



Review

Addressing Plastic Waste Challenges in Africa: The Potential of Pyrolysis for Waste-to-Energy Conversion

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Abstract: Plastic waste poses a significant challenge in Africa and around the world, with its volume continuing to increase at an alarming rate. In Africa, an estimated 25–33% of daily waste is made up of plastic, posing a threat to the environment, marine life, and human health. One potential solution to this problem is waste-to-energy recycling, such as pyrolysis, which involves the conversion of waste materials into oil, char, and non-condensable gasses through a thermochemical process in the absence of oxygen. Given the abundance of waste in Africa and the continent's energy challenges, pyrolysis offers a sustainable solution. This review delves into the concept of pyrolysis, its products, thermodynamics, and endothermic kinetics, presenting it as a promising way to address the plastic waste problem in Africa. Despite the African Union's goal to recycle plastic waste, the continent faces significant barriers in achieving this target, including infrastructural, economic, and social difficulties. It is crucial to implement sustainable strategies for managing plastic waste in Africa to mitigate environmental degradation and promote a cleaner and healthier living environment. Pyrolysis technology is highlighted as a viable solution for plastic waste management, as it can convert plastic waste into valuable byproducts such as oil, char, and syngas. Case studies from countries like South Africa and Nigeria demonstrate the potential for scaling up pyrolysis to address waste management issues while generating energy and job opportunities. This review underscores the need for investment, regulatory support, and public awareness to overcome the challenges and unlock the full potential of pyrolysis in Africa. Embracing pyrolysis as a method for managing plastic waste could lead to significant environmental and economic benefits for the continent.

Keywords: plastic waste management; pyrolysis; waste-to-energy; plastic recycling; circular economy; sustainable waste management



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1. Introduction

The global plastic waste disaster poses a substantial environmental concern, particularly in Africa, where the combination of a rapidly increasing population and inadequate waste management infrastructure has led to severe consequences [1,2]. In line with this,

the annual production of plastics is expected to rise significantly, worsening the waste problem. As depicted in Figure 1, the projections of global plastic production are based on a scenario that assumes current policies remain unchanged in the predictable future, highlighting the urgent need for improved waste management and policies to lessen the environmental impact.

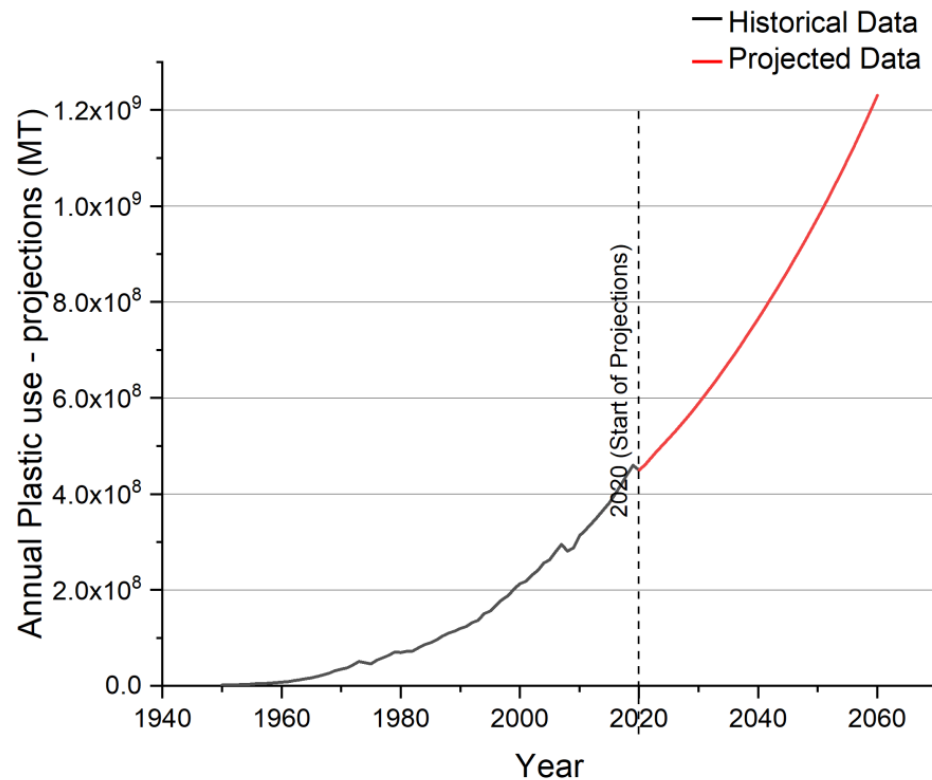


Figure 1. Global plastic production and the projection until the year 2060 [3,4].

As the situation intensifies, it becomes increasingly clear that innovative solutions are essential for tackling plastic waste in Africa. The existing recycling rates are very low, ranging from 15% to 25%, resulting in a substantial amount of plastic that contaminating soil and aquatic environments and hence increasing the health concerns among the living beings through the food chain [5]. Annually, the African continent produces around 17 million tons (MT) of plastic waste, and among which a substantial quantity is deposited into aquatic environments, resulting in extensive harm to marine life and ecosystems [6]. The success of programs aiming at decreasing plastic waste is sometimes hindered by poor governance, inadequate resources, and a lack of emphasis on addressing core issues such as insufficient recycling infrastructure and waste management systems [6]. Unfortunately, the majority of plastic wastes in Africa are either openly burned or dumped in landfills, resulting in environmental contamination and posing health problems [5,7]. The widespread use of Single-Use Plastics (SUPs) is a significant issue, and although several African countries have introduced limits on SUPs, the implementation of these bans is inconsistent, and viable alternatives are often not readily available [8,9]. Evidence from research indicates that plastic wastes that are either in micro- or nanoparticle states are widespread in African water sources, with PES, PE, and PP being the predominant types discovered [10]. In order to effectively address plastic pollution, it is crucial to implement sustainable solutions such as the circular economy (CE) and international collaboration [6]. In addition, there is a requirement for increased external financial and technical assistance, agreement among stakeholders, and efforts to raise awareness in order to improve waste management and enforce environmental rules [1]. Promoting the adoption of eco-design concepts and the

utilization of easily recyclable materials in the plastic and textile sectors can contribute to waste reduction [7]. Moreover, it is crucial for future studies to give priority to the detection and categorization of plastic polymers in order to devise efficient measures to mitigate their impact on the environment [10]. To effectively tackle the plastic waste crisis in Africa, it is necessary to adopt a comprehensive strategy that encompasses the enhancement of waste management infrastructure, the enforcement of strict laws, the promotion of recycling, and international collaboration [1,5–7].

Most African countries are challenged by the complex problem of effectively addressing the epidemic of plastic waste, which has been worsened by various interconnected factors. An important problem is the insufficient waste management infrastructure, which is basic in numerous areas, resulting in improper disposal techniques, including open burning and landfill dumping. These practices contribute to environmental contamination and pose health risks [5,10]. Although SUP laws have the highest acceptance rate worldwide, their effectiveness is constrained by inadequate governance, limited resources, and insufficient enforcement mechanisms [6,9]. Moreover, the recycling industries in most of the African countries are not well equipped as less than 10% of nations have efficient recycling facilities [7,11]. The lack of comprehensive studies on plastic pollution in soil and aquatic systems hinders the development of effective mitigation techniques [10]. The full potential of recycling in terms of economic and environmental benefits is limited by deficiencies in infrastructure and a lack of financial assistance [11]. Novel approaches, like the conversion of PO plastic into sulfur (S)-free fuel oil using pyrolysis, show promise. However, its practical application is difficult because it requires the development of secure, effective, and cost-effective methods that can generate profits for operators in areas where the average daily wage is below USD3 [12]. The global plastic convention in 2024 offered a chance for international cooperation and inventiveness, and had the potential to offer a legally enforceable structure to effectively tackle plastic pollution in all ecosystems [6,7,13]. To tackle these difficulties, it is necessary for the international community, local governments, companies, and civil society to collaborate and create sustainable solutions that may successfully reduce the plastic waste crisis.

The significance of determining sustainable solutions for plastic waste management in Africa cannot be overstated, considering the continent's rising plastic pollution epidemic and its deep environmental and socio-economic consequences. Africa, with a population surpassing 1.4 billion, produces almost 17 MT of plastic waste per year. This amount is predicted to increase as the population is estimated to reach 2.5 billion by 2050 [6]. The continent's insufficient waste management infrastructure worsens the issue [6,10]. The infiltration of fragmented plastic objects into terrestrial, aquatic, and atmospheric systems presents a significant issue. While research on marine habitats has received more attention, there is a lack of studies on freshwater and terrestrial systems [10]. Hence, it is imperative to tackle plastic waste management in Africa by implementing sustainable strategies. This is crucial, not only for the preservation of the environment but also for the improvement of public health, economic progress, and overall well-being on the continent. In addition, efforts like the African Plastics Recycling Alliance seek to overhaul recycling infrastructure. It is crucial to implement sustainable solutions in order to reduce environmental degradation, encourage the recovery of resources, and guarantee a cleaner and healthier future for Africa [14,15].

