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Status of Production, Consumption, and End-of-Life Waste Management of Plastic and Plastic Products in Nigeria: Prospects for Circular Plastics Economy

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Abstract: This study is motivated by the need to understand and proffer sustainable circular economy solutions to the persistent challenges associated with plastic waste management in Nigeria. Despite the emerging awareness and increased number of studies conducted on plastic and plastic products in Nigeria, the challenges and opportunities associated with their production, consumption, and post-consumption management are still poorly understood. Besides the large quantity of plastic and plastic products produced locally in Nigeria, a substantial quantity of these products in various forms and polymer types also comes into the country through importation. This results in a high consumption rate and, by extension, a huge volume of plastic waste generated daily exceeding the capacity and ability of the authorities to manage. In this work, we reviewed the available literature to analyze the status of the production, importation, consumption, and post-consumption management of plastic waste in Nigeria. It is estimated that out of 27.3 million tonnes of municipal solid waste currently generated in Nigeria's urban cities per annum about 11.2 million tonnes is collected, of which about 1.1 million tonnes is plastics. It is further projected that by 2040, about 40.5 million tonnes of municipal solid waste will be generated, and only about 1.6 million tonnes of the plastic component will be collected for disposal. Based on the outcome of the analysis, the current study further suggested how adopting circular economy principles can help mitigate the impact of plastic waste on Nigerian society.

Keywords: plastic waste; Nigeria; waste management; circular economy; waste disposal

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1. Introduction

Plastic as a consumer product has become an important part of our everyday life. It has found a broad application in almost all areas of human endeavor and forms a critical component in most finished consumer products. Basic household items, commercial products, and industrial equipment usually have parts and components made of plastic. For instance, the hardware part of electronic and electrical gadgets, hand rests of furniture, handles of kitchen utensils, waterproof packaging of most fast-moving consumer products, etc., are common applications of plastics. Plastics have several exceptional qualities which include (i) high durability which makes them desirable for packaging, industrial use, medical equipment, and so much more; (ii) cost effectiveness which makes them easy to produce and readily available; and (iii) high flexibility which makes them easy to be fashioned into a variety of shapes and forms [1]. However, the greatest documented application of plastic and plastic products is in packaging, especially in single disposable usage [2,3].

At the global level, it is estimated that about 8300 million metric tons (Mt) of virgin plastics may have been produced since the 1950s [2]. The production of plastics was predicted to be 260 million metric tonnes worldwide in 2007 [4]. This projection rose to 359 million tons in 2018 and 400.3 million tons in 2022 [5,6]. Because they mainly come as single-use items and packaging materials, about 50% of plastic products fall into the disposable product category [7]. As a result, the pace at which end-of-life plastic waste streams are generated has increased. About 6300 Mt of plastic waste may have been generated as of 2015, of which only 9% may have been recycled and 12% incinerated, while the remaining 79% is considered to have been accumulated in landfills or the natural environment [2]. It is further projected that following the current trend in production and consumption, about 12,000 Mt of plastic waste will be in landfills or the natural environment by 2050.

Because of its increased presence in municipal solid waste and the difficulties associated with its management, treatment, and disposal, plastic waste material has received special attention. It has become a global menace adversely impacting the three major components of the environment—air, water, and land. These adverse impacts in a broad sense have direct and indirect implications on the three pillars of sustainable development which include social equity, economic prosperity, and environmental protection. As a result of its detrimental effects on marine and coastal habitats, marine litter has gained international and regional attention as a pressing environmental issue [8,9]. This is one of the most significant negative effects of plastic production and consumption worldwide.

Although many studies in the literature have discussed the challenges of and solutions to the production, consumption, and end-of-life management of plastic waste, only a few studies have explored the developing countries' perspectives [10–14]. In developing countries, to be able to proffer circular economy solutions to plastic waste management problems, there is a need to study and understand the peculiarities associated with each country's and society's scenarios. This is essential since circular economy solutions are designed and implemented according to context simply because societies differ along socioeconomic, political, geographical, and even cultural particularities [15,16]. Against this backdrop, recent studies have analyzed the plastic waste management challenges in some developing locations and proffered a circular economy solution according to the prevailing information obtained from these locations [14,17–19].

In Nigeria, solid waste management has been a serious environmental challenge due to several factors such as inadequate resources, lack of technical capacity, poor policy regimes, absence of information/data, and ineffective institutions [20–23]. These challenges were recently complicated by the additional burden that comes with a continuous increase in the generation of plastic waste and other waste variants that require special management techniques, such as e-waste. None of the available studies on solid waste characterization in Nigeria have failed to highlight a significant plastic component. Studies have also shown that rivers are major sources of marine litter, and Nigeria ranks ninth in the global plastic marine litter release [24]. It has also been reported that more than 23,400,000 tons of plastics entered the Nigerian technosphere between 1996 and 2014 with only less than 12% of the resulting waste being recycled [9]. All these factors point to the need for sustainable solutions to the plastic pollution problems in Nigeria.

A growing body of literature has discussed the plastic waste challenges in Nigeria from different perspectives. For instance, a baseline study has tried to quantify the amount of plastic imported into Nigeria within a given period [9]. Many other scholars focused on discussing the challenges of plastic waste in Nigeria while suggesting specialized solutions. Some of the solutions suggested include formulating sustainable regulatory policies by the government [25,26]; raising awareness and quantifying the extent and presence of micro- and nanoplastics in the coastal environment [27]; socially friendly approaches to plastic waste management [28]; stakeholder education, polymer substitution, tax, and incentives to support the sustainability of life below water [29]; using plastic waste for electricity generation [30,31]; and adopting diverse recycling alternatives [3,7]. Some other authors

focused on policy arguments proposing legislative measures [32]. There are also works discussing the menace of microplastic pollution in Nigeria [33,34].

However, none of the available studies have studied plastic waste management in Nigeria in the context of the circular economy or with the aim of proffering circular economy solutions. Since it addresses the issue of the excessive extraction of virgin resources and related pollution, the circular economy framework for plastic waste management, which covers every stage of the value chain, is thought to be one of the best ways to mitigate the effects of plastic pollution [35]. In the current study, the entire plastic management landscape in Nigeria is discussed with the aim of proffering circular economy solutions. The current study is unique as it reviews in detail the status of the production, importation, consumption, and end of life waste management of plastics. The institutional landscapes and policy framework related to Nigeria's management of plastic waste are also informatively highlighted. The current work explains why and how circular economy concepts should be adopted and implemented as viable options for the efficient management of plastic waste in Nigeria.

2. Motivation for the Rising Global Advocacy for Effective Plastic Waste Management

The call for global actions towards achieving sustainable development has gathered traction in recent times, and part of this call centers on a reduction in the rate of conversion and utilization of non-renewable resources. Fossil fuels are an example of these non-renewable resources. Of all the fossil fuels processed globally, about 6% are used in the production of plastics [36]. To provide energy for their production, an additional 3–4% are also consumed [4].

Besides crude oil, other non-renewable energy sources such as coal and gas are used in plastic production [37]. Because of their short lifespan facilitated by single-use disposable items, the production and consumption of plastic and plastic products have continued to increase; hence, there has been an increase in the rate of utilization of these non-renewable resources. Consequently, the presence of plastic in municipal solid waste has also continued to increase. In exact terms, the World Bank report of 2018 shows that about 12% of municipal solid waste generated globally is plastic, while about 242 million tons of plastic waste was produced globally in 2016 [38]. The majority of the present worldwide approach to managing these wastes still adheres to a linear economic model, indicating an unsustainable course that puts natural resources at risk of depletion. Because of the non-biodegradable nature of petroleum-based plastic, when it accumulates in the environment, it can take hundreds or even a thousand years to degrade [4], having detrimental impacts on the components of the environment—air, water, and land—in various ways. In landfills, plastic waste streams occupy physical spaces and cause the landfill to get quickly filled up, thereby shortening its lifespan. When burnt, plastic discharges dangerous pollutants that can negatively impact public health. In developing/underdeveloped global regions where plastic wastes are indiscriminately disposed of due to poor waste management services, they can clog the waterways leading to flooding and soil erosion.

Depending on local environmental conditions, such as the exposure to UV light, oxygen availability, and temperature, even degradable plastics may remain in the environment for longer [39]. The right microbes must be present for plastic to decompose. As a result, degradation rates differ significantly between terrestrial and marine habitats as well as landfills [40]. A plastic object will eventually break down into smaller pieces of plastic debris due to weathering, but the polymer itself may not break down in a considerable amount of time [4,41]. This plastic debris can get into waterbodies, causing marine litter. A growing body of scholarly research indicates that, in the absence of action, the quantity of plastic debris entering the ocean will triple by 2025 [24]. According to the Ellen MacArthur Foundation [42], by 2050, there will be more plastic in the oceans than fish by weight if the current linear ("take–make–use–dispose") economic paradigm persists.

