developed with industries that consider environmental protection will create many so-called green jobs, with healthy, well-compensated workers, reduce marine pollution, and save species that could otherwise disappear in the long term. Energy savings achieved using recycled materials instead of raw materials are enormous, as shown in Table 3. This is very beneficial to the environment because it allows us to avoid the destruction of landscapes and to reduce CO_2 emissions, which are mainly responsible for the climate change that the planet is currently experiencing. Worldwide, eco-design using some DfEs should be implemented in every sector without exception to ensure that the sustainable management of resources and a "circular economy" are achieved.

As a recommendation, strict worldwide regulation and reorganization of e-waste management under the supervision of an international agency, such as the United Nations Environment Programme (UNEP), should be implemented through international legislation. Their mission should be to ensure that in all regions of the globe (or as many as possible) obsolete electronic devices have been collected and properly documented, control their transboundary movement, and produce a yearly report. This ensures that data on this matter are available and accessible to everyone, improves transparency, and raises worldwide awareness of the dangers of e-waste. UNEP should be a real mentor with respect to country/region-based e-waste collection/management at three levels (municipalities, cities, entire countries), advising them on how to use incentives to shift e-waste processing from an informal setting to a formal one as a source of income without endangering the health of workers. At the end of this process, the exact annual quantity of e-scrap produced worldwide should be known, and the next steps in the processing chain can be rationally and sustainably planned.

Author Contributions: Conceptualization, G.M.M. and V.-M.A.; Methodology, G.M.M. and V.-M.A.; Software, V.-M.A.; validation, G.M.M. and V.-M.A.; Formal analysis, G.M.M. and V.-M.A.; Investigation, G.M.M.; Resources, G.M.M. and V.-M.A.; Data curation, G.M.M. and V.-M.A.; Writing—original draft preparation, G.M.M.; Writing—review and editing, G.M.M. and V.-M.A.; Visualization, V.-M.A.; supervision, V.-M.A.; Project administration, G.M.M. and V.-M.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: The authors acknowledge TU Wien University Library for financial support through its Open Access Funding Programme.

Conflicts of Interest: The authors declare no conflict of interest.

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Review

An Imported Environmental Crisis: Plastic Mismanagement in Africa

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Abstract: Plastic waste pollution is currently one of the main items on international agendas. It leads to more and more leakages and constitutes a dangerous threat to living beings and the ecosystem (toxic substances). Globally, only 9% of plastic waste is recycled, while 22% of it is mismanaged. A large part of this waste ends up legally or illegally in Africa. This article uses the available data on plastic waste to shed light on the situation in Africa. Particular attention is paid to imports of plastics and the recycling sector, as well as ways to combat improper dumping and to prevent/reduce marine pollution (microplastics). The roles and responsibilities of actors and institutions in Africa will be discussed. It is urgent for the international community, in cooperation with the local plastic/textile industries, to establish an effective and well-structured collection system for plastic and textile waste. This will help maximize the collection rate and minimize landfills through recycling. It is also necessary to encourage both the plastic and textile industries to opt for product designs that use easily recyclable materials (eco-design), and this option is crucial.

Keywords: plastic footprint; plastic/textile waste; plastic recycling; toxic substances; microplastic; Corporate Social Responsibility (CSR)

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Citation: Moyen Massa, G.; Archodoulaki, V.-M. An Imported Environmental Crisis: Plastic Mismanagement in Africa. *Sustainability* **2024**, *16*, 672. https://doi.org/10.3390/su16020672

Academic Editor: Gioele Capillo

Received: 18 December 2023
Revised: 8 January 2024
Accepted: 10 January 2024
Published: 12 January 2024

1. Introduction

Africa hardly creates any of its plastics and uses them sparingly for essentials, e.g., storing water. But, Africa has become a dumping ground for the Northern Hemisphere's (i.e., Europe and the USA) plastic waste in the form of so-called "recycled" clothing and plastic feedstock. Global plastic production, estimated at 390.7 million tonnes in 2021 [1,2], has increased rapidly in recent decades [3] and will reach 1800 million tonnes by 2050 [4,5]. Landfill disposal is also increasing, leading to the widespread dispersal of plastic parts into marine environments [6]. The life cycle of plastics is estimated to be several hundreds of years [7]. Since 2015, it has been reported that 12% of plastic waste has been incinerated, with 79% ending up in landfill or leaking into the environment [8,9]. Single-use plastic packaging is the largest segment of plastics produced worldwide [10].

After Asia, the African continent is the place where the mismanagement of plastic waste is most widespread and visible [11]. From data resulting from more than 10 years of research, 33 African countries imported about 126 million tonnes (Mt) of polymers in primary form and 46 Mt of plastic products between 1990 and 2017 [12], which means all these countries imported around 172 million tonnes of plastic materials and polymers during this period [13], with an estimated value of USD 285 billion [14,15]. The import of unprocessed and/or processed plastics, finished products, or packaging made of plastics as well as plastic waste is constantly increasing. Adding to local production, mostly of single-use plastic packaging, the huge import of second-hand clothes (SHCs) with short lifespans in many African countries makes the situation worse. A sustainable solution must be found to this environmental problem.

Several sources and databases such as International Scientific Publications, reports from organizations, web pages, and policy documents were consulted to assess relevant information for this work. Over 300 articles were reviewed, using keywords such as "plastic production in Africa", "Africa plastic import", "second-hand clothes trade", "second-hand clothes waste in Africa", "plastic waste management in Africa", "plastic recycling in Africa", "plastic plants in the world", "micro-fibres in African wastewater", "microplastic in African aquatic environment", etc. We used the relevant literature and structured this article as follows: statement of the problem, waste management in Africa compared to Europe (EU-27+3), special problem areas, and solution approach initiatives.

This paper focuses on African countries that have received little attention to date and takes an approach to assessing the impact of plastic production and waste management in Africa. The situation is critical [16] and needs to be addressed. This study attempts to gather the existing literature and to empirically underpin the underlying issue of sustainability in Africa to generate results that redefine policy and industry on this topic.