Moreover, the significance of local industries is paramount. By using eco-design principles that emphasize recyclable materials, businesses can substantially diminish new plastic manufacturing and promote sustainable practices within communities [7]. Moreover, cultivating partnerships among governments, non-governmental organizations (NGOs), and the private sector is essential for developing effective waste collection systems that both

reduce environmental harm and enhance economic prospects through recycling activities. In support of these efforts, Table 1 presents case studies from different regions of the world that have successfully implemented plastic waste management strategies. These examples demonstrate how to reduce plastic waste and thus promote recycling initiatives.

Table 1. Case studies from different regions that have successfully implemented plastic waste management.

Sl. No.	Region and Country	Case Study	Technology Used	Output Products	Environmental Impact	Economic Benefits	Other Interesting Facts	Literature
1.	West Africa—Ghana	Road construction and pothole filling using recycled plastic waste	Melt-blending technique	Construction and repair of roads in Ghana	The waste disposal methods support Ghana's long-standing MDG of promoting environmental protection and sustainability.	Waste plastic-modified bitumen shows significant potential as an alternative method for plastic waste management in Ghana.	This study aims to generate scientific data to support the use of plastic modified bitumen for road construction and repair in Ghana, while also offering insights into alternative recycling options for plastic waste management.	[15]
2.	Middle East—Saudi Arabia	Plastic waste for laying roads	Shredding plastic waste Blending it with the asphalt	This research aims to enhance asphalt binder performance, resulting in longer-lasting roads.	This research highlights the risk of microplastic contamination from modified roads, affecting soil and water ecosystems.	Despite higher initial costs, plastic-modified asphalt extends road lifespan and reduces maintenance expenses.	Saudi Arabia's Vision 2030 prioritizes sustainability and environmental leadership. This research supports these goals by advancing a greener and cleaner economy.	[16]
3.	North Africa—Algeria	LDPE plastic bags as bitumen modifiers to enhance pavement durability in Algeria.	Recycled plastic waste (2–5 mm) is shredded, mixed, and blended, then aged.	Waste LDPE plastic-modified bitumen, added to asphalt concrete, increases the lifespan of Algerian road pavements.	The environmental benefit is the reduction in plastic waste through its use in road construction.	Incorporating plastic bag waste into asphalt enhances road durability, load-bearing capacity, and resistance to deformation, significantly reducing pavement degradation and costs in Algeria.	An interesting aspect of this research is its focus on thermal fatigue cracking, a common issue in desert countries like Algeria, which led the government to develop a new pavement design manual.	[17]
4.	Western India—Pune City	Plastic waste bitumen for road laying	Distress parameters such as cracking, rutting, potholes, and surface wear were assessed, and their severity measured using the Analytic Hierarchy Process (AHP)	The research led to the construction of roads in Pune city using a bituminous mix containing shredded waste plastic.	The proper recycling of plastics reduces landfill waste.	Conventional roads are costlier due to the need for frequent maintenance, whereas roads made with waste plastic require less maintenance, resulting in significant cost savings.	An interesting fact is that roads made with waste plastic require less maintenance, leading to significant cost savings compared to conventional roads.	[18]
5.	Middle East—UAE	Plastic waste bitumen for road construction	Composite (50% used rubber and 50% waste plastic) for bitumen	Enhanced bitumen performance in road construction.	The proper utilization of used tires and waste reduces landfill waste.	Adding waste plastic and tire rubber to bitumen as modifiers can increase the overall cost of asphalt mixtures by up to 40% due to the associated production processes.	By 2030, the waste generated by end-of-life tires in the USA and EU is expected to reach around 3700 and 3400 thousand tons, respectively, with global accumulation totaling about 5 billion tons.	[19]

Table 1. Cont.

Sl. No.	Region and Country	Case Study	Technology Used	Output Products	Environmental Impact	Economic Benefits	Other Interesting Facts	Literature
6.	West Africa—Nigeria	Plastic waste for pavement production	Melted waste plastics as a binder in the production of interlocking paving stones	The research was tested in Lagos, Nigeria, where heavy rainfall causes flooding. Plastic-infused roads in this region show increased strength and water absorption resistance, enhancing their durability.	Poor recycling in Nigeria allows plastic waste to contaminate water bodies, harming ecosystems and posing cancer risks to humans through fish consumption. Research highlights the environmental benefits of addressing this issue.	In Nigeria, Portland cement is the only mortar binder used for road construction, making it expensive. However, melting and mixing abundant plastic waste can reduce road construction costs by \$12–15 per kilometer.	Nigeria generates nearly 12 tons of plastic waste annually, ranking 9th globally with around 2.5 million tons of plastic waste each year. However, less than 8% of this waste is recycled.	[20]
7.	Asia—Korea	Waste plastic to energy	Pyrolysis and gasification	Plastic waste is converted into syngas, which fuels a combined cycle to generate electricity using both gas and steam turbines.	By converting plastic waste to energy in Korea, a significant amount of landfill waste shall reduce, helping to prevent soil and water contamination by microplastics.	The research has proven economic benefit, with the cost per unit of electricity being \$0.108 per kWh lower.	The design aspect of this research, particularly the smaller size of the gas heater for high-temperature processes like gasification, was crucial for upscaling sustainable waste-to-energy technology. It demonstrated an improved efficiency of about 8.2%.	[21]
8.	Asia—India	Waste plastic into alternate fuel	Plastic pyrolysis	The waste plastic oil produced through pyrolysis provides a cleaner alternative fuel, reducing emissions and contributing to cleaner engine technology.	When waste plastic oil is blended with 10% water, it results in significant reductions: 12.2% in NOx emissions, 9.8% in hydrocarbon emissions, and 22.2% in CO emissions.	The study does not provide quantified economic benefits of blended waste plastic oil, but it can be deduced that the fuel will be more cost-effective than diesel	An interesting fact is that blending waste plastic oil with 10% water can significantly reduce emissions, including a 22.2% reduction in CO emissions.	[22]
9.	European Union—UK	Plastics in circular economy	Life cycle assessment (LCA)	The research output on the incineration process focuses on converting waste to energy through pyrolysis and gasification, with the obtained gas used to drive steam turbines.	Proper recycling of plastics reduces landfill waste, which in turn decreases micro and nano plastics, sources of cancer and toxic air pollution that pose respiratory health risks.	A circularity policy for plastic waste reduces landfill revenue through recycling and refurbished products, and produces gas via thermochemical processes, decreasing fossil fuel use.	The UK, which is the focus of our research, generated 5.2 MT of plastic waste in 2018. The interesting fact is that 91% of this plastic waste was successfully recycled due to the country's strong recycling system.	[23]
10.	Asia—India	Medical plastic waste from healthcare facilities, particularly saline bottles, is reutilized for creating triboelectric nanogenerators (TENGs)	Triboelectric nanogenerator (TENG) technology, using saline bottle sheets as triboelectric material, fabricated in Vertical Contact Separation (VCS) and Single-Electrode (SE) modes.	The VCS-TENG generated a power density of 8.78 W/m ² , powering devices like LEDs and portable electronics. The SE mode produced 1.46 W/m ² for tactile sensing applications.	Reduces medical plastic waste in landfills, repurposing it for sustainable energy and sensing applications, minimizing environmental pollution.	Generates revenue through the creation of energy-harvesting and sensing devices, potentially reducing healthcare waste disposal costs.	The VCS-TENG powered 420 red LEDs and enabled sleep monitoring through an implanted TENG inside a pillow, showcasing the versatility of medical waste in energy and sensing applications.	[24]

Table 1. Cont.