In light of these developments, plastic waste is currently seen as a significant issue for solid waste management that is considered a top priority in the political agenda world-

wide [43]. A number of targets related to waste and resource management are included in the Sustainable Development Goals (SDGs) Agenda, which was adopted by 193 UN member states in September 2015 [44]. These targets have the potential to either directly or indirectly improve sustainable waste and resource management [45]. Four Sustainable Development Goals specifically aim to prevent, reduce, and promote the management of plastic waste, either directly or indirectly. They include Goal 6—clean water and sanitation; Goal 11—sustainable communities and cities; Goal 12—responsible consumption and production; and Goal 14—life below water [14,18]. Within the SDGs, the specific targets that deal with plastic waste, especially in the context of developing countries, include (i) Target 5 of SDG 12—supporting the developing countries to substantially reduce waste generation through prevention, reduction, recycling, and reuse; (ii) Target 1 of SDG 14—the conservation and sustainable use of the oceans, seas, and marine resources; (iii) Target 6 of SDG 11—paying special attention to municipal solid waste; and (iv) Target 3 of SGD 6—reducing pollution, eliminating dumping, and minimizing release of hazardous materials [46,47].

The United Nations Environment Assembly (UNEA-2) adopted resolution 2/11 in 2016 in response to the growing threat of plastic waste. The resolution called for an evaluation of the efficacy of pertinent national, subregional, and international governance strategies to combat marine plastic debris and microplastics [48]. A third assembly session (UNEA-3) in 2017 recognized the need for improved waste management strategies to address the problem of marine litter. These strategies should be based on cooperative partnerships between governments, regional organizations, the private sector—particularly important business players—civil society, non-governmental organizations, and all pertinent international and regional conventions and organizations [49].

3. Nigeria's Waste Management Challenges and Circular Economy Solution

3.1. The Background to the Nigerian Waste Management Challenges

In Nigeria, there are no officially available data on waste generation, collection, composition, and disposal. The waste management policies in Nigeria before 1999 were mainly articulated with the sole aim of achieving the collection and disposal of waste with no due consideration to the other essential elements of waste management such as waste characterization, waste data collection, waste recycling, and even resource recovery [20,22]. Consequently, it was difficult to assess the effectiveness and progress of solid waste management in Nigeria during this time. With the return of democracy to the country in 1999, the country witnessed economic prosperity that resulted in rapid urbanization, an increase in socioeconomic activities, and the resultant rise in the quantity of solid waste generated in the cities across the country.

As of 2019, the estimated quantity of solid waste generated by 106 million people living in urban areas in Nigeria was 66,826 tonnes per day (TPD). This value was projected to hit 125,473 TPD by 2040 with an urban population of 199 million [22]. The country's waste collection rate has not been officially determined due to the unavailability of data [50]. World Bank studies of 2012, however, suggest that for African low-income countries such as Nigeria, the waste collection rate is between 41% and 46%, which is projected to rise to about 60% by 2025 [51]. The waste collection services are largely limited to the visible areas within the urban center. The non-visible areas such as shanties, slums, and ghettos are not usually included in the waste collection services. There are no waste management services in rural areas in most African nations including Nigeria [22,38]. Waste segregation/sorting at the source point of generation is not widely practiced in Nigeria, as there is no effective legislature or policy to that effect [52]. As a result, solid waste is usually collected from households, offices, and establishments as an unsorted mix. The only effort at solid waste separation/segregation in Nigeria often occurs at the dumpsites or landfills, and it is often undertaken by informal waste pickers [53].

Self-delivery to the community bin is the dominant method of waste collection. However, house-to-house collections are reported in some high-income areas in places across the country [54]. Like other underdeveloped countries, the dominant methods of waste

disposal are still open burning, open dumping, and indiscriminate disposal at water bodies with limited availability of landfill facilities [23]. Nigeria still has no formal waste recycling program, and previous efforts to establish a formal waste recycling scheme were unsuccessful [53,55]. The prevalent method of waste recycling is through the informal waste sector. It has been recommended that these scavengers' unofficial waste recycling activities be safely included in the circular economy programs in Nigeria and other developing countries, even though they pose a risk to the health of the workers and the local population living close to the operation sites [15,56]. Waste landfilling in Nigeria is still not properly developed, as many major urban cities do not have landfills and hence practice open dumping [21,23]. According to Idowu et al. [57], a study on landfill classification in sub-Saharan African nations showed that most landfills in Nigeria are not standard, making it impossible for them to provide social, economic, or environmental advantages.

Other novel methods of waste treatment that involve energy and material recovery such as incineration, anaerobic digestion, and thermal and chemical treatment methods have not yet been developed or adopted in Nigeria [22].

3.2. Circular Economy as a Solution to the Waste Management Crisis in Nigeria

The circular economy has been regarded as a veritable means of tackling waste management even in developing countries [15]. It proffers solutions by considering the entire waste management value chain which includes generation, segregation, collection, transportation, disposal, recycling, resource recovery, and treatment. It also considers the entire product lifecycle beginning from virgin resource extraction to end-of-life product management. With a focus on waste management, the circular economy mainly emphasizes high waste recycling rates, the minimization of waste generation, the redesign of products, product reuse, and sustainable waste treatment methods [58]. It articulates the understanding that effective waste management should foster economic prosperity, environmental sustainability, social inclusiveness, and business opportunities. Waste management that is anchored on a circular economy would therefore provide benefits such as increased economic savings achieved through resource minimization, good environmental quality achieved through a reduction in waste, energy, and emissions, and job creation by an increase in the number of stakeholders and value chain actors that could participate in the reverse logistics in the supply chain [16].

In Nigeria's context, studies have explored and documented several conditionalities that can either serve as enablers or barriers to circular economy implementation in solid waste valorization. Some of the enablers include (i) streams of solid waste generated in Nigeria that have proven reusable and marketability value, (ii) the availability of a well-organized value chain of the informal waste sector, (iii) the existence of regulatory institutions through which circular economy programs can be introduced, monitored, and regulated at the macro level [56], and (iv) certain types of business models already operational in Nigeria that can facilitate the introduction of a circular economy at the micro level [59]. The absence of state-of-the-art waste disposal/treatment infrastructure, non-standardized policies, and poor and inefficient waste collection methods are some of the factors identified as barriers to effective circular economy implementation in solid waste management in Nigeria [60]. The current work supplements the available literature, as it studies and provides more specific information on the challenges and opportunities of achieving a circular plastics economy in Nigeria.

4. Materials and Method

We searched different databases (Scopus, Google Scholar, Science Direct, and Web of Science) for relevant articles on the consumption, production, and end-of-life management of plastic and plastic products in Nigeria. We also search for the grey literature such as national and local government publications, publications of international bodies such as the World Bank, International Solid Waste Association (ISWA) and United Nations agencies (e.g., UN-Habitat, and UNEP) policy briefs, project documents of international aid

agencies, and websites of non-governmental bodies and practitioners (e.g., Ellen MacArthur Foundation). Further materials were retrieved from the reference lists of the selected documents. The keywords for the search included but were not limited to "plastic waste management", "plastic production", "plastic consumption", "plastic waste pollution", "plastic waste recycling", plastic waste minimization", "plastic waste policy", and "circular economy". All search terms included the phrase "in Nigeria".

Records retrieved from the search were exported to Microsoft Excel (Version 16.0) for further analysis. One of the authors participated in the screening/selection of material, while another author independently examined the screening process to resolve disagreements and ensure consistency. We first removed irrelevant materials and duplicate records. At the second stage of the record screening, materials were removed based on the following criteria: (i) materials that do not report an outcome of interest as concerns plastic waste management elements in Nigeria such as recycling, resource recovery, waste treatment, collection, policy framework, and segregation/sorting; (ii) only articles published in English were considered; and (iii) articles from journals not indexed in a credible database such as Web of Science, PubMed, and SCOPUS were expunged to avoid including predatory materials. The collated materials were reviewed, analyzed, and categorized to answer the following questions:

1. What is the status of the production of plastic and plastic products in Nigeria?
2. What is the status of the consumption of plastic and plastic products in Nigeria?
3. What is the status of the management of plastic waste in Nigeria?
4. What are the prospects and opportunities for achieving a circular plastics economy in Nigeria?

5. The Status of Plastic Production and Consumption in Nigeria

5.1. Plastic Production in Nigeria

Plastics are made of polymers or long chains of repeating molecules [61]. They come from non-renewable resources like natural gas and mineral oil, as well as, more recently, plant-based and renewable resources like polylactic acid. According to Kosior and Mitchell [62], virgin fossil fuel is the source of over 90% of plastics manufactured. In order to give the polymers particular desired features, such as a greater efficiency, cost reduction, and the desired color, they are frequently processed including other materials, such as additives [43].

Nigeria is the only country in West Africa that produces plastic resin in addition to being the continent's largest producer of crude oil. The country is said to have produced 486 kt of resin in 2018 and 498 kt in 2019 [63]. Nigeria's plastic industry processed about 1094 kt of resin in 2018 and 978 kt in 2019. According to market reports, plastic production in Nigeria has grown rapidly at a rate of 13.9% annually, from 411 kt in 2015 to a projected 513 kt in 2020 [64]. Because Nigeria is also the highest importer of resin in West Africa, it is equally the largest producer of olefins and polyolefin plastics in the region with Indorama Eleme Petrochemicals Limited being the lead company [65]. The nation's plastic sector began with 50 registered businesses in the 1960s and is currently home to over 3000 enterprises that produce a wide range of goods, including shopping bags, tables, jerry cans, mats, etc. [63,66]. However, there are thousands of undocumented small-scale businesses producing plastic packaging materials (popularly known as nylon) across the country. These small-scale plastic businesses are easy to establish and have also created thousands of job opportunities, especially in the informal sector. The local plastic business is also said to be lucrative with minimal risk [67].