2. Statement of the Problem

2.1. Plastic Production in the World and by Region

Africa produces 5% and consumes 4% of the world's plastic [17,18]. Plastics are used daily for various purposes, e.g., for packaging goods, beverages, and food for easier transport; shoes; clothing; telecommunications; transport; etc. [15]. In 2021 [1], the regions with the lowest yearly plastic production were the Middle East, Japan, and the Commonwealth of Independent States (CIS), with an average of 11,721 kilotonnes (kt), followed by Latin America and Africa, with 15,628 and 19,535 kt; the EU-27+3 (current EU, Norway, Switzerland, and the United Kingdom), with 58,605 kt; the rest of Asia, with 66,419 kt; North America (the USA and Canada), with 70,326 kt; and China, with 125,024 kt, as the largest producer, as shown in Figure 1. In 2017, the share of plastic production in Africa and the Middle East was 7% and increased to 8% (5% for Africa) by 2021 [1]. According to the same source, it decreased by 4% in the EU-27+3 and by 1% in Japan, while it increased by 3% in China and by 1% in the Commonwealth of Independent States (CIS), and stagnated in all other countries during this period.

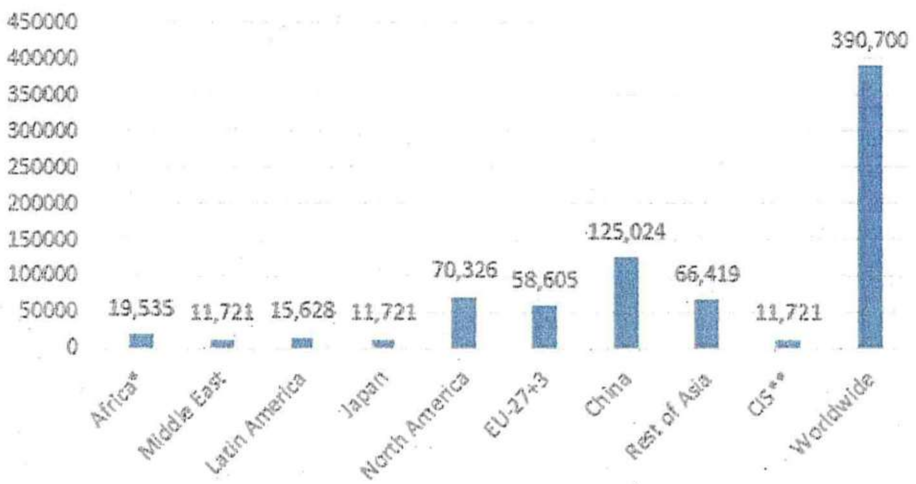

Figure 1. Annual plastic production worldwide and by region in kilotonnes (kt) in 2021 [1]; * Africa and the Middle East together produced 8% (the portion for Africa is estimated at 5%); ** Commonwealth of Independent States: Azerbaijan, Armenia, Belarus, Kazakhstan, Kyrgyzstan, Moldova, Russia, Tajikistan, Turkmenistan, Uzbekistan, and Ukraine.

2.2. Plastic Production in Africa

Figure 2 presents some of the plastic producers in Africa. The choice of African countries mentioned in this review is guided alone by the data availability (even if some are old) and confirms the data scarcity [19]. In 2020 [19], Egypt (2329 kt), South Africa (1410 kt), and Nigeria (513 kt) were among the biggest African plastic producers. Ethiopia's estimated production in 2022 was 386 kt [20], Ghana's was 205 kt in 2019 [21], and Kenya's was 130 kt in 2018 [22]. In 2018, Kenya produced around 30% [23] of the country's 433 kt of primary plastic material.

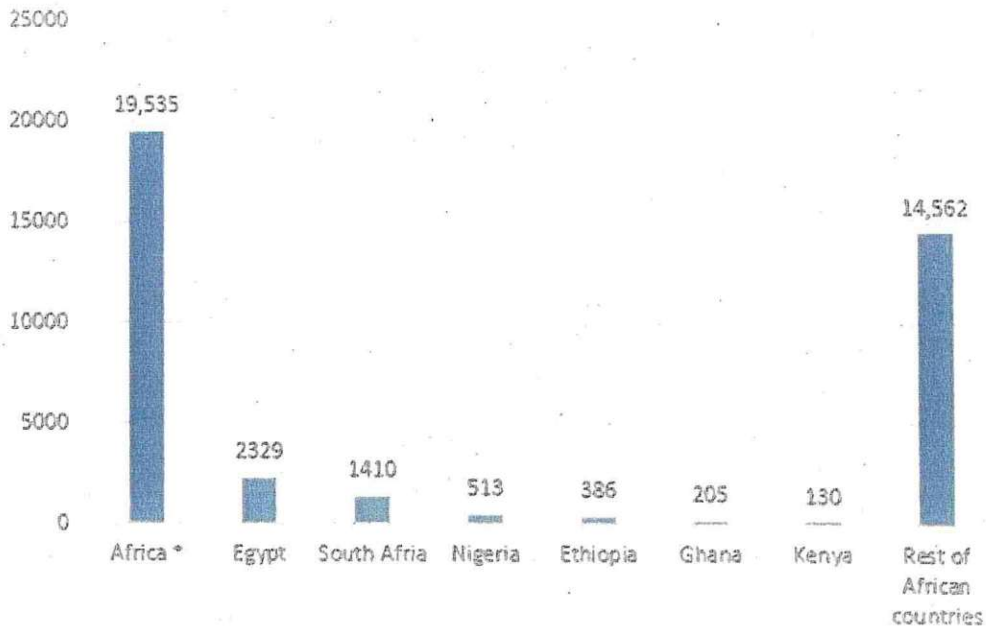

Figure 2. Plastic production in some African countries in kt per year [1,19–22]. * Africa and the Middle East together produced 8% (the portion for Africa is estimated at 5%).

Egypt is one of the largest polymer markets in Africa, accounting for over 20% of demand in 2017 and the country's polymer consumption is estimated at 2 million tonnes, with a per capita consumption of 21.8 kg/capita (investments in the plastics industry in Egypt amounted to USD 7.8 billion in 2016) [24]. In Rabat (Morocco's capital), the plastics manufacturer "Erum" completed an expansion of its plant in Tangier and inaugurated a new facility on 11 May 2023 [25]. The new plant (with a production capacity of 202 million product units) specializes in manufacturing plastic products for the clothing sector, such as plastic hangers [25]. The countries mentioned in this section are the most relevant African plastic producers and for which data are available. Countries from North, South, East, and West Africa are represented.