Sl. No.	Region and Country	Case Study	Technology Used	Output Products	Environmental Impact	Economic Benefits	Other Interesting Facts	Literature
11.	North America—USA, Texas	Waste plastic to energy	Flash Joule Heating (FJH)	Producing clean hydrogen and high-purity graphene by utilizing waste plastics as a feedstock	The environmental benefit is that waste plastic conversion produces no CO ₂ , resulting in a 39–84% reduction in greenhouse gas emissions compared to traditional H ₂ production.	The economic benefit of using FJH is the production of high-purity graphene, which can offset the cost of hydrogen production.	High-purity graphene produced by the FJH process, even sold at 5% of its market price, can fetch around \$300 per tonne.	[25]
12.	Asia—China	Waste plastic into value added product	Using a simple pyrolysis–catalysis process with a monolithic multi-layer stainless-steel mesh catalyst, value-added products are manufactured.	The value-added products obtained are MWCNTs and hydrogen (H ₂).	Upcycling plastic waste into MWCNTs reduces environmental pollution by diverting waste from landfills. Applying the pyrolysis–catalysis process to polypropylene (PP) significantly reduces CO ₂ emissions by 0.007 tons per ton of plastic.	Upcycling plastic waste into MWCNTs generates valuable products for high-demand industries, creating revenue and reducing waste management costs.	MWCNTs, with excellent properties for nanodevices and energy storage, account for up 97% of carbon nanotube production, driving a commercial cycle.	[26]
13.	Asia	Plastic waste food container into oil	Pyrolysis	The research aims to produce commercial oil for use in IC engines of commercial vehicles. Blending pyrolyzed plastic oil with diesel proved to be a better alternative fuel than conventional diesel, overcoming the high-viscosity issue of vegetable oil.	The pyrolysis of plastic waste produces alternative oil, reducing landfill waste and diesel engine pollution (NO _x , particulates), especially from food containers in countries like India. This solution addresses both waste management and fuel shortages.	The cost of producing Waste Plastic Oil (WPO) blended with 150 ppm of TiO ₂ nanoparticles \$0.70 per liter, offering a savings of \$0.37 per liter compared to the current diesel price of \$1.07 in India.	In 2019, World Wildlife Fund (WWF) reported that 75% of plastic became untreated waste, 20% was recycled, and 8 million tons polluted oceans. Post-pandemic, plastic waste in India surged to 20,000 tons due to increased food deliveries in plastic containers.	[27]
14.	Oceania—New Zealand	Plastic waste for construction	Reduce, reuse, and recycle using the 3R technique	The research found that the amount of plastic generated across various construction stages was approximately 112 kg.	Employing the reuse technique in construction projects minimizes construction and demolition waste and reduces construction costs.	Recycling construction and demolition waste reduces landfills, preventing the leaching of heavy metals, chemicals, and pollutants, while also reducing microplastic air pollution.	Despite being technologically advanced, New Zealand lacks proper plastic waste segregation in the construction industry, generating 25,000 tonnes of plastic waste annually, which this research aims to address through on-site sorting.	[28]

This review aims to critically analyze the current challenges of plastic waste management in the African context and explore the potential of pyrolysis technology as a sustainable solution for waste-to-energy conversion. By examining case studies, advancements in pyrolysis methods, and environmental and socio-economic impacts, the paper seeks to provide a comprehensive overview of how pyrolysis can address plastic waste issues while generating valuable byproducts like fuels and carbon-based materials. Ul-

timately, this review highlights the necessary policy, technological, and infrastructure advancements needed to support the widespread adoption of pyrolysis across Africa, contributing to both environmental protection and energy security on the continent.

2. Overview of Plastic Waste in Africa

Plastic waste generation and management in Africa present a complex challenge that was worsened by both local production and international imports. A significant proportion of this waste finds its way to Africa, either through legal or illegal means [7]. Figure 2 shows the presence of plastic waste, especially SUPs, in the surroundings of Ishaka town, Uganda, with the coordinates $0^{\circ}32'42.0''$ S, $30^{\circ}08'18.0''$ E in the African continent.



Figure 2. Illustration of plastic waste.

Africa has become a significant destination for plastic waste, with an estimated 17 MT mismanaged, largely due to ineffective regulations and poor monitoring [29]. Countries like Egypt, Nigeria, and South Africa are among the top plastic waste generators on the continent, with Egypt alone accounting for 18.4% of the total plastic waste generated in Africa [29]. In Johannesburg, South Africa, it is projected that the city produces around 6.7 megatonnes of plastic waste between 2021 and 2050. This amounts to an average of 0.22 megatonnes per year. The specific breakdown of this waste includes 17,910 tonnes of PS, 13,433 tonnes of PP, and 85,074 tonnes of PET annually [30]. The Southern African Development Community (SADC) has also seen a shift in plastic waste trade flows following the Chinese waste import ban, highlighting the region's growing role in global plastic waste management [31]. Despite the high adoption rate of single-use plastic policies across Africa, with 48 active policies in 39 countries, the effectiveness of these measures remains questionable due to policy design flaws and a lack of coherence [32]. In Nigeria, only about 9% of plastic waste is recycled, with the majority ending up in landfills or the environment [29]. Informal waste management systems are prevalent, particularly in urban areas like Lagos, Nigeria, where they play a crucial role in the collection and recycling processes [33].

Nigeria encounters substantial obstacles in the management of plastic waste, since a considerable proportion of plastics, including PET, HDPE, PVC, LDPE, and PP, are utilized for a short period of time before transitioning into waste. In Nigeria, the recycling process includes the steps of collecting, sorting, cleaning, shredding, melting, and molding. However, the varying molecular compositions of plastics make recycling operations more challenging [34]. In urban areas of Zambia, efforts to promote the recycling and reusing of plastic waste have not made significant progress due to structural obstacles that discourage individuals from engaging in waste valorization activities [35]. In Africa, the management of plastic waste encompasses both formal and informal systems. This is evident in Lagos, Nigeria, where informal waste management plays a crucial role in processing polymer-based waste products [33]. Table 2 provides an overview of waste generation and recycling rates across some key African countries, showcasing significant variations in both waste production volumes and recycling efficiencies.

Table 2. Data of waste generation and recycling rate of some key African countries [36].

Sl. No.	Country	Estimated Population (Million)	Area (sq km)	Total MSW Generated (MT per Annum)	Estimated Plastic Waste Generated (MT per Annum)	Rate of Recycling (%)	Disposal Methods
1	Cameroon	27.20	475,442	6	0.6	>20	Open dumping, burying, and burning
2	Côte d'Ivoire	26	322,462	2.9	0.6	>20	Open dumping, burying, and burning
3	Democratic Republic of Congo	108	2,344,858	3.44	1.06	>15	Open dumping, burying, and burning
4	Eswatini	1.15	17,364	0.23	0.04	-	Dumping, burying, and burning
5	Ethiopia	117	1,104,300	7	0.56	5	Dumping, burying, and burning
6	Ghana	31	238,535	4.6	1	9.5	Dumping, burying, and burning
7	Kenya	44	569,137	8	0.8	15	Dumping, burying, and burning
8	Mozambique	30.6	801,590	4.2	0.42	1	Dumping, burying, and burning
9	Namibia	2.54	824,292	0.25	0.02	-	Dumping, burying, and burning
10	Nigeria	218.5	923,768	32	2.5	>10	Open dumping, burying, burning, incineration and landfilling
11	South Africa	60.14	1,221,000	12.7	2.4	14	Open dumping, burying, burning, incineration and landfilling
12	Tanzania	59.73	945,087	17.4	1.21	4	Dumping, burying, and burning
13	Uganda	47	241,555	6.6	0.6	-	Dumping, burying, and burning
14	Zambia	18.38	752,618	2.6	0.36	3	Dumping, burying, and burning

In Ethiopia, for example, plastic waste is a significant component of solid waste, with 45% of respondents in Kebri Dehar city identifying plastics as the dominant waste type. The lack of public waste bins and insufficient community awareness about the environmental impacts of waste exacerbate the problem [37]. Across Africa, the issue of micro/nanoplastic pollution is compounded by the limited scientific infrastructure, which restricts research and policy development. This necessitates collaboration with established research laboratories in order to enhance the understanding and management of plastic pollution [38]. The broader context of waste management in developing countries,

including many in Africa, reveals that a significant portion of waste ends up in dumpsites, with 93% of waste in low-income nations being disposed of in this manner. This is largely due to economic constraints that limit the adoption of more sustainable waste management practices, like recycling and incineration [39]. In healthcare settings in Ethiopia, waste management practices are similarly inadequate, with poor segregation practices and a lack of pre-treatment for infectious waste, highlighting the need for improved training and infrastructure [40,41]. The predominant challenge in Africa is the need for a systemic change in waste management practices, supported by enhanced infrastructure, community education, and policy development to address the growing plastic waste crisis effectively.

2.1. Challenges in Managing Plastic Waste in Africa

The management of plastic waste in Africa is a complex task that involves various difficulties related to infrastructure, economy, and society. The difficulties are worsened by insufficient waste management systems, financial limitations, and social factors that obstruct the efficient treatment of plastic waste. Numerous African nations suffer from a lack of the requisite infrastructure to facilitate efficient waste management. This encompasses inadequate methods for collecting, recycling, and disposing of plastic waste, resulting in the buildup of plastic waste in landfills and natural habitats [6,10]. The recycling infrastructure in Africa is frequently basic, with an inadequate capability to handle the large quantities of plastic waste produced. The recycling rate in sub-Saharan Africa is low, with only 15–25% of plastic waste being recycled [5]. One of the main challenges in implementing advanced technologies, such as the use of pyrolysis to convert plastic waste into fuel, is the requirement for safe, efficient, and low-cost operations that can be profitable for local operators [12].

The meager market value of plastic waste results in a lack of economic motivation to recycle it. This hinders the allocation of resources towards the development of recycling technologies and infrastructure, hence sustaining the continuous buildup of waste [12]. The successful implementation of policies to effectively manage plastic waste necessitates substantial financial resources, a deficiency commonly observed in most African nations. This funding limitation hampers the capacity to enforce current policies and create novel initiatives [6,9]. The economic advantages of participating in plastic waste management activities, such as recycling, are not significant enough to attract widespread involvement, given that the average daily salaries in sub-Saharan Africa are less than USD 3 [12].