Nigeria does not have the indigenous resins required to produce PET plastic variants; hence, the local manufacturing sector is completely dependent on imports. Amorphous PET resin is imported from different parts of Asia such as China. Through the scientific method of Solid-State Polycondensation (SSP), the imported resin is reprocessed to be suitable for food-grade applications. The limited availability of other essential resources such as advanced technology/machinery, poor finances that could hinder large-scale production,

and an irregular power supply limit the Nigerian plastic industry to the production of mainly packaging and household items [68]. The other advanced forms of plastic and plastic products such as toys, automobile parts, construction materials, and other sophisticated applications are mostly imported [9].

Figure 1 shows the quantity of plastic produced in Nigeria between 2007 and 2020.

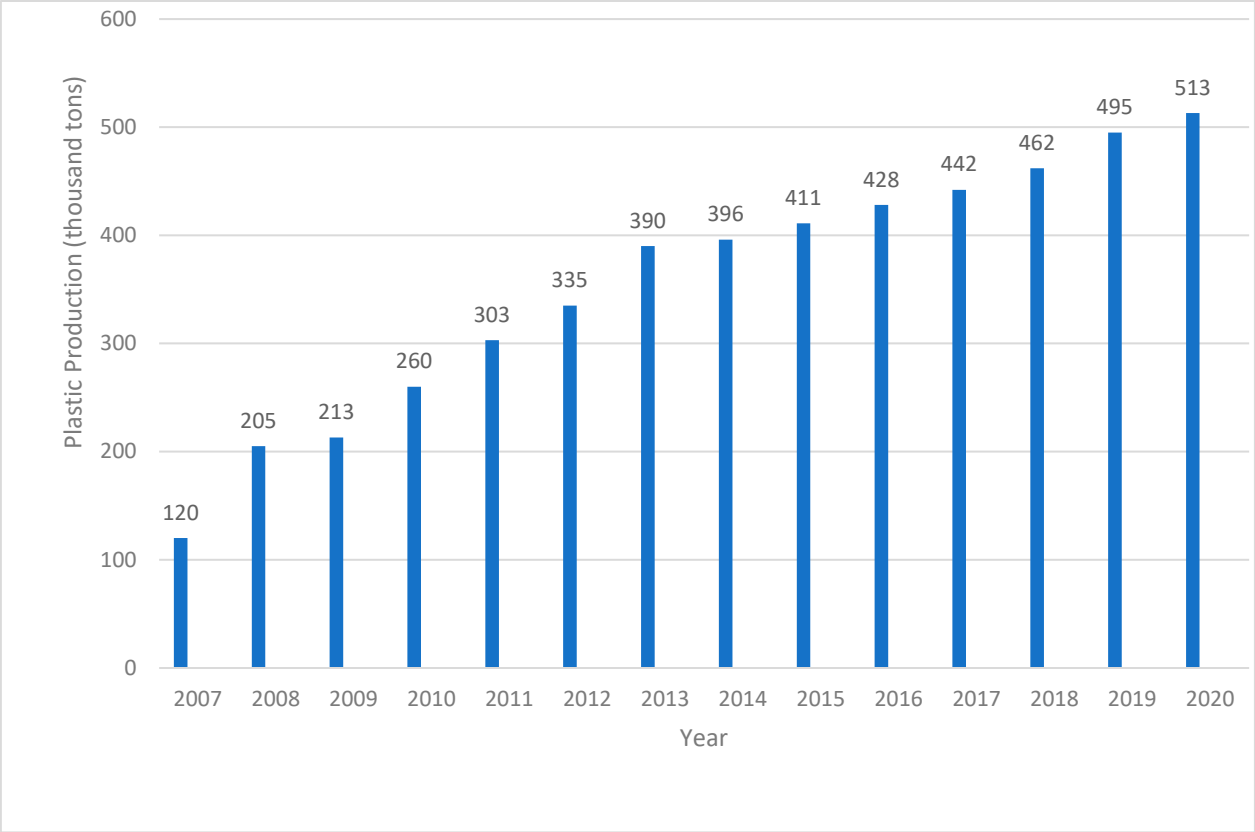

Figure 1. Plastic production in Nigeria from 2007 to 2020 (source: [64]).

5.2. Importation of Plastic and Plastic Products in Nigeria

Despite the huge availability of petroleum resources and large quantities of plastic and plastic products produced locally, Nigeria still depends on importation to meet its net plastic demand [68]. The import constitutes about 63% of the resins used in plastic production. There are no harmonized data on the importation of plastic and plastic products in Nigeria. A study conducted for the period 1996–2014 pointed out that approximately 14,200,000 tons of plastics in primary form was imported into Nigeria within this time. Approximately 3,420,000 tons of the total plastics was imported in the form of products, while approximately 5,545,700 tons was imported as product components. Another 194,000 tons of plastic toys was imported over six years [9].

Nevertheless, a different source stated that Nigeria imported 247,000 tons of plastic film in 2017 alone. With 137,000 tons imported, polyethylene (PE) was the most frequent type of plastic. As seen in Figure 2, the total import volume of polypropylene (PP) came to about 65,000 tons, placing it second in terms of quantity [69].

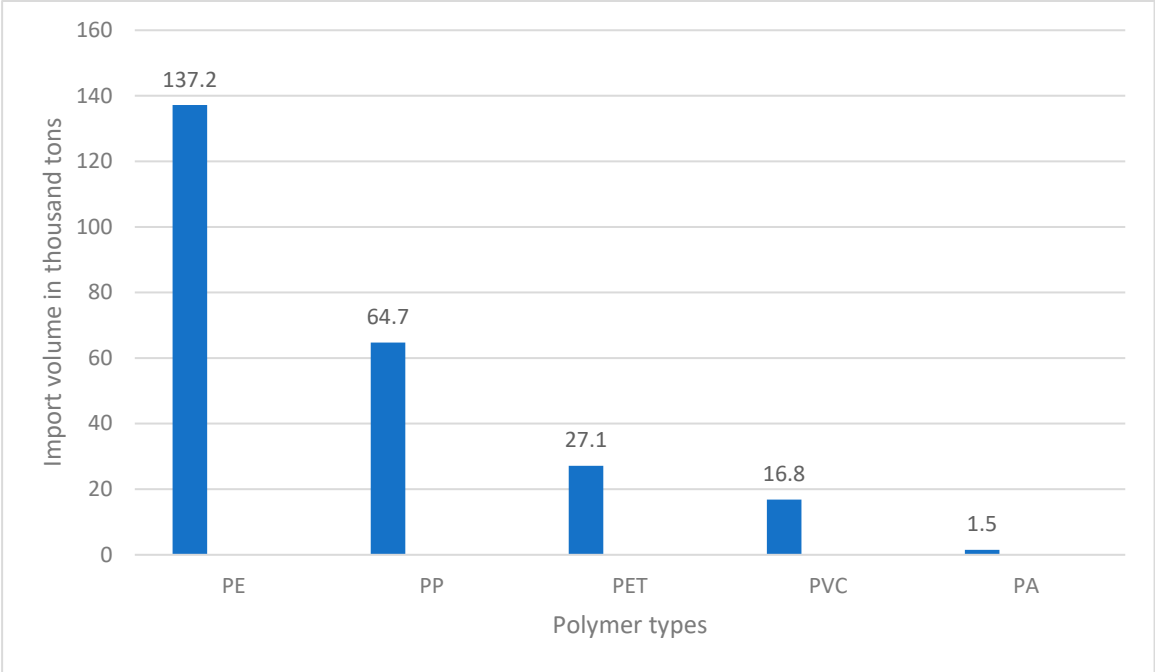

Figure 2. Plastic film imports in Nigeria in 2017, by type (source: [69]).

Nigeria imported USD 1.7 billion worth of plastic in total in 2019 [70]. This included net imports of all plastic resin. Nigeria is currently the top resin importer on the continent because imports account for around two-thirds of the country's virgin resin demand [63]. However, according to the Nigeria government's policy document titled "National Strategy for Competitiveness in Raw Materials and Products Development in Nigeria" published in 2017 by the Raw Materials Research and Development Council (RMRDC), the government has set import reduction targets for items including plastics and articles thereof for periods with 5-, 10-, and 15-year intervals, with the hope of achieving improvements in the availability of these materials locally [71] (see Table 1).

Table 1. Potential for percentage import reduction in plastic raw materials and products in the short, medium, and long term (source: [71]).