2.3. *Imports of Unprocessed and Processed Plastics for Products*

Imports of plastic raw materials from some African countries have increased significantly in recent years. It is not easy to find information concerning all African countries for the same year, so we used different references for different years. For example, from 2007 to 2020, imports for Algeria increased from 304 to 931 kt (+108%), Morocco from 374 to 659 kt (+76%), Tunisia from 209 to 326 kt (+56%), Nigeria from 513 to 848 kt (65%), and Ethiopia from 54 to 224 kt (+315%) [26]. Egypt and South Africa imported 896 kt and 539 kt of plastic raw material in 2020 [26]. In these 27 years (from 1990 to 2017), Africa imported 230 million tonnes (Mt) of plastic product components. The largest share of plastic components went to Egypt (43 Mt, 18.7%), Nigeria (39 Mt, 17.0%), South Africa (27 Mt, 11.7%), Algeria (26 Mt, 11.3%), Morocco (22 Mt, 9.6%), and Tunisia (16 Mt, 7.0%) [14]. Adding the 46 million tonnes of imported plastic products mentioned in Section 1, we can conclude that ((230,000 + 46,000)/27 = 10,222) kilotonnes of plastic products have been imported by the 33 countries on average per year in this period. Assuming that the percentage of countries mentioned above will roughly stay the same, the import quantity of each of these countries can be calculated. According to our references, with data from 2018 for Kenya; 2020 for Ethiopia; 2018 and 2020 for South Africa; 2019 and annual estimations for Ghana; 2020 and the average value across 27 years for Nigeria, Egypt, Algeria, Morocco, and Tunisia. South Africa, Algeria, Nigeria, and Egypt imported the most unprocessed plastics, while Ethiopia, Ghana, Algeria, Egypt, and Nigeria imported the most processed plastics. Figure 3 presents the yearly average imports of unprocessed and processed (products) plastics of some African countries in kt.

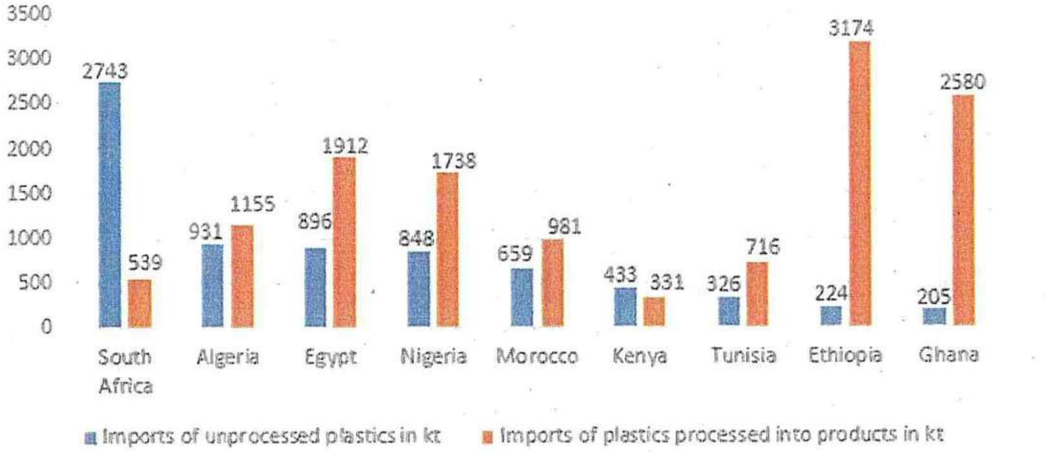

Figure 3. Average African imports of unprocessed plastics and processed plastics for products in kt per year [14,22,27–29].

2.4. *Import of Finished Products or Packaging Made from Plastics*

Many developing countries, including important producers of plastic, are net importers of plastic packaging. Africa's dependence on imports widely varies, ranging from 70% of plastic consumed in primary form as a product in Egypt and Nigeria to only 27% of primary plastics in South Africa [30]. Globally, according to the same source, 14 Mt of commercialized plastic packaging is significantly smaller than, for example, 196 million tonnes of primary plastic but has a high value in terms of exports, estimated at USD 53 billion in 2018. In addition, packaging products are typically single-use [30] or have a very short "in-use" lifespan (6 months typically or less) [9]. Lightweight, elasticity, and cheapness are properties that make plastic more attractive in the design of useful products. Most of the packaging used in Africa is poor single-use plastic bags (those intended to be used only once before being discarded) [31] for fresh vegetables and short-lived products for daily purchases. Egypt, Nigeria, and South Africa are the largest producers and importers of plastic polymers and products (including imported packaging). In addition, Ethiopia, Ghana, Kenya, and Mozambique are seeing growing production and imports of plastic goods [11]. The increase in imports of plastic products and packaging into African countries is a fact (many countries have formal retail outlets) [11]. According to a WWF [11] report, the COVID-19 pandemic enhanced e-commerce in various African countries and led to a rising consumption of plastic packaging, which is higher in comparison to the packaging consumed in physical stores. Data about the import of finished products or packaging made from plastic for individual African countries were rare, but the increasing tendency of its quantity has been documented.

2.5. *Import of Plastic Waste or "Pseudo-Products" That Are De Facto Wastes*

In general, waste management remains a major concern for many African countries [32,33]. The number of inhabitants, income of the population, and urbanization also have an impact on people's consumption patterns and the amount of waste produced, such as plastic waste, which continues to increase. In 2018, South Africa and Kenya imported, respectively, 18 kt [26] and 3 kt [29] of plastic waste. In 2018, the ban on plastic waste import in China showed serious consequences for exporters of plastic waste from developed countries, including the USA, the EU, and some other European countries, who were then forced to find new legal or illegal export possibilities in developing countries, mainly in Southeast Asia and African countries such as Ethiopia and Senegal [11]. The USA exported more than 1 million tonnes of plastic waste to Senegal in 2019 [34].

Plastic is also contained in electrical and electronic products. Moyen Massa and Archodoulaki [35] reported that Ghana and Nigeria in Africa are among the biggest recipients of e-waste from developed countries. According to them, approximately 400,000 used computers are imported every month, of which only about 50% are still working. Europe and the USA are among the largest exporters of electronic and electrical equipment to Africa. The authors mentioned that about 300 containers of used and/or discarded electrical and electronic equipment arrive at the ports of Tema in Ghana every month. An average of 75–80% of this imported equipment is already at the end of its life.

Every African consumes 5 kg of textiles per year [36], and due to the increasing exports of used clothing from industrialised countries to developing countries, clothing waste in Africa is on the rise. In general, a considerable amount of used clothing shipped in Africa is already unusable. Greenpeace [37] reported that 30–40% of imported SHCs in Kenya are of such poor quality that they can no longer be sold.