There is a widespread lack of public knowledge about the environmental consequences of plastic waste and the significance of recycling. This leads to a lack of participation from the community in waste management procedures [5,6]. The efficacy of waste management systems can be influenced by cultural perceptions and attitudes towards waste management. Certain populations exhibit a deficiency in the desire to engage in recycling initiatives as a result of deeply ingrained practices and attitudes [35]. The formulation and execution of measures intended to diminish plastic waste frequently exhibit incongruity and the absence of logical connection. Numerous initiatives are ineffective in terms of tackling the fundamental reasons for plastic pollution, such as insufficient recycling infrastructure and weak governance [6,9]. Although these problems are substantial, there are prospects for enhancement. To address these obstacles, it is crucial to prioritize the advancement of a CE, raise public consciousness, and promote global cooperation. Moreover, the use of cutting-edge technologies and strategic policy changes that prioritize the generation of value and equitable distribution can significantly contribute to the progress of plastic waste management in Africa. However, tackling these difficulties necessitates a collaborative endeavor by governments, corporations, and communities to establish sustainable and efficient solutions.

2.2. Environmental and Health Impacts of Improper Plastic Waste Management

The inadequate handling of plastic waste has significant adverse effects on the environment and public health. The enduring presence of plastic waste in ecosystems, along with insufficient disposal and recycling methods, intensifies environmental deterioration and presents substantial health hazards. Ecosystem degradation occurs when plastics, which are incapable of being broken down by natural processes, remain in the environment for extended periods, causing substantial ecological damage. Plastic gathers in landfills, and bodies of water, causing disturbances in ecosystems and acting as a geological marker of the Anthropocene period [42,43].

The incorrect disposal of plastics, such as bottles and sachets, obstructs drainage systems and pollutes water bodies. Consequently, there has been a rise in the likelihood of flooding and the infiltration of microplastics into aquatic ecosystems. These microplastics have the potential to penetrate the food chain and have adverse effects on human health [44,45]. The presence of plastics in landfills leads to the release of detrimental compounds into the soil and air, adding to pollution. The burning of plastic waste, which is a commonly used form of disposal, releases hazardous compounds that worsen air quality and contribute to climate change [44,46].

Plastics contain chemicals such as phthalates and bisphenols, which are associated with endocrine disruption and reproductive problems. These compounds can permeate into food and water, presenting immediate health hazards to both humans and wildlife [47,48]. The breakdown of plastics into microplastics leads to the formation of tiny particles that are widespread in the environment and can be consumed by both people and animals. This gives rise to worries over the accumulation of substances in living organisms over time, which may lead to health effects such as long-term illnesses and problems related to growth and maturation [42,49].

Employees working in waste management and recycling facilities face the risk of being exposed to air pollution and harmful substances as a result of insufficient safety regulations. Exposure to these issues can result in severe health issues, emphasizing the necessity to improve regulatory systems [50]. Numerous areas suffer from a lack of essential infrastructure required for the efficient management of plastic waste, resulting in haphazard disposal and worsening environmental and health problems. This is especially apparent in underdeveloped nations, where the availability of recycling facilities is restricted [45,46]. The global trade of plastic waste from rich nations to poor nations frequently leads to environmental injustice, as these countries may lack the capability to safely handle and dispose of the waste. This practice poses a threat to human rights, including the right to a healthy environment [50].

Although the adverse consequences of inadequate plastic waste management are substantial, there are emerging strategies and technologies designed to alleviate these problems. The advancement of biodegradable polymers, enhanced recycling methodologies, and regulatory interventions, such as prohibitions on disposable plastics, are positive measures. However, the effectiveness of these solutions hinges on the necessity of worldwide collaboration and dedication. To tackle the plastic waste challenge effectively, it is necessary to adopt a comprehensive strategy that encompasses lowering plastic consumption, improving waste management infrastructure, and promoting public awareness and education.

Mechanical vs. Chemical Recycling: Environmental Impacts and Advantages

Mechanical and chemical recycling of plastics differ primarily in their processes and their ability to handle diverse plastic waste types. Mechanical recycling involves physically breaking down plastics, such as shredding and melting, and reforming them into new products. However, this method is limited by polymer degradation, which occurs after

multiple recycling cycles, reducing the quality of the material. As a result, mechanical recycling is only effective for uncontaminated plastics and is not suitable for complex waste types. On the other hand, chemical recycling involves breaking down polymers into their monomers or other chemical feedstocks, which can then be used to create new plastics or other materials. This method is highly beneficial for handling contaminated and complex plastics, such as multi-layered or mixed-material plastics, that cannot be processed through mechanical recycling [51–53].

In terms of environmental impacts, mechanical recycling generally has a smaller carbon footprint due to its lower energy requirements [51,54]. It is a simpler and less energy-intensive process, making it more sustainable when dealing with high-quality, uncontaminated plastics. However, its effectiveness is limited when dealing with contaminated waste. Chemical recycling, while more energy-intensive, holds greater potential for reducing landfill waste, as it can handle a wider range of plastics, including those that are contaminated or multi-layered. However, chemical recycling comes with a challenge, which is the management of toxic byproducts that must be carefully controlled to minimize environmental harm [51–53,55].

The advantages of mechanical recycling lie in its cost-effectiveness and simplicity. It requires fewer resources and energy, making it ideal for recycling high-quality plastics, and is typically more economically viable in areas with established recycling infrastructure. Chemical recycling, in contrast, provides a more versatile solution by enabling the recycling of diverse waste streams, including those that are complex or contaminated. It offers a significant advantage in terms of reducing plastic waste that cannot be recycled mechanically, thus contributing to the circular economy (CE), though it requires higher investment and the careful management of its environmental byproducts [51,55,56].

3. Plastic Pyrolysis Technology: Principles and Process

Plastic pyrolysis is a thermodynamic process that transforms plastic waste into useful commodities including pyrolysis oil, syngas, and char. This process involves the heat degradation of plastics in the absence of oxygen, causing the fragmentation of lengthy polymer chains into smaller molecules [57,58]. The plastic pyrolysis process is depicted in Figure 3.

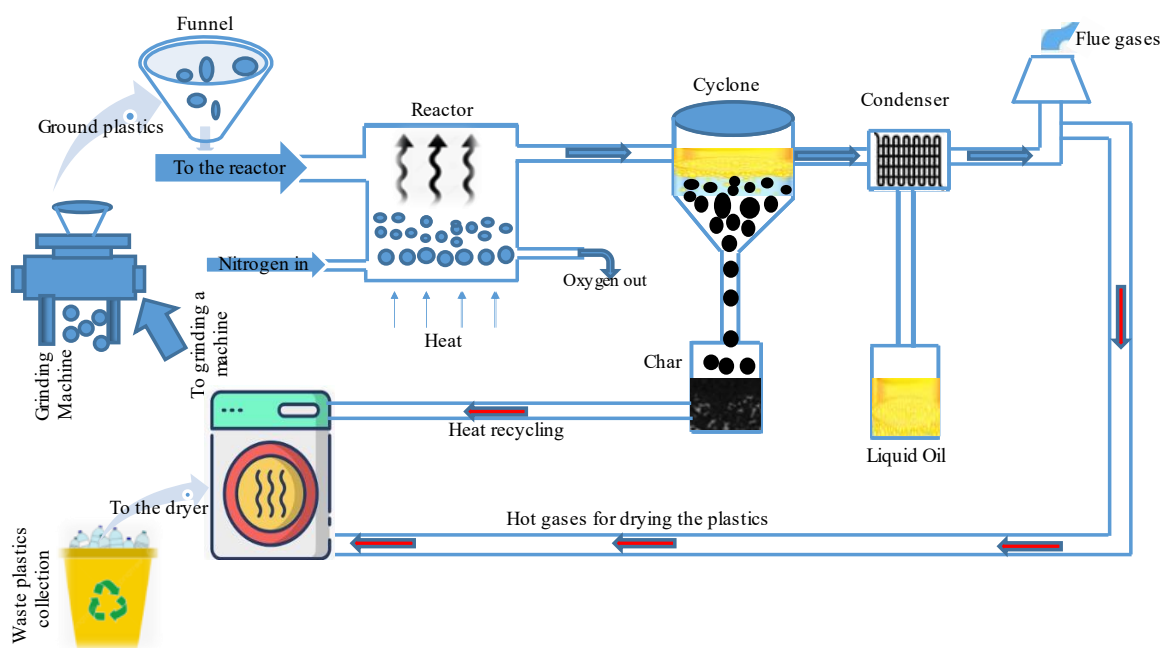


Figure 3. Schematic illustration of plastic pyrolysis process.