HS CODE	Broad Category of Raw Materials and Products	% Reduction in Imports					
		Short Term (0 < 5 Years)	Avg	Medium Term (5 < 10 Years)	Avg	Long Term and over 10 Years	Avg
39	Plastics and articles thereof	10		30		50	
40	Rubber and articles thereof	5		35		60	
(39–40)	Plastics and articles thereof	15	7.5	65	32.5	110	55

5.3. Plastic Consumption in Nigeria

The demand for plastic consumables in Nigeria, such as gift items, plastic cups, toys, furniture, etc., is so high that the local manufacturers in the country cannot satisfy the market demand. Apart from local buyers, entire Economic Community of West African State (ECOWAS) subregions rely wholly on Nigeria for their plastic products [72]. Nigeria consumes the most plastic in plastic packaging. According to data published in 2020, 54% of plastic in Nigeria was used as packaging material, and 16% was used by the construction industry, which is the second largest sector consuming plastic in Nigeria [73] (see Figure 3). Nigeria is said to have an annual growth rate of roughly 3.6% in its per capita plastic consumption.

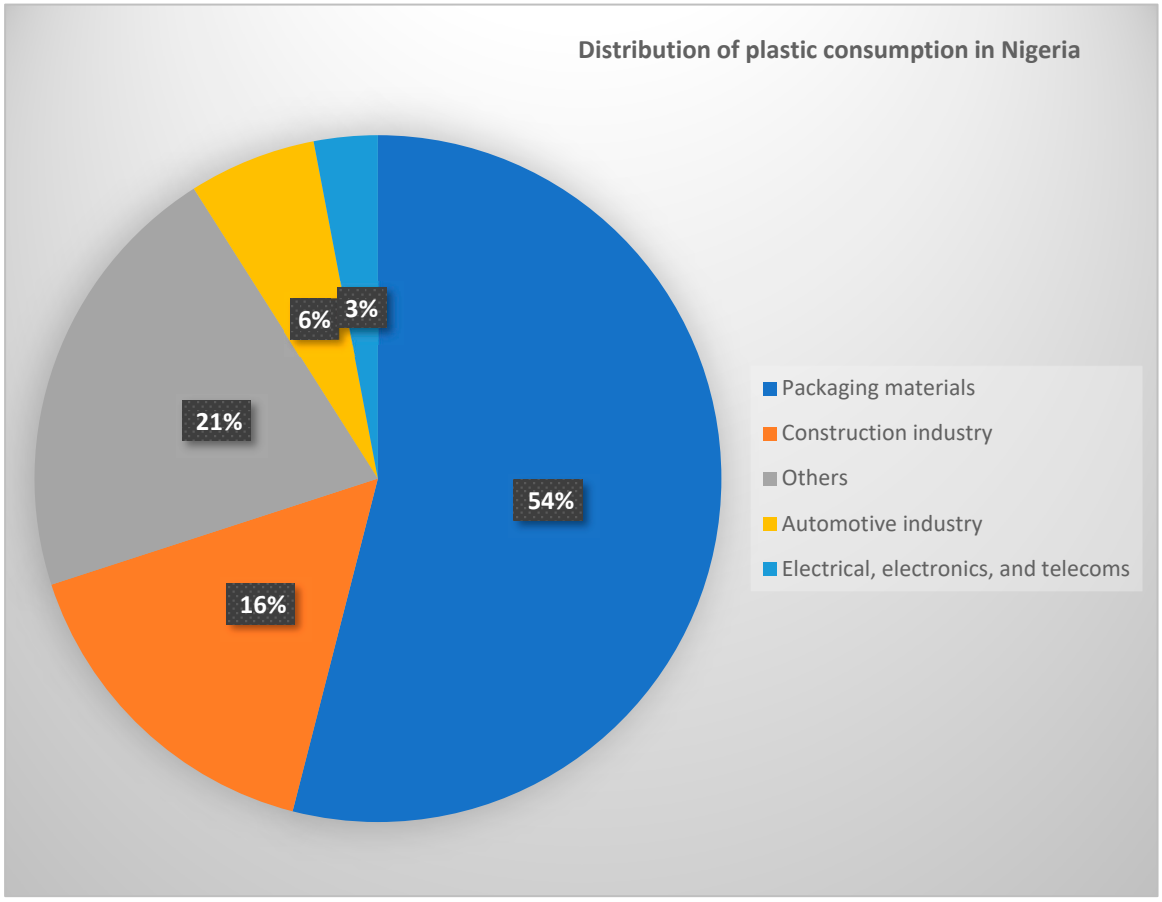

Figure 3. Distribution of plastic consumption in Nigeria in 2017 (source: [73]).

For example, it increased from 4 kg in 2007 to 5.9 kg in 2018, with a projection of reaching 6.8 kg in 2022 [68]. In Nigeria, short-lived products account for a disproportionate amount of plastic consumption [26]. If this trend is further examined, it is likely to result in a low average service life for all plastic products and, as a result, a high proportion and generation rate of plastic waste in municipal solid waste.

Most of the plastic consumed in Nigeria can be classified into the five major polymer types which include polyethylene terephthalate (PET), high-density polyethene (HDPE), polypropylene (PP), polystyrene (PS), and polyvinylchloride (PVC) (see Table 2). There is a high demand for PET bottles in Nigeria, and this demand comes from several multinationals and small- and medium-scale enterprises that are involved in the production of fast-moving consumer products including bottle-packaged water. The plastic-producing companies usually process the PET resin into preforms which are supplied to the consuming companies that subsequently use them to manufacture PET bottles. It is predicted that 225,000 tons of PET is consumed per year in Nigeria [68].

Table 2. The key plastic polymer components available in Nigeria and their major industrial applications (source: [26,68]).

Name of Polymer	Industry	Product
Polyethylene terephthalate (PET)	Food and beverages and textiles	PET preforms, packaging containers, and PSF
High-density polyethene (HDPE)	FMCG	FMCG product packaging such as shampoo bottles
Polypropylene (PP)	Food and beverages, household goods, and construction	Household items, cement bags, packaging containers, and films

Table 2. *Cont.*

Name of Polymer	Industry	Product
Polystyrene (PS)	Automobile and electronics	Knobs, instrument panels, trim, energy absorbing door panels, and sound dampening foams
Polyvinylchloride (PVC)	Construction and footwear	PVC pipes, PVC doors, and window frames

6. The Status of Plastic Waste Management in Nigeria

6.1. Sources of Plastic Waste

(i) Household solid waste (HSW)

Households are the major sources of municipal solid waste in Nigeria, and the pattern of waste generated from households could change according to consumption patterns [74]. Consumption patterns, however, are affected by socioeconomic, environmental, and demographic factors linked to the households (e.g., income, culture, family size, etc.). There are no formally documented data on the quantity of plastic waste constituents present in the typical HSW in Nigeria. Waste composition analysis of HSW conducted in Abuja, Nigeria's capital city, shows that the quantity of plastic waste generated is 7.3%, 9.2%, and 10.1% for low-, medium-, and high-income households, respectively [52]. Plastic is the third largest component after organic and paper.

(ii) Packaging industry

The vast majority of plastic waste constituents present in typical municipal solid waste samples in Nigeria are packaging materials [26,27]. The most prominent plastic polymer types generated as packaging waste are polyethylene (PE) and PET. They are commonly used in the packaging of fast-moving consumer products (e.g., sachets and bottled water) and also as single-use shopping bags [27]. During a normal dry season, around 70% of Nigerians are reported to drink at least one bag of sachet water per day [75]. This corresponds to about 50–60 million nylon sachet plastics that are used and discarded every day [56]. Disposable plates, mugs, cutlery, and other consumer goods are packaged in single-use plastic bags.

(iii) Agricultural industry waste

In the agricultural sector, a number of plastic polymer types are utilized, including HDPE, PVC, PE, and PP [18]. Plastic materials have found applications in the agricultural sector in Nigeria. For instance, they serve as packaging for manure and other organic materials used in agriculture, cover for mulching, irrigation pipes, agricultural films, and storage material for agricultural chemicals such as pesticides [76]. The end-of-life products are generated as plastic waste in cities and rural areas across Nigeria.

(iv) Commercial sources/public establishments

Several categories of plastic waste are generated from daily activities that take place in commercial centers and public establishments across the country. This plastic waste is used in packaging, especially single-use disposable variants, at various commercial centers. The commercial centers/public institutions include offices, shopping malls, community centers, urban markets, schools, establishments, etc. For instance, a solid waste quantification analysis conducted at the University of Nigeria showed that about 8.53% of the total waste stream generated is plastic [77]. Similar waste characterization conducted at the University of Lagos showed that polyethylene bags are the largest constituent at 24% [78].

(v) Construction industry

Because of the wider application of plastic materials in the construction industry in Nigeria, construction waste is made up of plastic components. Aside from packaging materials, the construction industry is the second largest consumer of plastic in Nigeria [68].

PVC and PP polymer types, for instance, are used in plumbing materials, electrical wiring and fittings, pipes, ceilings, roofs, window frames, door frames, tanks, fittings, etc. The majority of these items come into the country through importation [9]. This results in a large volume of plastic waste arising from the usage of the imported finished consumer products.

(vi) Medical/biomedical sources

Nigeria has diverse medical facilities that generate enormous amounts of waste, with high quantities of plastic constituents. These medical facilities include clinics, laboratories, research centers, etc. The types of plastic waste generated include hand gloves, syringes, catheters, medicine containers, IV tubes, etc. [79]. Waste characterization conducted in select hospitals in Umuahia, a location in southeast Nigeria, indicated a high quantity of plastics [80].