3. Waste Management in Africa Compared to Europe (EU-27+3)

3.1. Recycling Rate

In terms of increasing waste generation, a direct correlation exists between the volume of generated plastic waste, the population growth [13], and the Gross Domestic Product (GDP) [14]. Plastic is not inherently bad and contributes multiple benefits to society, and it has become an essential element of modern life and plays a key role in global progress toward sustainability [11]. Plastic products are helpful in daily human life and only need to become sustainable. The approach of a circular plastic economy (CPE) will be the best in this context. This approach is a system applying the principles of circular economy to the plastic value chain, including the design, manufacture, use, and end-of-life phases. A CPE will promote innovative design, encourage recycling, and incentivize the reuse of materials. The intention is to foster a move toward more sustainable interventions for the plastic challenge through innovation [38]. Due to lax regulations and improvements to its economy, Africa is also contributing to the rise in plastic pollution [39]. Poor management of plastic waste can be observed in almost all African countries: in most sub-Saharan African countries, it is over 80% [40], except South Africa (54%). In Mauritania, the rate is 82%; in Egypt, 67%; in Morocco, 66%; in Tunisia, 60%; in Algeria, 58%; and in Libya, the lowest, at 23% [24]. In general, short-life products (plastic packaging) and medium/long-life products (agriculture, electronics, automotive, construction, and others) generate more than 80% and less than 35% of waste, respectively (with a product consumption of 100% in both cases) [41]. According to Embrandiri A. et al. [42], 49.2% of plastic waste in Africa has plastic packaging as a source. In 2015, Africa generated 19 million tonnes of plastic waste, of which 17 million tonnes were mismanaged [11,43], compared to 60–99 million tonnes (15.8–26.1%) of globally mismanaged plastic waste in the same year. In addition, more than 380 million tonnes of such waste were generated worldwide (including in Africa), and it is projected to triple by 2060 [31]. Figure 4 presents the plastic waste data for some African countries (in kt). This figure shows that Egypt, Nigeria, South Africa, Algeria, the Republic Democratic of Congo (DR Congo), and Tanzania are the largest producers of plastic waste in Africa, with an average of more than 1000 kt. Ghana, Kenya, Angola, Cameroon, Côte d'Ivoire, Morocco, and Uganda generate over 500 kt on average, while Mozambique, Ethiopia, and Zambia over 300 kt.

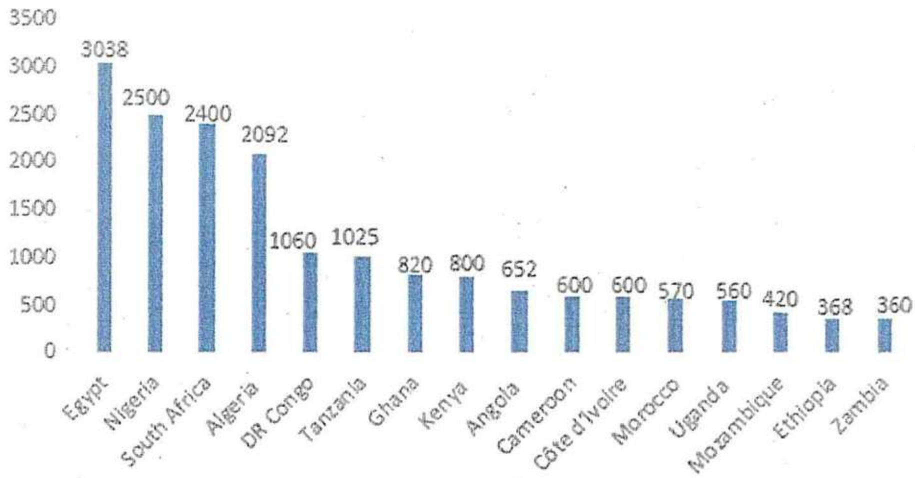

Figure 4. Average data on plastic waste for some African countries per annum in kt [9,44].

In 2019, Klynveld Peat Marwick Goerdeler (KPMG) International [45] forecasted an estimated 12.3 Mt of plastic waste to be sent to recycling facilities in Europe in 2020, while in Africa, small-scale plastic recycling plants existed only in some countries, namely [46] Tunisia with a processing capacity of 30,000 tonnes/year, South Africa 19,200 tonnes/year, Morocco 15,200 tonnes/year, Algeria 7200 tonnes/year, Zimbabwe 4380 tonnes/year, Côte d'Ivoire 1800 tonnes/year, and Ghana 1200 tonnes/year. In the EU-27+3, there are recycling plants with a capacity of over ten million tonnes per year, whereas in the African countries mentioned above, there are only 78,980 tonnes per year. These data confirm the lack of recycling plants with sufficient capacity on the continent. Table 1 compares the recycling rate in the EU-27+3 (current EU-27, Norway, Switzerland, and the United Kingdom combined) with data from some African countries. The average "correct" recycling rate including energy recovery in the EU-27+3 (77%) is higher than the African countries (<46%). Most African countries still have a low average recycling rate (<20%), as shown in Table 2.

Table 1. Post-consumer plastic waste treatment in Kenya, South Africa, and Ghana compared to EU-27+3 [1,26,29,47].

Process	EU-27+3 (%)	South Africa (%)	Kenya (%)	Ghana (%)
Recycling/Incineration (energy recovery)	77	45.7 *	36 *	25 *
Landfill	23	44.3	8	58
Open burning	Ban	10	56	17

* Recycling, all properly disposed processes and/or energy recovery.

The incineration of plastic waste produces tonnes of toxic air pollutants if it is not carried out properly. In addition, the post-treatment of incinerators requires a large amount of land and funding [48]. Open-field incineration of plastic waste, as practiced in many African countries, is one of the main sources of pollution [49]. Municipal solid waste (MSW) contains about 12% plastics, which can release toxic gases into the atmosphere when incinerated [49]. Although the incineration of solid plastic waste results in a 90–99% volume reduction [50] (i.e., a reliable reduction in landfill), it is often carried out in an open field in most African countries, with all the associated negative environmental impacts (e.g., CO_2 emissions and some infectious diseases). Therefore, this is not a suitable solution [51], although the associated energy would be useful in the cement industry for example (a "clean" incinerator with suitable filters) or using suitable filters for plastic waste burning in a vacuum chamber in anaerobic conditions to produce steam which will help to generate electrical energy effectively because such power plants produce on average more CO_2 than the gas-fired equivalents. The presence of toxic substances in recycled plastic waste has been confirmed [52,53]. Some concentrations of PAHs and polychlorinated biphenyls (PCBs) have been detected in sediment cores of the Lagos (Nigeria) lagoonal system, which may pose a significant ecotoxicological risk to estuarine organisms [54]. Table 2 shows the toxic substances associated with plastic waste.

Table 2. Associated toxic substances in plastic waste [55].