Pyrolysis is increasingly being recognized as an environmentally friendly technique for handling plastic waste and thus promoting circular economy (CE). The process is affected by several elements, such as the plastic type, temperature, catalysts, and reactor design, which govern the amount and composition of the products. Moreover, the integration of advanced reactor designs can significantly enhance the efficiency and yield of pyrolysis processes.

Recent advancements in catalyst development for chemical recycling have focused on enhancing sustainability and eco-friendliness. For example, coal fly ash-based zeolite catalysts have been utilized for transforming single-use plastics into lighter hydrocarbons, offering an economical and effective approach [59]. Additionally, the use of activated carbon from cotton waste in catalytic pyrolysis has shown potential for improving plastic waste conversion [60]. Moreover, innovations in ex situ catalyst bed integration for LDPE pyrolysis, employing thermodynamically closed systems, have led to more energy-efficient processes under milder operating conditions [61].

The utilization of fluidized bed reactors has shown promise in optimizing thermal conditions and improving the uniformity of heat distribution, which is crucial for effective plastic degradation [62]. Additionally, co-pyrolysis, where plastics are processed alongside biomass, has emerged as a viable strategy, not only increase to the diversity of feedstock but also to mitigate the environmental impact by utilizing organic waste materials [63]. This dual approach not only maximizes energy recovery but also aligns with the principles of a CE, thus providing a sustainable pathway for managing plastic waste while generating valuable resources [64]. The following elements, such as plastic pyrolysis mechanism, pyrolysis byproducts, pyrolysis process stages, types of pyrolysis, pyrolysis outputs, and synergistic and environmental considerations, are discussed in this section.

3.1. Plastic Pyrolysis Mechanism

Thermal decomposition, also known as pyrolysis, is the process of subjecting plastics to elevated temperatures (usually ranging from 400 °C to 900 °C) without the presence of oxygen. This leads to the breakdown of polymer chains into smaller hydrocarbon molecules. The process can exhibit either endothermic or exothermic behavior, which is determined by the specific kind of plastic and the prevailing conditions [65,66]. The process of pyrolysis in plastics can occur by many reaction paths, such as depolymerization, random scission, and chain-end scission. The pyrolysis process of polymers such as PET and nylon is influenced by the presence of C-O and C-N bonds. The specific cleavage of these bonds results in the formation of various products [67].

Activation energy, a critical parameter, determines the energy required to initiate these decomposition reactions. A lower activation energy enhances reaction rates, making pyrolysis more energy-efficient and scalable. Catalysts like zeolites play vital roles in reducing activation energy, improving reaction kinetics, and selectively enhancing the production of value-added substances such as aromatics and olefins [68,69]. For example, PE and PP exhibit lower activation energies compared to PVC, which requires higher temperatures for complete pyrolysis due to its chlorine content, affecting product composition [70,71]. The temperature and heating rate significantly influence pyrolysis. Higher temperatures favor gas production, while lower temperatures enhance liquid yields. Rapid heating can lower activation energy, accelerating reaction rates [71,72]. Reactor design also impacts process efficiency, influencing heat transfer, residence time, and product separation [72,73]. Understanding activation energy's role is crucial in optimizing pyrolysis processes for energy efficiency and product yield, enabling advancements in sustainable waste management.

3.2. Pyrolysis Byproducts

Pyrolysis predominantly yields liquid oils, which can serve as viable substitutes for traditional liquid fuels. These oils possess characteristics that closely resemble those of traditional diesel fuel, making them well suited for use in energy-related applications [73]. Non-condensable gasses, including hydrogen, methane, and ethylene, are created as gaseous products. These gasses can be utilized as feedstocks for chemical synthesis or energy generation [71]. The solid residues produced from pyrolysis include char and coke, which have potential uses in carbon materials and as soil amendments [66].

In addition to their direct applications, the products of pyrolysis also contribute to a circular economy (CE) by providing a pathway for waste management. For example, the conversion of agricultural residues into biochar not only mitigates GHE but also enhances soil fertility and structure, promoting sustainable agriculture [66,73]. Moreover, the ability to fine-tune pyrolysis conditions such as temperature and feedstock composition can optimize the yields of both liquid fuels and gaseous products, thereby increasing economic viability and energy efficiency [71,74]. This adaptability underscores the potential of pyrolysis in addressing energy demands while simultaneously managing waste, thus promoting environmental sustainability through innovative recycling methods. The integration of such technologies into existing waste management systems can create a more resilient and resource-efficient economy, paving the way for reducing reliance on fossil fuels and minimizing landfill use. The pyrolysis byproducts are presented in Table 3.

Table 3. Pyrolysis byproducts.

Products	Composition and Characteristics	Potential Uses
Pyrolysis oil	Pyrolysis oil, also known as plastic oil, is a complex mixture of hydrocarbons. It can include monoaromatic compounds like phenol and styrene, as well as aliphatic and aromatic linkages [75,76]. The oil's quality can be enhanced by co-pyrolysis with biomass, which improves the hydrogen-to-carbon ratio, leading to more valuable petrochemicals and reduced coke formation [66].	Pyrolysis oil can be refined into fuels such as gasoline and diesel, although it often requires further processing to meet commercial fuel standards [76]. It can also serve as a feedstock for producing chemicals and lubricants, offering a sustainable alternative to fossil fuels [66].
Syngas	Syngas, primarily composed of hydrogen and carbon monoxide, is produced during pyrolysis, especially when using CO ₂ or steam as gasifying agents [77,78]. The H ₂ /CO ratio in syngas can be adjusted for specific applications, enhancing its versatility [78].	Syngas is a valuable fuel for electricity generation and can be used in internal combustion engines, offering a sustainable alternative to natural gas [79]. It also serves as a precursor for producing hydrogen and other chemicals, supporting various industrial processes [78].
Char	Char is a solid residue rich in carbon, often containing inorganic components like silicon [80]. Its composition can vary depending on the feedstock and pyrolysis conditions [75].	Char can be used as a clean fuel in industries such as cement production or as a precursor to activated carbon. It also shows promise as an adsorbent for wastewater treatment, providing a low-cost alternative to traditional adsorbents [75,80].

Although plastic pyrolysis shows potential as a solution for waste management and resource recovery, there are still obstacles to overcome in order to optimize the process for various types of plastic and enhance its economic viability. Efficient catalysts and reactor designs are essential for improving the quantity and quality of pyrolysis products. Moreover, it is crucial to comprehend the environmental consequences and energy demands of pyrolysis in order to ensure its sustainable adoption. Pyrolysis has the potential to make a substantial impact in terms of reducing plastic pollution and promoting CE as research advances.

3.3. Pyrolysis Process Stages

Pyrolysis is a thermochemical decomposition method that converts organic materials into valuable products, including oil, char, and gasses. The process is commonly categorized into three primary phases such as feedstock preparation, heat decomposition, and product recovery. Every stage is essential for maximizing the yield and enhancing the quality of the pyrolysis products.

3.3.1. Feedstock Preparation

The selection and characterization of the feedstock have a substantial impact on the pyrolysis process and its results. Municipal solid waste is frequently used as a feedstock but requires special preparation processes in order to maximize the effectiveness of the pyrolysis of the polymers. Biomass, polymers, and municipal solid waste are frequently used as feedstocks, but each one requires special preparation processes in order to maximize the effectiveness of pyrolysis [81,82]. It is crucial to accurately characterize feedstocks, which involves determining their moisture content and chemical makeup, in order to forecast how they will behave during pyrolysis and the distribution of resulting products [83].

Moreover, the interaction between different feedstock types can significantly influence the pyrolysis outcomes. For example, the co-pyrolysis of biomass with plastics has been shown to enhance the yield and quality of liquid products, as the presence of polymers can alter the thermal decomposition pathways and promote synergistic effects during the process [84]. This blending not only maximizes resource utilization but also mitigates some environmental concerns associated with plastic waste by converting it into valuable fuels or chemicals [85]. Moreover, understanding the specific interactions at play requires a thorough investigation into the chemical properties of each component, which can lead to optimized operational parameters tailored for mixed feedstock scenarios, ultimately improving energy recovery and reducing emissions in thermochemical processes [86].

3.3.2. Drying

The presence of moisture in biomass might disrupt the pyrolysis process by weakening the concentration of the resulting stream. Thus, drying is an essential process with which to guarantee effective thermal breakdown. Particle size reduction can improve heat transport and enhance the homogeneity of the pyrolysis process [87]. Moreover, the optimization of drying methods plays a crucial role in enhancing the efficiency of pyrolysis. Advanced techniques such as microwave-assisted drying have been shown to significantly reduce moisture content while preserving the structural integrity of biomass, thus facilitating more uniform thermal treatment [73,88]. This method not only accelerates the drying process but also minimizes energy consumption compared to conventional drying approaches, thereby improving overall sustainability [89]. Additionally, integrating pre-treatment processes like mechanical crushing can further improve heat transfer during pyrolysis, leading to higher yields of valuable bio-oil and char products [90]. Such innovations highlight the importance of optimizing each stage of biomass processing to achieve both economic and environmental benefits.