(vii) Other industrial sectors

Plastic and plastic materials have found wide applications in other industrial sectors in Nigeria yielding high volumes of plastic waste [9]. For instance, the electrical and electronic industries (e.g., waste of electronic and electrical equipment, solar PVC panels, Christmas lights, etc.), the transport industry (e.g., automobile parts), and the tourism industry (e.g., hotels, beaches, etc.).

6.2. Characterization, Composition, and Generation Rate

There are no comprehensively documented data on waste characterization in Nigeria. However, there are some available studies that were conducted in locations across the country [22]. None of the studies on solid waste characterization in the Nigerian locations have failed to highlight significant plastic components (see Figure 4).

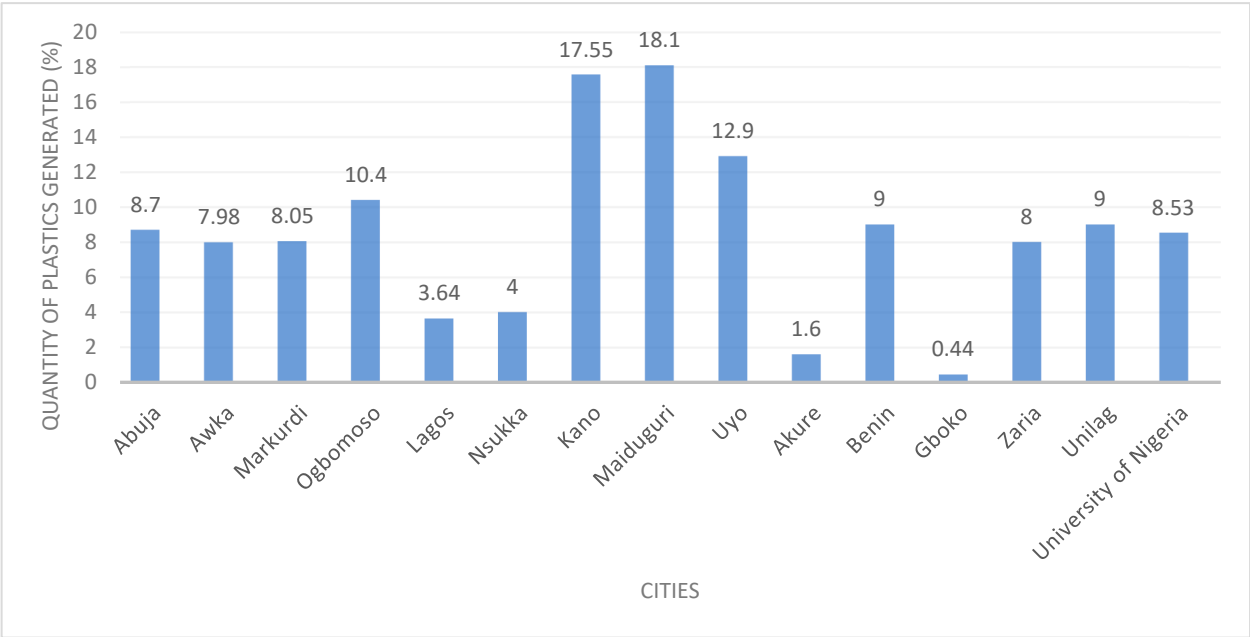

Figure 4. Waste characterization conducted in locations in Nigeria highlighting plastic components (source: [22]).

There is no law on solid waste segregation/separation in Nigeria, and there are no specific detailed documented data on the characterization of plastic waste constituents [22]. However, there are also a few studies on specific plastic waste composition analysis. For instance, the characterization of plastic waste was conducted in a dumpsite in Calabar, Nigeria, on 21 plastic samples which were categorized into representative plastics. The

plastic categories were PET bottles, LDPE, PP, HDPE, PS trays, PVC fibers, and PVC others. PET bottles were the highest component at 28.5%, followed by PP, LDPE, and HDPE. PS trays, PVC fibers, and PVC others were the least prevalent plastics at the dump site [81]. In a plastic waste characterization analysis conducted in Ilorin, Nigeria, it was reported that the dominant plastic waste stream was polyethylene at 57.07% followed by PET at 12.83%. Polystyrene, polypropylene, and others were produced at 12.12%, 11.08%, and 6.76%, respectively. PET and polyethylene are highly prevalent in the plastic waste stream in Nigeria, indicating how widely used and consumed they are in a variety of consumer and commercial goods [82]. Plastic makes up the largest amount of microdebris found in a Nigerian river, accounting for 59% of the total. Other waste components found in the sampled river included metal, cloth, paper/cardboard, rubber, ceramics/glass, wood, medical, and agro-based waste.

Among the plastics, PET made up the largest percentage (29%), followed by PE (22%), PVC (16%), PP (14%), and miscellaneous plastics (6%) [34]. It is estimated that Nigerian households and businesses produce about 230,000 tons of end-of-life PET waste annually. PET bottles, films, and containers are the main PET waste products generated. About 260,000 tons and 430,000 tons of end-of-life waste of PP and PE, respectively, are estimated to be generated in Nigeria annually [68].

6.3. Collection and Transfer

There are two main ways to collect plastic waste: curbside collection or "bring-scheme" collection. In the absence of either highly committed public behavior or deposit refund schemes that create a direct economic incentive to participate, "bring-scheme" collection typically produces low collection rates [4]. In suburbs where population density is high enough to realize economies of scale, the house-to-house collection of end-of-life plastics is more cost-effective. However, the best collecting plan may differ depending on the area, the kind of housing, and the available sorting facilities. The use of transfer stations in solid waste management planning and execution in Nigeria is not reported in the literature [20,21]. In general, there is a poor collection rate for solid waste (including plastics) in cities across Nigeria, to the extent that uncollected plastic waste is reported to cause the blockage of water channels, resulting in flooding [23,26].

6.4. Sorting/Segregation

Co-mingled solid recyclables are sorted using both human and machine techniques. Sorted waste plastic is usually cleaned to get rid of adhesives, pulp fibers, and food residues before being broken into flakes for efficient recycling. In Nigeria, plastic waste is not segregated or sorted at the point of generation such as households, offices, and establishments. However, because of their reusability and marketability within the local markets, plastic waste variants especially PET bottles are manually sorted and collected at waste bins, dumpsites, and landfills by informal waste recyclers [53]. The informal waste management activities are mainly motivated by economic hardship. The use of machines in waste sorting has reportedly not been used in waste management in Nigeria.

6.5. Disposal

The indiscriminate disposal of plastic waste has been reported in places across Nigeria [27,83]. A large amount of plastic generated in Nigeria ends up in landfills and/or open dumpsites located across the country [26]. Landfilling is a recognized method of solid waste disposal. Even though it is not ranked as high as recycling, resource recovery, and reuse, it is still regarded as a crucial technique for disposing of waste because other waste treatment methods, such as incineration, still leave residue that must be disposed of in landfills [57]. From a sustainability perspective, the main disadvantage of disposing of plastic waste in landfills is that no material resources utilized in its creation are retrieved. The material flow is linear instead of cyclic. The outright burning of solid waste is still common in many developing countries including Nigeria [38]. A large quantity of plastic

waste generated in Nigeria is still disposed of by outright burning [26,82]. It is also reported that the indiscriminate dumping of municipal solid waste in drainage channels, at railway tracks, in bushes, and in water bodies is still common in Nigeria [23].

6.6. Reuse and Recycling

Reuse in the context of waste management involves the use of end-of-life products repeatedly in a product cycle before they finally enter the waste stream. This practice is rampant in Nigeria, facilitated by the informal waste sector. Several end-of-life plastic products are collected from waste bins, dumpsites, and landfills by waste pickers. They sort and sell these products to the cottage industry which reuses them in the secondary packaging of several consumer products [56]. For example, in informal markets, PET bottles are reused in the secondary packaging of products such as palm oil, groundnuts, cashew nuts, etc.; end-of-life paint containers are reused as buckets in households.

Once a solid recyclable material finally enters the waste stream after the reuse stage, it can either be retrieved through recycling or resource recovery processes. When it comes to plastic and plastic products, recycling is the process of reprocessing recovered plastic to make a new product, but resource recovery also includes energy recovery, which involves using the plastic's calorific value as fuel, gas, or energy through controlled heating [4]. Both procedures, however, do not lessen the need for virgin materials, which lowers the overall effectiveness of the circular economy [58]. Plastic recycling can be conducted in three main ways: (i) primary recycling, which involves mechanically reprocessing plastic waste into products with similar characteristics; (ii) secondary recycling, which involves processing plastic waste into products with different characteristics; and (iii) tertiary recycling, which involves recovering chemical constituents and producing basic chemicals and fuel from segregated municipal solid waste [4,26]. Composting biodegradable plastics is an additional example of tertiary recycling [84]. Another name for it is biological or organic recycling. Although the chemical technology for recycling plastic has been created, the high costs of plants and processes in comparison to inexpensive petrochemical feedstocks have limited the applicability of this technology [4,85].