Toxic Substances		
Polycyclic Aromatic Hydrocarbons (PAHs)	**Persistent Organic Pollutants (POPs)**	
	Legacy POPS	**New POPs**
Benzo(c)fluorene, Dibenzo[a,l]pyrene, 5-Methylchrysene, Cyclopenta(cd)Pyrene, Dibenzo[a,e]pyrene, Benzo(j)fluoranthene, Dibenzo[a,i]pyrene, Dibenzo[a,h]pyrene, Benzo(a)pyrene, Acanaphlene, Acanaphthylene, Anthracene, Benz(a)anthracene, Benzo(b)fluoranthene, Benzo(k)fluoranthene, Benzo(ghi)perylene, Chrysene, Dibenz[a,h]anthracene, Fluoranthene, Fluorene, Indeno[1,2,3,cd]pyrene, Naphthalene, Phenanthrene, Pyrene	Pesticide Aldrin, Chordane, DDT, Dieldrin, Endrin, Haptachlor, Hexachlorobenzene (HCB), Mirex, Toxaphene, Dioxin-like POPs, Polychlorinated biphenyls (PCBs), Polychlorinated dioxins (PCDDs), Polychlorinated furans (PCDFs)	BFRs: Hexabromocyclododecane (HBCD), Tetra and pentabromodiphenyl, ethers (TeBDE, PeBDE), Hexa and heptabromodiphenyl ethers (HxBDE, HpBDE), Decabromodiphenyl ether (deca-BDE). Others: Alpha-hexachlorocyclohexane, (a-HCH), Beta-HCH, Chlordecone, Dicofol, Hexabromobiphenyl (HBB), Pentachlorobenzene (PCBz), Lindane, Pentachlorophenol (PCPh), Pentafluorooctane sulfonic acid (PFOS), Perfluooctanoic acid (PFOAS), Poplychlorinated Naphtalenes (PCNs), Short-chain chlorinated paraffins (SCPPs), Endosulfan, Hexachlorobutadiene (HCB)

3.2. *Energy Recovery in Large Plants and on a Small Scale (Use of Used Textiles as Substitute Fuel in the Domestic Sector)*

In 2017, the first conversion of plastic waste into synthetic fuel oil was developed in Kenya and a waste-to-energy plant was commissioned in Ethiopia [42]. The recycling rate for the EU-27+3 in 2021 (42% [1]), shown in Table 1, provides accurate data on energy recovery through plastic incineration plants and confirms that this process is more developed in Western countries. The incineration of plastics purely for volume reduction is not sustainable and is contrary to the goal of the circular economy, which includes the reduction, reuse, and recycling of plastic waste. Material or energy recovery is the best approach as it offers the best environmental outcome [56]. Bassay et al. [56] propose incineration, conventional pyrolysis, conventional gasification, and catalytic gasification as recycling methods for the thermal treatment of plastic waste in Africa. In 2017, Nunes, L.J.R. et al. [57] presented a study on the use of waste from the textile industry (more specifically, cotton waste) as a renewable resource for the production of thermal energy (production of cotton briquettes in Portugal). The construction of large and small plants to convert textile waste into energy for the domestic sector may be more attractive for African countries. Studies on the conversion of used textiles into fuels in Africa were not found in this survey.

3.3. *Orderly and Irregular Landfilling*

South Africa is the 32nd largest producer of plastics globally, and the plastic industry plays a significant role in the country's economy [58]. In 2018, South Africa properly disposed of 44% [26] of its plastic waste. In most developing countries (including in the African continent), plastic waste is not properly landfilled [9]. There exist more open dumpsites of mixed waste (irregular landfilling), like in Figure 5. Plastic waste is often openly incinerated in such landfills.

Figure 5. Unofficial mixed landfill waste near Mokolo coal market (Yaounde—Cameroon).

In South Africa, 10% of plastic waste is openly incinerated, 17% in Ghana, and 56% in Kenya (Table 1), with all the negative consequences for the environment and living creatures. The biggest problem in landfilling waste is its degradation without any appropriate expert control (negative impacts on human health and the environment). Plastic waste is even more hazardous due to its long lifetime [49], as it can undergo several negative transformations during this time due to the presence of toxic substances and/or additives and become a source of pollution for groundwater. Landfilling, as shown in Figure 5, is not a long-term solution [51] as it contributes to water crises in the affected countries, especially in African drought areas [59]. Table 3 shows the share of textile waste in the waste stream, the estimated recycling rate, and the disposal methods in some sub-Saharan African countries. In all countries listed in the table, the recycling rate is below 20% and even below the EU-27+3 average (77% including incineration with energy recovery). In South Africa, open dumping, burying, burning, incineration, and landfilling are the disposal methods [9]. Dumping, burying, and burning are used in Ghana, Kenya, and most African countries [9].

Table 3. Textiles waste, estimated recycling rate, and disposal methods in some sub-Saharan African countries [9].

	Nigeria	Ethiopia	Dem. Rep. of Congo	Cameroon	Côte d'Ivoire	Mozambique	Rwanda	Tanzania	Uganda	Zambia
Textiles waste in waste stream (%)	5	N.S.	N.S.	N.S.	2.8	N.S.	N.S.	2	1	N.S.
Estimated recycling rate (%)	<10	5	<15	<20	<20	1	10	4	N.A.	1–3
Available disposal methods	Open dumping, burying, burning, incineration, and landfilling	Dumping, burying, and burning	Open dumping, burying, and burning	Open dumping, burying, and burning	Open dumping, burying, and burning	Dumping, burying, and burning	Dumping, burying, and burning	Dumping, burying, and burning	Dumping, burying, and burning	Dumping, burying, and burning

N.S., Not Specified; N.A., Not Available.

4. Examples of Africa's Own and Imported Plastic Waste

4.1. Bags for Drinking Water Supplies

Water scarcity is a big problem in Africa, where 325 million people lack access to safe water [60]. In Ghana, 150,000 bags are produced daily by larger companies and 45,000 bags by small companies for sachet water (85% of the plastic waste generated in Ghana [14]). In addition, over 60 million sachets are consumed daily, with about 1500 sachet water factories alone in Lagos (Nigeria) [14]. In many African countries, low-density polyethylene (LDPE) and high-density polyethylene (HDPE) are polymers used to produce bags for drinking water. Figure 6 presents an example of a 500 mL sachet water.

Figure 6. Example of sachet water (English translation of Non-English character: MINERAL WATER, *to maintain its quality, EAU GOLDEN is regularly checked by an approved laboratory, kept away from sunlight*).