3.3.3. Thermal Decomposition

In thermal decomposition, the initial phase consists of the evaporation of unbound water and volatile chemical compounds. Preparing the feedstock for future breakdown is of the utmost importance. Primary decomposition refers to the process of breaking down complex molecules into simpler ones. The temperature and heating rate are crucial factors that impact the quantity and makeup of pyrolysis products. Higher temperatures typically result in an increase in gas generation and a decrease in char yield [91,92].

Secondary reactions, such as cracking and reforming, take place at elevated temperatures during pyrolysis, leading to additional changes in the composition of the resulting products. These reactions can improve the quality of bio-oil by facilitating the production of short-chain hydrocarbons [93,94].

Moreover, the optimization of pyrolysis conditions is essential for maximizing product yield and quality. For example, varying the process temperature not only significantly influences the quantity but also the physicochemical properties of the resulting bio-oil.

Maintaining moderate temperatures during plastic pyrolysis enhances oil conversion rates while minimizing undesirable heavy residues [95]. Additionally, the use of catalysts has been shown to further accelerate thermal cracking reactions, promoting the formation of valuable hydrocarbons at lower operational costs [96]. As research continues to evolve in this area, understanding the intricate balance between temperature, residence time, and feedstock composition will be pivotal in developing economically viable pyrolysis technologies capable of addressing waste management challenges effectively. This comprehensive approach not only aims to optimize bio-oil yields but also seeks to improve the overall sustainability of the plastic waste conversion processes, paving the way for innovative solutions in renewable energy production.

3.3.4. Product Retrieval

Pyrolysis vapors undergo condensation to separate bio-oil from gasses that cannot be condensed. The effectiveness of this technique relies on the cooling system and the makeup of the vapors [97]. The solid char that is obtained from the reactor can serve as a bio-adsorbent, a soil amendment, or a solid fuel [82]. Non-condensable gasses can be recycled to supply heat for the pyrolysis process or utilized as a fuel for power generation [82].

Although the pyrolysis process is a sustainable approach with which to transform waste into useful goods, there are still difficulties in optimizing each stage for various types of feedstocks. Additional research and development is needed to determine the economic viability and ecological sustainability of large-scale pyrolysis plants [82]. Incorporating modern analytical methods, such as thermogravimetric analysis, can further our comprehension of pyrolysis dynamics and promote process efficiency [81]. Although the pyrolysis process is a sustainable approach with which to transform waste into useful goods, there are still difficulties in optimizing each stage for various types of feedstocks. Additional research and development is needed to determine the economic viability and ecological sustainability of large-scale pyrolysis plants [82]. Incorporating modern analytical methods, such as thermogravimetric analysis, can further our comprehension of pyrolysis dynamics and promote process efficiency [81]. To enhance the efficiency of pyrolysis operations, it is essential to consider the integration of advanced catalytic processes that can improve product yield and quality. For example, the application of specific catalysts, such as HZSM-5, has shown promising results in increasing the production of valuable aromatics during the pyrolysis of LDPE waste, thereby contributing to a more circular economy for plastics [61]. Moreover, optimizing reaction parameters like temperature and pressure can significantly influence the composition of both bio-oil and char, suggesting that tailored approaches for different feedstocks can lead to superior environmental outcomes [82]. By focusing on these innovative strategies, researchers not only aim to maximize energy recovery but also seek to mitigate the ecological footprint of plastic waste management using pyrolysis technologies [61]. These advancements highlight the potential of pyrolysis as a sustainable solution, paving the way for further research into enhancing catalyst efficiency and exploring new feedstock options to diversify and improve the overall yield of valuable products.

3.4. Types of Pyrolysis

Plastic pyrolysis is a thermochemical process that decomposes plastic waste into valuable products like fuel oil, gasses, and char. This process can be categorized into slow, fast, and flash pyrolysis, each displaying distinct characteristics, advantages, and disadvantages. Understanding these differences is crucial for optimizing plastic waste management and energy recovery. The types of pyrolysis are presented in Table 4.

Table 4. Types of plastic pyrolysis.

Pyrolysis Categories	Process Characteristics	Advantages	Disadvantages
Slow pyrolysis	Heating plastic waste at a slow rate, typically ranging from 5 °C/min to 20 °C/min depending on reactor design and desired product yield, and maintaining it at a moderate temperature for an extended period. This method is often conducted in batch reactors, which are suitable for processing polymeric waste [72,98,99].	Produces a higher yield of solid char, which can be used as a carbon-rich material for various applications [72]. The liquid oil produced is aromatic-rich and has fuel properties comparable to kerosene and diesel [100].	Lower liquid and gas yields compared to fast and flash pyrolysis [100]. Longer processing times and higher energy consumption due to prolonged heating [72].
Fast pyrolysis	Fast pyrolysis involves the rapid heating of plastic waste at rates exceeding 100 °C/min to moderate temperatures, typically around 500 °C, with short residence times [101].	Produces a higher yield of liquid oil, which can be used as a fuel in gas turbines and other applications [101]. The process is relatively cheaper and can be more energy-efficient than slow pyrolysis [101].	The quality of the liquid oil may be lower, with longer carbon chains that are not always suitable for direct use in internal combustion engines [101]. Requires precise control of process parameters to optimize product yields [101].
Flash pyrolysis	Flash pyrolysis is characterized by extremely rapid heating rates, often exceeding 1000 °C/min, and very short residence times [69].	Can achieve the complete conversion of plastic feedstocks in a very short time, enhancing process efficiency [69]. Produces a high yield of gaseous products, which can be rich in valuable compounds like C3 and C4 hydrocarbons [69].	Requires advanced reactor designs and precise control of heating rates, which can increase operational complexity and costs [69]. The rapid process may lead to incomplete cracking of polymers, resulting in waxy residues [69].

While each type of pyrolysis has its benefits and limitations, the choice of method depends on the desired end products and the specific characteristics of the plastic waste being processed. Catalysts can significantly influence the efficiency and product distribution in pyrolysis, with zeolites like HZSM-5 being commonly used to enhance liquid yield and improve oil quality [69,98]. However, the economic feasibility and environmental impact of large-scale pyrolysis operations remain critical challenges that need to be addressed through ongoing research and technological advancements.

3.5. Synergistic and Environmental Considerations

The pyrolysis process for plastic waste management presents both synergistic and environmental considerations that are crucial for its optimization and sustainability. Synergistic interactions in pyrolysis, particularly in co-pyrolysis scenarios, have been shown to enhance the efficiency and quality of the products obtained. For example, the co-pyrolysis of LDPE, PVC, and PVB demonstrates significant synergistic effects, such as accelerated mass loss and reduced activation energy, which improve the process efficiency and product quality [70]. Similarly, the co-pyrolysis of scrap tires with plastics like PP and PS not only enhances the production of lighter HCs but also effectively eliminates sulfur-bearing compounds, thereby reducing environmental hazards [99]. The environmental benefits of pyrolysis are further underscored by its potential to convert plastic waste into valuable products, thus mitigating the release of hazardous materials and contributing to CE principles [102]. However, the environmental impact of pyrolysis is not entirely benign, life cycle assessments (LCAs) indicate that while pyrolysis is more environmentally beneficial than incineration or landfill, there is a need for more comprehensive studies to fully understand its sustainability and integration into waste management systems [103]. Moreover, the choice of catalysts and operating conditions, such as temperature and feedstock composition, significantly influences the pyrolysis process, affecting both the yield and environmental footprint of the resulting products [104,105]. The economic viability of pyrolysis is also promising, with studies showing potential profits from the production of pyro-oil, which can be used as a fuel with reduced emissions of harmful gasses like CO and NO_x, thus offering both economic and environmental advantages [106]. Overall, while pyrolysis presents a viable solution for plastic waste management, its success pivots on

optimizing synergistic interactions and addressing environmental considerations through comprehensive assessments and strategic process design.

4. Pyrolysis for Plastic Waste Management

Plastic waste is being more widely acknowledged as a promising material for pyrolysis because of its chemical characteristics, quantity, and ability to generate valuable products. The byproducts from plastic pyrolysis can then be further processed to create fuels and chemicals. This approach not only tackles the environmental concerns linked to plastic waste but also contributes to the CE by transforming plastic waste into valuable resources. In the following discussion, we examine the factors that make plastic waste a suitable choice for pyrolysis, with the backing of recent research findings.

Plastic waste, specifically polyolefins (PO) such as PE and PP, is widely available and possesses advantageous chemical characteristics for pyrolysis. These plastics exhibit a favorable hydrogen-to-carbon ratio, which facilitates the production of HCs during pyrolysis [63,66]. The analysis of plastic waste, both in terms of its immediate properties and its underlying causes, reveals that it has a high heating value. This means that it can be effectively used as a raw material for energy recovery through pyrolysis [63].