The mechanical recycling (primary and secondary types) of plastic is common in Nigeria, while chemical recycling (tertiary) is not commonly practiced [68]. Annually, about 10,000 tons of PE and PP plastic waste is recycled mechanically in Nigeria. The low recycling rate for PP and PE can be attributed to several factors which include the difficulty in recycling and challenges in distinguishing between PE and PP polymers from other types of plastic [68].

6.7. Energy Recovery

Incineration

While incinerating plastic waste eliminates the need for landfills, there are worries that hazardous substances could be discharged into the atmosphere in the process [86]. This is because additives consisting of some potentially harmful compounds are frequently found in plastics. In mixed plastic debris, for example, polyvinyl chloride (PVC) and halogenated additives are frequently included. These materials are not fit for incineration because doing so could release halogenated contaminants into the atmosphere. For this reason, as a waste management method, the incineration of plastic waste is less recommended than landfill and mechanical recycling. The fact that incineration is especially vulnerable to waste stream contamination is another drawback [84]. This is true, especially in Nigeria, where solid waste is collected as co-mingled waste streams. Notwithstanding, incineration could reduce the need for landfills, as it significantly reduces the volume of waste that would have gone to the landfill and provides a chance for energy recovery. The incineration slag can be further processed and recycled as a construction material.

Further, the pollution aspect of incineration can be fixed at more cost by employing advanced filters. Incineration is, therefore, a more likely option for reducing emissions than landfills, but the technique is still not cheap due to associated high capital and maintenance

costs. For these reasons, except for a few isolated cases in which it is applied to the treatment of medical waste, incineration has not been widely embraced as a solid waste management technology in Nigeria [22].

Other waste-to-energy treatment methods

Among the components of typical municipal solid waste, plastic has the highest content of low heating value (LHV) [87]. The conversion of solid plastic waste to energy through waste-to-energy (WTE) technologies/processes (pyrolysis, thermo-chemical processes, etc.) has been suggested as one veritable method of plastic waste treatment in Nigeria [25]. However, waste-to-energy conversion technologies have not been extensively adopted as waste treatment methods in Nigeria and other African countries due to the associated high capital and maintenance costs [50].

7. Appraisal of Plastic Waste Policy Landscape and Institutional Framework in Nigeria

Nigeria is a signatory to the Stockholm and Basel conventions, as well as the United Nation's Sustainable Development Goals (SDGs). The country has voiced concerns about the effects of microplastics, plastic waste, and marine litter and has emphasized the need to reduce consumption and ensure environmentally sound management practices [88]. Nigeria drafted the first national policy on the environment in 1991 which has been repeatedly revised to date. There are also national policies on solid waste management that provide guidelines on how solid waste should be managed in the country. Following the increased danger posed by plastic waste in the environment, a special guideline on plastic waste management was issued by the Federal Ministry of Environment in 2020. The policy was drafted with the input of several stakeholders such as producers, state government representatives, the organized private sectors, civil society organizations, academicians, waste management practitioners, and international organizations. The policy instrument elaborated on pertinent issues concerning plastic waste management in Nigeria such as an institutional framework, stakeholders' roles and responsibilities, funding and resource mobilization, a legislative framework, guiding principles, and strategies for policy implementation. Although the circular economy was mentioned in the policy document as one of the guiding principles, it did not informatively highlight the modalities and feasible roadmap to achieving the circular plastics economy at three levels, which include the micro-, meso-, and macro levels. The specific Nigerian context under which this circular economy could be implemented was not discussed. For instance, several strategies to achieve effective plastic waste management such as a ban on certain categories of plastic and the implementation of extended producer responsibilities were itemized, but details on how these instruments should be adopted and implemented were not documented in the policy paper. Also, the policy guideline mentioned the importance of informal waste recycling to plastic waste management, but there were no reliable details on how they can be either integrated into the formal system or given a platform to operate. Other critical factors that could hinder the implementation of a circular economy (e.g., citizen engagement, social inclusion, financial sustainability, knowledge creation, etc.) were mentioned without clear information on how they can be tackled. It is also observed that the policy may not have been drafted following a scientific baseline study that could have provided reliable data and information on waste management for credible policy engagement.

Also, highlighting inconsistencies, the legislative foundations for solid waste management in Nigeria are equally weak [22]. For example, a landmark bill intended to outlaw plastic bags in Nigeria has drawn criticism for being inadequate since it is not appropriately drafted to produce the desired outcomes [32]. It suggests complete prohibitions and harsh penalties for the manufacture, distribution, and use of plastic bags for residential and commercial packaging, much like a number of other plastic regulations that have been put into place throughout Africa. However, the bill lacks alternatives and market-based instruments that could influence consumer behavior, such as tradable permit schemes, subsidies, and incentives, liability and compensation schemes, taxes, charges, fees, fines, penalties, and schemes for plastic bag usage [89]. This is because imposing a levy on specific types of

plastic may yield revenue for government-funded environmental initiatives [90]. Additional flaws in the proposed legislation include limited public consultations, jurisprudence, practicability, and inadequate notice to the public [32].

As of 2021, which was two years after the passage of the bill in Nigeria's House of Representatives (lower house), it is yet to be either ratified by the Senate (Upper House) or assented to by the executive [91]. This points to the government's low commitment to environmental policy implementation. However, the Lagos state government in 2024 became the first state in Nigeria to ban Styrofoam, a plastic polymer variant used for food packaging [92].

8. Future Projections of Plastic Waste Generation and Collection Rates in Nigeria

The current quantities of plastic waste generated and collected as a component of municipal solid waste in Nigeria will be calculated for 2024 and projected further into 2040. Although numerous elements affect how much solid waste is generated in cities, the population of the city, the population growth index, and the amount of waste generated per capita are the generally acknowledged factors that are sensitive to projections [93]. Adopting the 2006 population census figure, P_{2006}, of 140,431,790 and annual population growth, rate r, of 2.5% [94], the projected total Nigerian population for the future year 20XY is given by the following:

$$P_{20xy} = P_{2006}\,(1 + r/100)^{20XY-2006} \quad (1)$$

If we assume Nigeria's current urban population of 54.28% for 2023 to remain constant [95], the urban population for the future year will be

$$P_{20XY(URBAN)} = 0.5428 \times P_{20XY} \quad (2)$$

The growth in the total and urban population from 2024 to 2050 is shown in Figure 5.

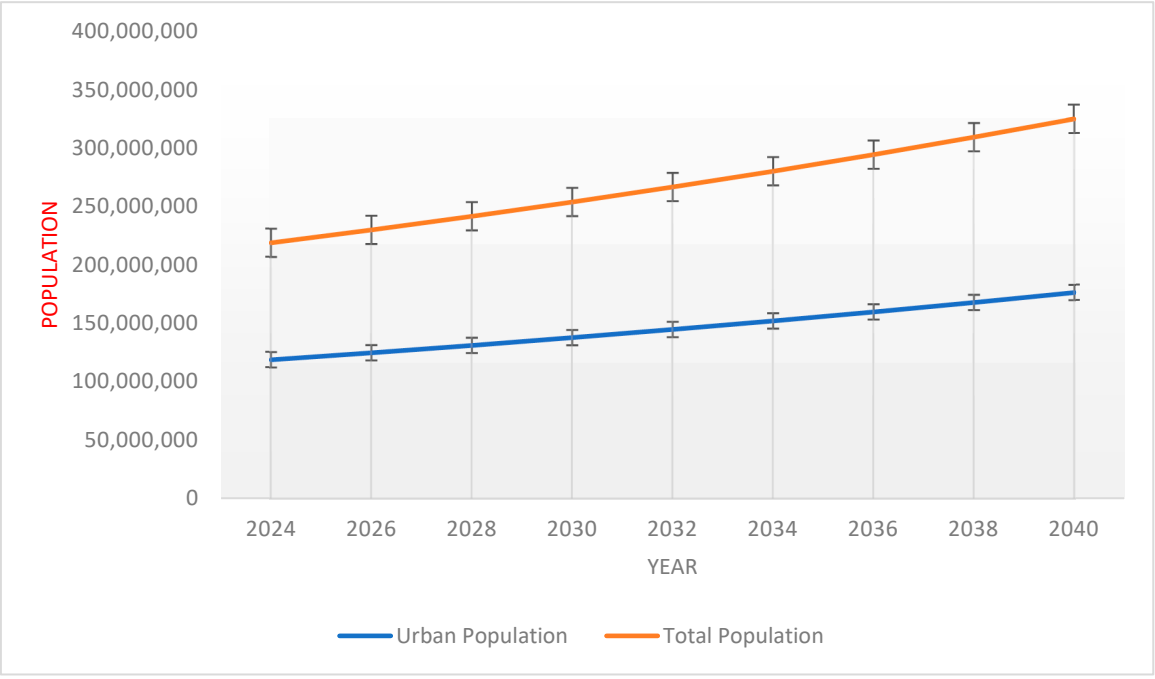

Figure 5. The current and projected urban population vs. total population.