4.2. Imported Used Clothing

The fast fashion business model, which drives the second-hand trade, leads to a colonial relationship between the Global North (GN) and the Global South (GS), with the GN exporting unwanted old clothes to mainly African countries [61]. That said, the GN does not want to dump these clothes locally to distort their environment further but rather exports them legally or illegally to Africa and other places in the world. A huge part of imported unwanted second-hand clothes (SHCs) comes from the US (export volume of around 500,000 tonnes per annum) and the UK (around 319,998 tonnes per annum) land in Africa. [62]. Kenya was Africa's leading importer of second-hand clothing (184,000 tonnes) in 2021 [63]. Ghana, Benin, Tanzania, Kenya, and Uganda received between 2% and 4% of the world's exported SHCs [64]. Current data on the import of SHC into African countries are difficult to find, as they are also traded illegally in this sector. Figure 7 shows the import of SHC to some African countries.

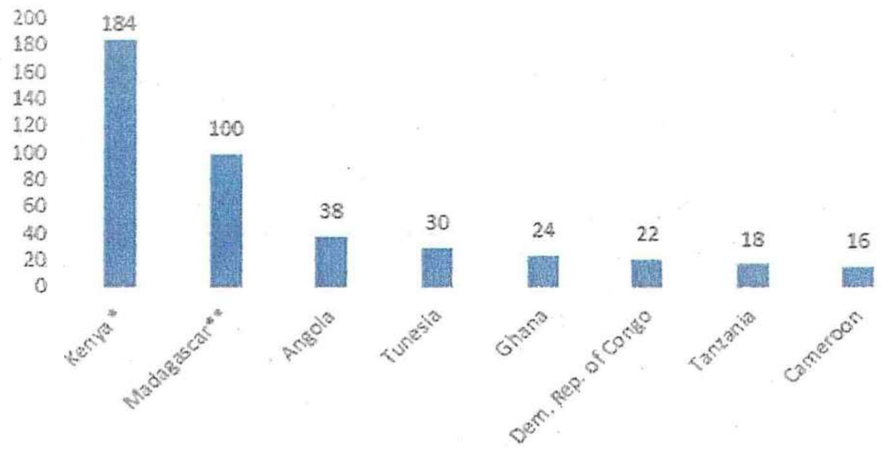

Figure 7. Average imports of SHCs for some African countries per annum from 2015 to 2019 in kt, Kenya (in 2021 *) and Madagascar (estimated annual imports **) [63,65,66].

4.3. Plastic Leakage and Marine Pollution

Mismanaged waste from African shipping and maritime activities such as aquaculture and fishing also ends up in the oceans. Imported, abandoned, lost, or otherwise discarded fishing gear contributes to an estimated 640,000 tonnes of additional marine litter worldwide (including Africa) [67]. In South Africa, it is estimated that 29% of household waste is disposed of by "self-help" [58]. The gaps in the country's waste collection pose some challenges, such as the fact that the local waste recycling economy is largely driven by the informal waste sector and there is still a significant amount of post-consumer materials (599 kt/a according to a 2019 in-country plastic recycling survey) that are not or cannot be recycled, some of which is disposed of in compliant landfills, but which also leads to illegal dumping [58].

Around 80% of all plastic waste in Ghana (similar to most African countries) has land-based sources, whilst 20% has ocean-based sources [68]. Fred-Ahmadu H. O. et al. [69] used the ATR-FTIR method to attest the presence of microplastics such as polystyrene (PE), polypropylene (PP), polyvinyl chloride (PVC), polyamide (PA), polystyrene (PS), polyurethane (PU), ethylene vinyl acetate (EVA), acrylonitrile butadiene styrene (ABS), polyethylene terephthalate (PET), and a mixture of PE and PP in epipsammic sediments in Nigeria. The same source reported the presence of microplastics in Ghanaian coastal la-goon sediments. Kan R. F. et al. [70] confirmed the presence of microplastics in the Nile River (Egypt). Microplastics have been found also in the sediment of the complex la-goon-channel of Bizerte (Northern Tunisia) [71]. According to the WWF [11], four big African rivers—namely, Congo, Niger, Nile, and Zambezi—are among the 14 major rivers around the world to have been identified as plastic leakage hotspots from land-based sources, close to urban centres with high waste generation but poor waste management systems. It is possible that microplastics and other contaminants have synergic effects on the health of organisms or can serve as transport vectors for other contaminants [72–74]. When plastic waste enters the environment in Africa, it begins to decompose and fragment in combination with solar radiation, cold, heat, drought, and rain, resulting in so-called "secondary microplastic", as opposed to microscopic material manufactured for use in various products, such as microbeads in beauty products (used also in Africa) and/or residues from the local plastic industry (primary microplastic) [75–77]; both of these land in the African marine ecosystem and become microplastic (MP) pollution. Due to the small debris that they are or have become, these MPs subsequently become a serious threat to marine fauna and flora on the one hand, and the presence of toxic substances in them has dangerous consequences on the human food chain on the other hand. Many studies reported MP presence in (i) fish [78–85] (fibres are the most common MPs from a morphological view, with 57.6–86.5% of observed particles) [78]); (ii) salt [78–82,84,86,87] (the presence of microplastics in salt samples has been reported, namely, 8–102 particles/kg in lake salt and 9–16 particles/kg in rock salt [78]); (iii) drinking water [78–90] (which ensures adequate hydration for health, maintains the dietary nutrient-to-calorie ratio, and helps bodily functions [78]), with a worldwide investigation of both bottled and tap water confirming microplastic contamination [78]; and (iv) rice [78,91] (which is the staple food for around 50% of the world population and provides more than 20% of global dietary energy in the human diet [78]), among others. In 2016, an American Chemistry Council (Trucost) study [92] estimated the damage caused by plastic waste (including macroplastics, microplastics, and nanoplastics) to oceans at USD 5 billion and to human health and ecosystems at USD 63 billion in the case of the business as usual policy. Not many articles have been published on marine pollution in Africa; only 59 plastic studies have been conducted on African aquatic environments and were published from 1987 to September 2020 [33]. Worldwide (including Africa), 22 million tonnes of macro- and microplastics on average leaked to the environment in 2019 [93].

5. Initiatives to Solve the Problem

To fight against plastic waste leakage, some African countries including Senegal, Côte d'Ivoire, Mali, Ghana, Kenya, Ethiopia, Malawi, Mauritius, Tanzania, Uganda, Eritrea, and Congo [9,94] have banned single-use plastic bags, but the enforcement and execution of this measure are quite challenging [9].