Pyrolysis can treat a diverse array of plastic materials, including those that are mixed and polluted, a task that is typically difficult for alternative recycling techniques. The ability to adapt is essential for effectively handling the varied makeup of plastic waste found in real-world scenarios [70,107]. The process produces valuable products, such as pyrolysis oils, that can be further processed into fuels like gasoline and diesel, as well as chemical feedstocks like olefins and aromatics. These products have diverse applications in multiple industries, hence improving the economic feasibility of the method [66,100,108].

4.1. Advancements and Challenges in Technology

The efficiency and quality of products derived from plastic waste have been enhanced by advancements in pyrolysis technology, including the utilization of catalysts and optimized reactor designs. Catalytic pyrolysis, for example, improves the production and characteristics of liquid fuels [109]. Although there have been significant breakthroughs, there are still obstacles that need to be addressed. These challenges include the requirement for pre-treatment to eliminate impurities and the development of universal upgrading procedures to enhance the quality of pyrolysis oils to be on par with fossil-derived feedstocks [110].

Although plastic waste shows potential as a suitable raw material for pyrolysis, there are some difficulties associated with the process. The intricate makeup of plastic waste, which includes additives and impurities, can have an impact on the quality of the pyrolysis products. Consequently, current research is dedicated to enhancing pre-treatment and upgrading methods in order to improve the quality of the product and the efficiency of the process. Moreover, the economic viability of pyrolysis operations on a wide scale relies on obtaining inexpensive raw materials and fine-tuning process variables to achieve the highest possible output and quality. Although there are difficulties, the possible advantages for the environment and economy make plastic waste a convincing material for pyrolysis.

4.2. Advancements in Pyrolysis Technology for Plastic Waste

Recent advancements in pyrolysis technology for plastic waste have focused on enhancing the efficiency and sustainability of converting plastic waste into valuable products. Catalytic pyrolysis has emerged as a promising method, with significant research dedicated to optimizing catalysts and reaction conditions to improve product yield and quality. For example, the use of metal-incorporated activated carbons, such as nickel and iron, has

shown superior catalytic activity, leading to higher yields of hydrogen and CNTs, which are valuable for various industrial applications [111]. Additionally, the development of biochar catalysts derived from waste biomass has demonstrated potential in enhancing gas yields, particularly methane and hydrogen, while reducing undesirable byproducts like benzoic acid [111]. The integration of catalytic systems, such as tandem catalysis, has also been explored to efficiently manage halogen-containing plastics, facilitating the upcycling of halogens into functional materials [112]. Moreover, advancements in thermo-catalytic pyrolysis have enabled the conversion of PO into liquid fuels, with the introduction of acid or base catalysts shifting the reaction mechanism to improve the yield and composition of liquid HCs [105,113]. These innovations are complemented by the exploration of new catalyst materials, such as metal carbonates, which have shown high conversion rates of waste polyolefins into liquid HCs, offering a sustainable alternative to fossil fuels [113]. Overall, these advancements highlight the potential of catalytic pyrolysis as a versatile and efficient technology for plastic waste management, contributing to the circular carbon economy by transforming waste into valuable chemical feedstocks and fuels [114].

Martínez-Narro et al. [111] investigated the catalytic advancements in plastic waste pyrolysis highlights the effectiveness of metal-incorporated activated carbons and zeolites in enhancing both yield and product composition. Metal-activated carbons, specifically those incorporating nickel (Ni) and iron (Fe), have shown significant catalytic activity, with Ni-AC yielding high amounts of hydrogen (4.24 wt%) and CNTs with smaller diameters (30 nm) and a yield of 34.5 wt%, while Fe-AC produces higher gas yields (68.8 wt%) and CNTs with larger diameters (60 nm). This differentiation suggests that Ni-AC is more suitable for hydrogen and CNT production, whereas Fe-AC could be optimized for gas production. Additionally, the zeolite HZSM-5 catalyst emerged as particularly effective for monomer recovery, achieving the highest gas yields (78 wt%) by converting heavy plastic fractions into lighter monomers such as C_2H_4 and C_3H_6 . These findings indicate that advanced catalysts, tailored to specific outputs, can significantly enhance the efficiency and value-added potential of plastic waste pyrolysis processes.

Singh [113] investigated and highlighted important advancements in the pyrolysis of waste PO, such as LDPE, HDPE, and PP, into valuable liquid HC, leveraging $MgCO_3$ as a catalyst. This approach demonstrated a high conversion efficiency, achieving a 92% transformation of PO into liquid HC, with an additional 7.52% recovery of light gasses and only 0.48% residue. The high efficiency underscores the potential of $MgCO_3$ -catalyzed pyrolysis to convert substantial portions of waste plastics into usable petrochemical products. Analysis of the resulting HC revealed a varied composition, including both aliphatic and aromatic compounds, alongside functional groups like alcohols, acetates, and esters. This diversity suggests that the liquid products are well suited for multiple applications, as feedstock in petrochemical industries, as alternative automotive fuels, and as inputs for diesel furnaces. The findings indicate that $MgCO_3$ -catalyzed pyrolysis could play a critical role in developing sustainable waste-to-energy solutions, aligning with the broader objectives of reducing plastic waste and providing renewable energy sources.

Zhang et al. [115] investigated and presented an innovative approach to the upcycling of PO, particularly LDPE, through microwave-assisted catalytic pyrolysis, addressing the challenge of processing these common plastics due to their chemically inert $C(sp^3)$ - $C(sp^3)$ bonds. Utilizing a novel porous ternary NiFeAl-T composite catalyst as a microwave absorber, the process efficiently converts LDPE into valuable products, including hydrogen and MWCNTs. Optimizing the calcination temperature of the catalyst emerged as a key factor, as lower temperatures enhance metal-metal interactions and form porous structures with improved microwave absorption and energy dissipation, which are critical for breaking C-C and C-H bonds. The optimized NiFeAl-450 catalyst achieved a high

hydrogen yield of 60.5 mmol per gram of LDPE, with 85.1 vol% H₂ concentration, indicating highly efficient conversion. The process also produced MWCNTs, which have various industrial applications, further increasing the process's value. Stability tests confirmed the catalyst's durability, showing consistent hydrogen and MWCNT yields in repeated cycles, highlighting its potential for industrial use. These findings indicate that microwave-assisted catalytic pyrolysis could be a transformative solution for plastic waste management, converting waste into high-value products while reducing environmental impact and promoting sustainable resource recovery.

Paucar-Sánchez et al. [116] investigated and explored catalytic pyrolysis as a promising method to convert post-consumer plastic waste into usable fuels, addressing environmental concerns by transforming waste into valuable energy resources. Catalytic pyrolysis involves the thermal decomposition of plastics in the presence of a catalyst, which accelerates the breakdown of complex polymers into simpler HCs suitable for fuel production. The choice of catalyst is critical, as it affects both the conversion efficiency and the fuel quality, with an emphasis on selecting catalysts that maximize yield and produce fuel products with properties like conventional fossil fuels. The results confirm that catalytic pyrolysis can efficiently convert mixed plastic waste into liquid fuels, viable for energy applications, highlighting the dual benefit of reducing plastic pollution and offering a renewable energy source. Environmentally and economically, this approach not only provides a sustainable alternative to fossil fuels but also supports circular waste management principles. The research findings demonstrate significant potential, further research is essential to optimize catalyst performance and scale the process, with prospects for integrating catalytic pyrolysis into existing waste management frameworks to enhance sustainability and energy recovery.

Nazarloo et al. [60] investigated and introduced an innovative approach to plastic waste management by utilizing activated carbon derived from Waste Cotton Fabric (WCF) as a catalyst, addressing both plastic and bio-based waste in a sustainable manner. The activated carbon was synthesized from WCF using H₃PO₄ as an activating agent, with the careful optimization of the impregnation ratio and activation temperature to enhance its catalytic properties. When applied as a solid acid catalyst in the pyrolysis of LDPE, the activated carbon reduced the degradation temperature of LDPE by 12 °C, indicating an efficient catalytic performance. This process led to a high yield of fuel-range HC, notably carbocyclic compounds, with light aromatics such as benzene, toluene, and xylene comprising up to 43% of the output. Moreover, the process demonstrated selectivity by reducing the yield of heavier hydrocarbons beyond C₁₁, essential for the efficient production of specific fuel products. Aligned with CE principles, this method promotes resource efficiency by reusing bio-based waste as an eco-friendly catalyst, highlighting its dual role in waste management and sustainable energy recovery. The study suggests future research opportunities in optimizing catalyst properties and expanding the approach to other plastic wastes, positioning WCF-derived activated carbon as a viable, sustainable solution for plastic waste management and energy production.