Assuming $Q_{Capita20XY}$ = per capita waste generation of 0.63 kg/capita/day [52], the total quantity of urban waste generated in Nigeria's urban areas for future years will be

$$Q_{20XY} = 0.63 \times P_{20XY} \text{ (urban)} \quad (3)$$

Assuming a waste collection rate of 41%, which is an average value for low-income countries [52], the total municipal solid waste collected for the current and future years is calculated as

$$Q_{20XY(Collected)} = 0.41 \times Q_{20XY} \quad (4)$$

This equals 30,708.5 tonnes per day (TPD) for the current year 2024 and 45,587 TPD for the year 2040. Since 10% of the collected waste is plastic [26], the total municipal solid waste and plastic waste stream collected for 2024 to 2030 is shown in Figure 6.

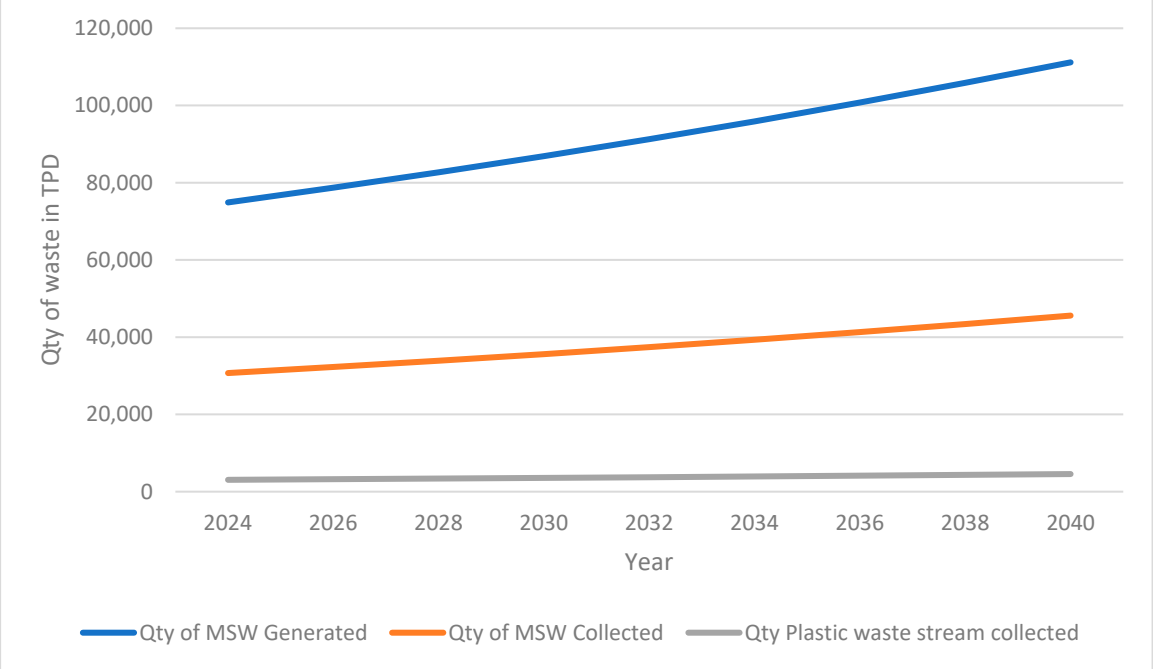

Figure 6. The quantities of MSW and plastic waste stream generated for the current and future years.

Extending waste collection services to rural areas will increase the expected quantities of plastic waste to be collected for recycling, disposal, and/or resource recovery. An increase in the population growth index and rapid urbanization resulting from the surge in rural–urban migration and other socioeconomic derivatives such as the increase in family income are factors that could affect the future quantities of plastic waste generated in Nigerian cities. Improvements in the waste management policy implementation, the establishment of stronger institutions, the availability of economic resources, and the adoption of modern technologies are factors that could influence the quantities of plastic waste collected in the future.

9. Prospects for Achieving Circular Plastics Economy in Nigeria

About 95% of all plastic packaging material, which translates to USD 80 to 120 billion, is lost yearly to the current linear plastic economy after a first short-use cycle. Existing waste collection systems are currently unable to collect about 32% of all plastic packaging waste, resulting in these wastes escaping to the natural environment, littering the oceans and clogging the urban facilities [42]. Thus, it should come as no surprise that the linear economy has played a major role in the global plastic waste crisis, both environmentally and economically, with damage to marine ecosystems alone estimated to be worth USD 13

billion yearly [42,96]. It has been suggested that the plastic industry must change, moving its focus from single-use and disposable products to a model focused on recapturing value and reducing waste, which is known as the circular economy, to mitigate growing environmental concerns while simultaneously maintaining an increase in demand [18]. To effectively address all stages of the value chain and minimize the effects of the extensive extraction of non-renewable resources, losses due to waste, and emissions that are linked to plastics throughout their lifecycle, a circular economy framework for plastic products must be designed [97]. The European Commission [35] proposed that seven components are required to achieve a transformation into a circular economy which include skills and knowledge, organizational innovation, social innovation, technological innovation, financial instruments, awareness/dissemination/internationalization, and multistakeholder involvement. These components are not the same for all communities and societies, which simply implies that a circular economy is applied according to context based on societal peculiarities [16].

Aligning with the goals of sustainable development, the plastics industry is crucial to the Nigerian economy, and enhancing its sustainability can open up new commercial and economic prospects for innovation [88]. The general economic value of most Nigerian industries including the plastic industry is always evaluated without considering the additional value that could be derived from the recycling sub-sectors [22]. In a broad sense, achieving a circular plastics economy will entail reducing plastic waste and pollution through product design, retaining a product in the supply chain for longer, and regenerating and preserving natural resources. How these can be achieved in Nigeria's context is discussed in what follows.

Alternative materials/biodegradable plastics: One acknowledged way to achieve a circular plastics economy is to decouple plastics from fossil fuels in exchange for renewable feedstock [42]. Since most oil-based polymers are not biodegradable, recycling them is challenging. Variants of biodegradable plastic have the potential to address a number of waste management problems, particularly with regard to disposable packaging that is difficult to separate from organic waste in agricultural or culinary applications. In this case, compostable and degradable materials should be properly labeled and handled in a way that enhances waste management procedures rather than undermines them [84].

The use of alternative materials for achieving a plastic circular economy can be viewed from three perspectives which include (i) adopting alternative input material for plastic production, (ii) substituting plastic with other eco-friendly materials in certain applications, and (iii) reducing the consumption of fossil-based plastics. Although using alternative feedstock material for plastic production is already possible in developed countries [34], the production logistics are still expensive when compared to fossil feedstock. According to recent life cycle studies, biopolymers, particularly poly lactic acid (PLA), can reduce greenhouse gas (GHG) emissions by up to 40% and the amount of non-renewable energy used by 25% when compared to standard petrochemical-based plastics [85].

In Nigeria's context, to achieve a circular economy in plastic waste management, the only two viable options, therefore, include moving towards substituting plastic as much as possible and reducing its use. First, natural leaf-type packaging which is still useful in Nigeria's countryside has been suggested as a good replacement for plastic packaging especially in specialized food types in urban areas [98]. Natural leaf packaging can be made abundant in the cities through sustainable urban tree planting and maintenance. It offers better circular economy prospects than plastic packaging, as the end-of-life waste can easily be converted to compost. However, natural leaf-type packaging being biodegradable would require segregation and composting facilities across the country for appropriate disposal.

Second, the reduction in plastic consumption can be achieved by posing and enforcing effective policies, implementing market-based instruments, and appropriate legislation. The implementation of these instruments is discussed in what follows.

Extended Producer Responsibility (EPR): The low cost and ease of production associated with plastics and its allied products, especially packaging material, has triggered

an increase in their production and consumption and hence high waste generation. One way to regulate indiscriminate production is through economic and market-based instruments. Extended Producer Responsibility (EPR) has been an effective circular economy tool deployed across the globe for waste management regulations. It makes the producer responsible for the management of their end-of-life products throughout the product lifecycle [99]. It also incentivizes the producers to redesign their products to ease recyclability. Because many consumer products (including plastics and packaging) available in Nigeria's market originate from small- and medium-scale enterprises that often lack the financial capacity to implement EPR, Collective Producer Responsibility (CPR) has been suggested as appropriate for Nigeria [59]. In CPR, producers pay eco-modulation fees according to their capacity and the nature of the products they place in the market, whilst extra funds can be mobilized from grants and other tax variants. The deposit refund system (DRS) is a variant of EPR where fees are imposed on product consumption which would be refunded to the consumers when the end-of-life products or packaging are returned for recycling or effective disposal. The DRS has a huge potential to be an essential tool for promoting the recycling of plastic waste in Nigeria. The implementation of a minimum monetary value for all classes of plastic waste can stimulate informal recycling and waste segregation at the source, create jobs in urban cities, and provide job security for waste pickers. More details on the drivers and barriers to the implementation of Extended Producer Responsibility for the circular economy in Nigeria can be found in [59].

Other policy and economic instruments: The feasibility of recycling thermoplastics is influenced by two important economic factors. These include the costs of recycling in comparison to other acceptable modes of disposal and the price of recycled polymers compared to virgin polymers. This economic dynamic implies that, besides the outright ban on certain categories of plastic [32], the policy framework in Nigeria needs to introduce other market-based instruments to drive behavioral changes, incentivize recycling/reuse, and subsidize the use of secondary material for plastic production in Nigeria. For instance, considerable evidence has shown that a high rate of recycling is associated with an increase in tipping fees [100]. Policies and laws must be placed inside a specific framework of environmental plans with efficacy indicators in order for them to accomplish the goals for which they are intended. This is especially true for economic instruments.