In South Africa, the preferred waste management method is recycling. Due to collection difficulties, as mentioned above (mostly driven by the informal sector), only 40.3% of short-lived plastics and 17.7% of all converted plastic are taken from recycled-content landfills and recycled at recycling plants [58].

In Rwanda, the combination of a strict legal regime, enforcement, and arguably successful policy has been implemented to substantially reduce plastic pollution [19]. After a study conducted by the Rwanda Environment Management Authority (REMA) in 2003 [95], which provided some evidence of local discussions for anti-plastic action, the Rwandan government responded by initiating nationwide campaigns to increase awareness about the issues in 2004. In 2005 [95], Rwanda banned the import and use of plastics that are less than 100 microns thick. In 2008 [95], Rwanda's anti-plastic bag legislation, which banned the importation and use of non-biodegradable packaging bags, became one of the strictest laws. However, a person who intends to manufacture, import, export, or use plastic carry bags and single-use plastic items for exceptional reasons can apply for authorization [96]. A competent authority establishes the guidelines for the procedures and conditions for the issue of exceptional authorization. Imported products packaged in plastic material or single-use items are subject to an environmental levy following relevant laws [96]. In addition, every manufacturer, wholesaler, or retailer of those products must put in place mechanisms to collect and segregate used plastic carry bags and single-use plastic items and hand them to the recycling plants [96]. Every person/entity recycling this waste must do it in a way that protects the environment. Any person/stakeholder who violates the legislation pays up to a FRW 10,000,000 administrative fine, depending on the law that was violated (USD 1 = FRW 1237). A lack of monitoring and data management systems limits the government's ability to quantitatively measure and assess the impacts and effectiveness of plastics policies needed to design, improve, and implement plastics policies for the effective management of plastic waste [97]. According to the same source, Rwanda needs to invest in establishing data collection and management systems for plastics and plastic waste. However, some qualitative improvements have been achieved through this legislation in Rwanda.

6. Discussion

In 2015, plastic consumption in Africa was 16 kg (24 kg/year in South Africa [14]) per person, which is the lowest compared to the global average of 45 kg and 136 kg in Western Europe [11], but it is steadily increasing. A study estimated that plastic waste will increase to 165 million tonnes in Africa by 2030 [98]. Consumption patterns and demographics in Africa are constantly changing over time, putting considerable pressure on the waste management system (especially in large cities that attract more unemployed young people) [99].

In 2021, we surveyed Cameroon with 305 participants (40% women and 60% men); 220 valuable responses (72%) were received, mainly from the country's two major cities, Douala and Yaounde. Of the 220 respondents, all admitted to coming into contact with plastics (particularly single-use plastic packaging) daily, but only 64 people (29.1%) are aware of the problem of plastic waste, sort it out, and then pass it on either to third parties or to NGOs for "appropriate" treatment (to avoid it ending up in an open landfill). Sixteen people (7.3%) throw their plastic waste in the rubbish without thinking about what happens to it but are aware of the environmental problems associated with it. These people consider themselves powerless to do anything about it, as they see it as a matter for the municipalities and the state. One hundred forty people (63.6%) stated that they have other concerns, such as the problem of economic survival and worrying about what will happen to the plastic waste afterward (question about the priority of life). Based on our survey, we can assume that each African consumer receives on average 3–4 pieces of single-use packaging (depending on purchasing power) per day as packaging for products bought in markets and/or shops. Consequently, plastic waste will continue to increase in Africa if nothing is done to introduce a recycling process to change this paradigm. This compels the consideration that a recycling strategy needs to be planned and implemented. Figure 8 presents a schematic illustration of plastic waste recycling in Africa.

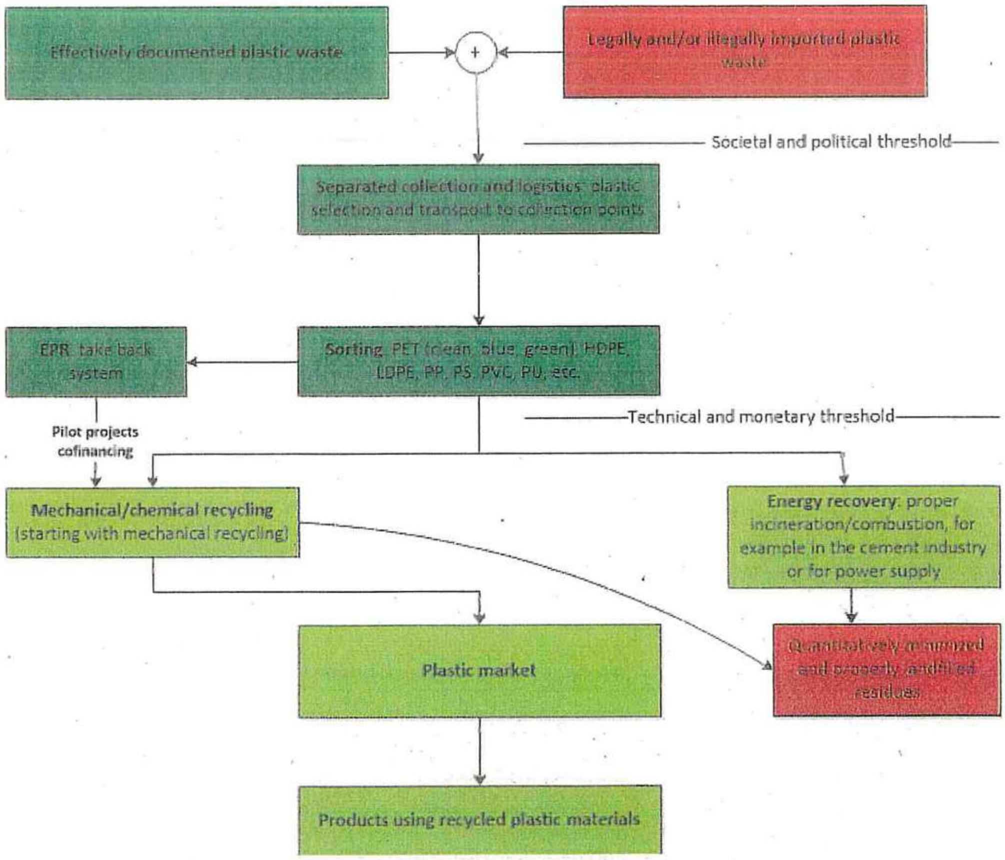

Figure 8. Schematic illustration of plastic waste recycling.