State-of-the-art waste treatment facilities: The absence of state-of-the-art waste treatment facilities has hindered effective waste management in line with the circular economy in places across Africa and in Nigeria [22,50]. It has been established that the key methods of resource recovery from plastic waste are thermo-chemical processes (combustion, pyrolysis, or gasification). These novel waste treatment facilities are expensive to build and maintain, which has limited the technology's potential for widespread use as an energy recovery option in developing countries, more particularly in Africa [50]. However, Ferronato et al. [15] have proposed mechanical biological treatment (MBT) as a low-cost substitute for conventional methods for treating waste and recovering energy from it in developing nations. According to [101], MBT minimizes the volume and mass of solid waste that would have been deposited in the landfill, deactivates the biological and chemical processes within the waste to prevent the formation of contaminants, provides an opportunity for waste segregation, and thereby improves the calorific value of the stabilized waste. The stabilized high-calorific-value waste can be used for the production of refuse-derived fuel (RDF). RDF could be a very important energy source for industrial processes (e.g., cement plants). With good filters, RDF is a cleaner energy option than coal and preferable in industrial applications. MBT also promises other circular economy benefits, like less emissions from landfills and minimizing leachate formation and unpleasant odors. Furthermore, the landfills will have a longer lifespan. To promote employment creation, mechanical treatment might be implemented for the sorting of recyclable materials, or it could be applied manually [15]. In the sorting section, coarse recycling fractions (e.g., plastics, bottles) can be separated. Because emissions from landfills after the treatment of waste are reduced by about 90%, MBT is, therefore, more appropriate for developing countries such as Nigeria where land-

fills are not standardized [101]. Also, as a measure against the high-cost waste-to-energy technologies, frugal technology has been suggested as a method of producing low-cost waste treatment facilities in developing countries [102]. The high cost of waste-to-energy technologies is mainly because these technologies are often imported. With collaboration among stakeholders such as research institutes, waste management authorities, and energy commissions, cost-effective waste-to-energy (frugal) technologies using locally available materials can be built in Nigeria for plastic waste management. In addition to these, the construction of controlled landfills across the country is still recommended.

Informal waste recycling: The criticality of the informal waste sector to circular economy implementation in developing countries cannot be overemphasized. Its formalization is an essential requirement often suggested for solid waste valorization [15,22]. In the absence of formal recycling schemes in Nigeria, informal waste recycling schemes, through their well-organized value chain, have facilitated the collection, segregation/sorting, reuse, and recycling of recyclables including plastics. They operate at street bins, dumpsites, and landfill locations, salvaging values from waste. They also move from house to house buying clean recyclables from households. Economic hardship and the need for survival have been the motivating factors. Plastic recyclables such as PET are among the most sought-after recyclables collected by waste pickers. They work with rudimentary tools and often under precarious conditions. Their safe inclusion in waste management in Nigeria is a factor that would enhance the circular economy in solid waste management in Nigeria. To achieve this safe inclusion, their working conditions, operational guidelines, occupational health, safety, and retirement benefits need to be regulated.

Plastic waste upcycling: Upcycling may significantly reduce the environmental impact of plastic production and consumption, and it is an effective technique to turn waste plastic into high-value products [103]. When plastic waste can be upcycled, it means that it can be used again without losing its value or functionality. Finding upcycling methods for plastic waste will help cut down on the amount of waste dumped in landfills and waterways. In addition to the other benefits of the circular economy, it minimizes the reliance on non-renewable petroleum resources and lowers greenhouse gas emissions [104]. By using chemical, thermal, and biological processes, plastic waste can be upcycled into carbon nanomaterials (CNMs) [28]. Because plastics have a high carbon content, there are opportunities to use them as an inexpensive feedstock for upcycling to create value-added goods like CNMs. Owing to their special qualities, CNMs are widely used in the manufacturing of batteries, supercapacitors, paints, printer toners, and lubricants, among other goods. In Nigeria, there is a high demand for each of these commercial and industrial products. Plastic waste can also be upcycled into polymer composite materials (PCMs). Since PCMs are specialized and of superior quality, their usage in the production of common products is costly. This is because they were created for high-end applications. These financial constraints offer chances to solve the social and environmental issues that plastic waste is currently posing. Nonetheless, numerous streams of waste plastic are inexpensive, adaptable, and readily available, making them ideal for upcycling into composite materials made of plastic. It is pertinent to mention that the upcycling of plastic waste into CNMs and PCMs in Nigeria's context will largely depend on a cost–benefit analysis of the associated technologies, scientific processes, and considerations for the safe management of risks associated with nanoplastics.

Circular business model: The concept of circular economy foresees the introduction of sustainable approaches into business, which can be achieved by the cyclic flow of material that emphasizes the redesign of products, the elimination of waste, resource cycling, and the increased longevity of products [105]. A notable business model known as the returnable glass bottle process, used by breweries and beverage companies, has been identified as a veritable means through which circular business models can be operationalized in Nigeria's context [106]. Though it is used in the management of end-of-life glass bottles, it can be applied also to the management of end-of-life PET bottles, since most breweries/beverage companies also produce products packaged with PET bottles. Adopting digital innovations

and circular business models has also been suggested as a measure to achieve a circular plastics economy in Africa [107].

Industrial symbiosis: Industrial symbiosis is an industrial ecology concept where companies, communities, and institutions exchange energies, waste products, and materials in an interdependent manner [108]. It is analogous to biological symbiosis. A waste product from a participating member of the industrial ecosystem could serve as feedstock for another member. The plastic industry in Nigeria has demonstrated a certain level of interdependency with other industrial sectors. For instance, the PET preforms and plastic nylon used by the water packaging industry and most multinationals come from local plastic firms. The generated plastic waste can be used to produce upcycled products such as carbon nanomaterials which could be useful in other industrial sectors. This arrangement has provided an opportunity to design industrial symbiosis through eco-industrial parks.

Data availability: The implementation of a circular economy is a process that would require continuous appraisal and assessment based on the available data and information. A lack of information/data has been hinted as one of the major challenges to circular economy implementation in developing countries. Nigeria requires a national baseline study for a start that would collate and document essential waste management indicators for the country. Waste management data such as the waste collection rate, the waste generation rate, and waste composition analysis need to be established for specific solid waste streams such as organic, paper, plastics, etc. A demographic and health survey (DHS) has been conducted in Nigeria since 1990 at intervals of five years. Through this survey, basic socioeconomic and health data are collected by the government for optimal resource allocation and national development planning. It is our opinion that waste management data could be collected along with this survey in the future.

Improved collection through social initiatives: The rate of waste collection in the current waste management system in Nigeria is poor and thereby not appropriately situated to achieve the circular economy. The cities' waste collection trucks are often not able to access inner cities due to poor road networks which makes waste collection only limited to the visible parts of the cities. The majority of waste generated in these inner cities is often disposed of indiscriminately, especially into water bodies which are one of the main sources of marine litter. In recent times, social initiatives such as Wecyclers have begun to emerge, and they apply informal methods to collect recyclables including plastics from unserved urban populations [22]. Through incentive policies that could support these social initiatives, in the form of grants, training, and provisioning of modern waste collection equipment, the government can support them to serve informal and underserved urban areas in solid waste collection. In South Africa, for instance, a similar initiative called 'Packa-ching" is currently operating a sustainable waste collection model for low-income households. A typical Packa-ching business unit operates as a business model managed by an entrepreneur. The business unit would receive initial support which could include waste collection equipment and other operational logistics. These supports would be systematically withdrawn as the volume of recyclables they collect and sell increases.

10. Conclusions

The menace of plastic waste is an enormous challenge to Nigeria and other developing countries. Proffering sustainable solutions can only be possible by exploring the opportunities that the circular economy provides, which entails a holistic analysis of the entire value chain. The current work reviews the status of the production, importation, consumption, and end-of-life waste management of plastics and plastic products in Nigeria. The large volume of plastics and polymer products produced locally together with a substantial volume imported in different polymer formats eventually yields a large volume of waste. Nigeria lacks the essential resources and critical infrastructure to manage this waste, which results in large quantities of it ending up in dumpsites, landfills, and marine environments. The absence of data makes it difficult to quantify this waste and the associated economic and environmental implications with certainty. Given these challenges,

the current work proposes several circular economy principles that could be adopted, such as the use of alternative materials, extended producer responsibilities, the adoption of policy and economic instruments, the deployment of state-of-the-art waste treatment facilities designed specifically for developing countries, the implementation of circular business models, and industrial symbiosis. It is our opinion that the existing series of policy guidelines which include environmental policy guidelines, solid waste policy guidelines, and plastic waste policy guidelines should be harmonized for effective implementation. The proposed circular economy measures, when articulated with the understanding that they can be implemented with both bottom–up and top–down approaches at micro-, meso-, and macrolevels, could limit the menace of single-use plastic variants.

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