Another solution for the plastic waste problem in Africa is to enter into agreements with the plastics industry (Extended Producer Responsibility, abbreviation EPR), allowing producers to take back product waste and/or to finance the recycling of product waste at the end of their life (investment in innovative and clean technology for suitable product designs). In 2021 [100], South Africa introduced mandatory Extended Producer Responsibility (EPR) and implemented initiatives such as Deposit Refund Schemes (DRSs), which are source segregation programs that are expected to reduce the amount of plastic waste entering the environment by improving collection. The roles and responsibilities of actors and institutions involved in plastic waste in Africa are meaningful. Nevertheless, it is important for the international community, in cooperation with the plastics industry, to establish an effective and well-structured collection system for plastic waste. This will help to maximize the collection rate and to truly minimize landfills through clean recycling. Incentivizing the plastic and textile industries to opt for product design that uses easily recyclable materials (eco-design) is also crucial.

Recycling second-hand clothes can reduce greenhouse gas emissions by 53%, pollution associated with chemical processing by 45%, and water eutrophication levels by 95% [101], and could contribute to the sustainable management of resources and well-being of the population in Africa. Every phase of the life cycle of textile waste recycling (i.e., collection, sorting, transport, and recycling) creates employment and gives opportunities for small and/or family businesses. African countries need to consider the vast amounts of textile waste generated by the second-hand trade (legal and/or illegal) as a possible source of income by introducing a new recycling policy on this issue. The results of a study [57] on the conversion of textile waste into energy show that cotton briquettes made from textile waste have a calorific value of 16.80 MJ/kg and a cost of 0.006 EUR/kWh when used as fuel. This means an annual reduction in fuel costs of 80% and 75% compared to heating oil and wood pellets, respectively. According to the same source, for the domestic sector, it is possible to produce briquettes from a blend of 90% cotton and 10% polyester [57] in small-scale and/or large-scale plants. Furthermore, imports of SHC in Africa have a negative financial impact on the local garment production market due to their low prices.

The link between climate change and plastic pollution is that plastics are mainly made from fossil fuels such as fuel oil, gas, and coal. Global (including Africa) life cycle GHG emissions from conventional plastics were 1.7 gigatonnes (Gt) of CO_2 equivalent (CO_{2e}) in 2015 and are projected to increase to 6.5 Gt CO_{2e} (26% growth) by 2050 at current consumption patterns [102], which will exacerbate the climate change problem. This means that if nothing is done, the contribution of plastics to greenhouse gas emissions will also increase in Africa. CO_2 emissions from the production of polyester are 2–3 times [39] higher than cotton. However, cotton production consumes large amounts of water and accounts for 11% of global pesticide consumption [103], making it an environmental problem for Africa.

The increasing plastic pollution in Africa is due to years of accumulation of waste without any treatment measures. Most studies mention that Africa is a net importer of plastics. Comparing the amount of plastic production in Africa (19,535 kt in 2021) and the annual average of plastic imports over 27 years ((230,000 + 172,000)/27 = 14,889 kt) for 33 African countries, it can be said that the contribution of plastic imports is equivalent to 76% of African plastic production in 2021 and is therefore significant. Knowing that the data for 33 countries are based on estimates, and if we also take into account the data from the other 21 African countries (Africa consists of 54 countries) that are not included in this statistic and the amount of (legally and/or illegally) imported plastic/textile waste, we can probably be sure that plastic pollution in Africa is an imported environmental crisis. We need more studies on this in the future.

Planned regulations should mandate companies to manufacture sustainable and repairable products, exerting a significant influence on their product design. Producers, importers, and consumers should address a hierarchy of measures and essential considerations:

- Evaluate the necessity of using the material;
- Implement strategies to minimize the quantity of used material;
- Opt for materials with easy recyclability;
- Design products for straightforward dismantling at the end of their life cycle.

7. Conclusions

Most African countries import a large amount of plastic products and "pseudo-products that are de facto wastes" every year, but there is not enough up-to-date statistical data and concrete information on the production and import of plastics across the continent. A lack of data leads to underestimation of the problem and deliberate ignoring. The growing population in Africa and the improvement in living standards go hand in hand with increasing plastic consumption. Therefore, without a sound environmental policy, Africa's own and imported plastic waste will lead to a dramatic situation and require a global approach. Banning the illegal/legal trade of unwanted second-hand clothing from industrialized countries to Africa and between African countries themselves is part of the solution. The best option to reduce textile waste is to slow down the production of new clothing and to increase the quality and lifespan of these new products, as proposed in the European Commission's waste hierarchy (2018) [69]. In production, textile companies need to choose and/or develop knitting techniques that reduce fibre loss [104]. The construction of large-scale plants with high exhaust gas purification capacities to utilize used textiles as a substitute fuel for the household sector is the best option for African countries.

In Africa, it is essential to improve plastic waste management strategies through a better collection system, a ban on improper landfilling, the reuse of plastic products, and the improvement of plastic recycling by the local plastics industry. We believe that awareness campaigns for better individual consumption behaviour of plastic products are very important.

Considering the aforementioned disparities and problems that surround the current plastic waste management strategies (including microplastics and nanoplastics), the following can be recommended: (1) Plastic waste should be monitored in the environment globally, with a requirement for all countries to establish a database on their collection and treatment. As a global problem, plastic waste needs the approach to this global solution to be more efficient. (2) Plastic monitoring systems need to be harmonized in terms of regular reporting, monitoring, and assessment of sources, pathways, flows, and balances of waste in the environment to support waste management policies and regulations [105]. (3) Stakeholders need to get involved early in the development of plastic waste prevention measures, which is linked to the psychological importance of taking responsibility for measures, to increase their commitment to the implementation of measures when they are finally adopted (Corporate Social Responsibility, abbreviated as CSR: multinational corporations/companies need to contribute to improvements in worldwide social and environmental standards) [105]. (4) Sustainability awareness should be promoted among the population by recommending well-designed programs that help people see links between their daily activities and plastic waste generation/management [105].

The limitations of this study are the lack of updated data and the low number of studies on plastic exports and imports in Africa, which are the consequence of less transparency among all stakeholders.

Author Contributions: Conceptualization, G.M.M. and V.-M.A.; methodology, G.M.M. and V.-M.A.; software, V.-M.A.; validation, G.M.M. and V.-M.A.; formal analysis, G.M.M. and V.-M.A.; investigation, G.M.M.; resources, G.M.M. and V.-M.A.; data curation, G.M.M. and V.-M.A.; writing—original draft preparation, G.M.M.; writing—review and editing, G.M.M. and V.-M.A.; visualization, V.-M.A.; supervision, V.-M.A.; project administration, G.M.M. and V.-M.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was financially supported by TU Wien University Library through its Open Access Funding Programme.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

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