Aisien et al. [117] examined the pyrolysis of WPP, using both thermal and catalytic methods to convert plastic waste into valuable HC. In the catalytic process, a spent FCC catalyst was utilized to enhance the breakdown of WPP, with experiments conducted in a batch reactor across various temperatures (300 °C, 350 °C, 375 °C, and 400 °C) and catalyst-to-plastic ratios (5, 7.5, and 10 wt%). Thermal pyrolysis alone yielded 83.3 wt% liquid oil, 13.2 wt% gasses, and 3.0 wt% char, indicating an effective conversion of WPP into liquid fuel. However, with the FCC catalyst, the liquid oil yield decreased to 77.6 wt%, while gas yield increased to 19.7 wt%, reflecting the catalyst's influence in promoting lighter HC formation. The analysis of the liquid oil from catalytic pyrolysis using GC-MS revealed a broad range of HC, spanning C₄ to >C₁₇, with compositions like gasoline and diesel,

30.83% paraffins, 44.6% olefins, 19.44% naphthalene, and 5.13% aromatics. These results suggest that catalytic pyrolysis with FCC catalysts can yield fuel-grade HC, offering a sustainable way to manage plastic waste and produce alternative fuels. The increased gas yield observed in catalytic pyrolysis implies potential for process optimization to target specific HC types, enhancing its utility in energy recovery and waste management.

Yim et al. [118] investigated and presented the environmental issues associated with wax, a persistent and potentially toxic byproduct of plastic waste pyrolysis, by exploring its catalytic conversion into valuable BTEX compounds (benzene, toluene, ethylbenzene, and xylene). The process employs zeolite-based catalysts, particularly HZSM-5, known for its balanced Brønsted and Lewis acid sites and microporous structure, which favor BTEX formation. Two types of waxes were examined, such as spent wax (SW) from plastic waste pyrolysis and commercial paraffin wax (PW). Results indicated that SW produced higher oil (54.9 wt%) and BTEX (18.2 wt%) yields compared to PW (32.3 wt% and 14.1 wt%, respectively), likely due to SW's lighter HC, accessing the catalyst's active sites more readily for cracking and isomerization reactions. Additionally, modifying HZSM-5 with gallium (Ga) further enhanced oil and BTEX yields by 2.24% and 28.30%, respectively, through the introduction of new Lewis's acid sites that adjusted catalyst acidity. Environmentally and economically, this study highlights a feasible method of converting harmful wax into valuable chemicals, contributing to pollution reduction and carbon capture. The research suggests future directions in catalyst optimization, varied feedstock exploration, and economic analysis in order to advance sustainable waste conversion processes, positioning catalytic pyrolysis as a viable solution for environmental and economic challenges.

Abnisa [119] investigated the use of natural mineral catalysts to enhance the pyrolysis of mixed plastic waste for liquid fuel production, comparing the effectiveness of bentonite with that of HZSM-5, a commonly used zeolite catalyst. The results demonstrate that both catalysts improved liquid yield, with bentonite achieving a higher yield of around 60% compared to HZSM-5's 56%, significantly surpassing the 42.55% yield obtained from uncatalyzed thermal pyrolysis. Both catalysts also minimized tar formation and completely eliminated wax, thus producing cleaner liquid fuels. Bentonite was particularly effective in increasing alkanes and alkenes, resulting in a higher-quality liquid fuel with desirable aromatic and aliphatic components. Optimal pyrolysis conditions were identified at 500 °C, with 1 g of bentonite used per 200 g of plastic feedstock, maximizing liquid yield and minimizing undesirable byproducts. This research highlights the environmental and economic advantages of using bentonite, a cost-effective natural mineral catalyst, in sustainable plastic waste management, offering an efficient pathway to cleaner fuel production. These findings reveal the potential of natural catalysts to produce valuable liquid fuels while addressing plastic waste challenges in an economically and environmentally viable manner.

4.3. Case Studies of Successful Pyrolysis Implementation for Plastic Waste

Pyrolysis has emerged as a promising method for plastic waste management, with successful implementation across various regions. In India, a pyrolysis system was developed to convert waste plastics into oil and diesel, offering a cost-effective alternative to traditional fuels. This system demonstrated the potential to extract 10–20 mL of oil from 180 to 380 g of plastic waste, highlighting its viability as a sustainable energy source [120]. In Korea, the government has recognized the potential of pyrolysis under the concept of an 'urban oil field,' aiming to increase the treatment of waste plastic through pyrolysis from 0.1% in 2021 to 10% by 2030. This initiative is part of a broader strategy to enhance the eco-friendliness of waste management practices by using pyrolysis as a complementary method to physical recycling [121]. In Italy, the COREPLA consortium conducted pyrolysis tests on plastic solid waste, excluding PET, PVC, and PTFE, using γ -alumina as a catalyst. These

tests revealed that higher pyrolysis temperatures increase the yield of gas and condensate products, which are primarily long-chain aliphatic hydrocarbons similar to diesel [122].

Additionally, a study in the United States analyzed the life cycle impacts of converting post-use plastics into new plastics via pyrolysis, demonstrating significant reductions in greenhouse gas emissions compared to traditional end-of-life management practices. The LCA revealed that using post-use plastics (PUPs) in pyrolysis to produce HDPE and LDPE results in significant reductions in GHG emissions. Specifically, for a 5% substitution rate (SR) of pyrolysis oil with fossil-derived feedstocks, there was a 23% decrease in GHG emissions for HDPE and an 18% decrease for LDPE compared to virgin plastic. In contrast, a 20% SR only showed a 4% reduction for HDPE and a 3% reduction for LDPE due to the additional hydrotreating step required to remove chlorine from the pyrolysis oil. The study indicated that GHG emissions from PUP pyrolysis could be further reduced by 50% in the United States and 131% in the European Union if the emissions from current PUP incineration practices were accounted for as emission reduction credits, highlighting the potential for advanced recycling technologies to contribute to climate change mitigation [123].

Basransyah et al. [124] investigated and established that the total waste generation in Pananjung Village, Indonesia, a beach tourism destination, is 5387.83 kg/day, with a significant portion of this waste coming from non-domestic sources such as hotels, restaurants, and tourists. The composition of plastic waste accounts for 10.11% of the total waste, which includes both recyclable and non-recyclable plastics. The research identified that recyclable plastics include PETE, HDPE, PP, and PE, while non-recyclable plastics consist of plastic bags, PS, and other types of plastic. The study suggests that non-recyclable plastic bags can be effectively managed through pyrolysis technology, which converts them into fuel oil, categorized as gasoline, with HC chains ranging from C5 to C12.

Mibei et al. [125] indicated that indigenous clay from Kisumu County, Republic of Kenya, was successfully used as a catalyst for the catalytic pyrolysis of plastic waste, resulting in high liquid fuel yields. The study showed that the liquid fuel produced from waste plastics using the local clay catalyst can be utilized as an alternative fuel source for industrial applications, such as in diesel engines and turbines for electricity generation, and as a heating source in boilers and furnaces.

Javed et al. [126], from Pakistan, studied this topic and found that the pyrolysis of five commonly used plastics (PET, HDPE, LDPE, PP, and PS) resulted in high yields of fuel conversion, with HDPE showing the highest yield at 82%, followed by PP (61.8%), PS (58.0%), LDPE (50.0%), and PET (11.0%). The calorific values of the derived fuels were comparable to those of conventional fossil fuels, indicating their potential as viable alternatives for energy needs. The research demonstrated that the pyrolysis products contained alkanes and alkenes with carbon number ranges suitable for fuel applications, and the process was conducted in a cost-effective manner, making it applicable to small-scale and industrial replication in developing countries like Pakistan. This approach could significantly contribute to addressing energy shortages and plastic waste management issues.

Omol et al. [127] from Gulu Municipality, Uganda, found that catalytic pyrolysis is more efficient than purely thermal pyrolysis for the production of fuel oil from PE plastic wastes. Specifically, the use of aluminum chlorides on activated carbon yielded the highest amount of oil (105 mL), at a maximum temperature of 400 °C, compared to the yield of 100 mL from acid-activated clay mineral and 88 mL from purely thermal pyrolysis. The research highlighted how the degradation of plastics occurs at lower temperatures during catalytic pyrolysis, making it a more economically feasible method. Acid-activated clay mineral was identified as a good heterogeneous catalyst that is recoverable after use, posing

no environmental threats, unlike the homogenous catalyst (aluminum chlorides), which is unrecoverable and has negative disposal impacts.

Tulashie et al. [128], from Ghana, investigated this and found that the pyrolysis of mixed plastic waste at 350 °C for 2 h resulted in the production of crude fuel oil, which contained 21 functional groups predominantly made up of aliphatic compounds, indicating its potential as a viable alternative fuel source. Analytical methods such as FT-IR and GC-MS revealed that the fuel oil produced falls within the diesel fuel range (C12–C24), with behenic alcohol being the most abundant compound, and it has a kinematic viscosity of 1.036 mm²s⁻¹, which decreases with increasing temperature, suggesting its suitability for various applications.

A summary of plastic pyrolysis data from the recent literature is presented in Table 5.

Table 5. Summary of plastic pyrolysis data from recent literature.

Type of Plastic	Reactor	Catalyst	Process Parameters			Output Products	Literature
			Temperature (°C)	Pressure (bar)	Duration (min)		
Both pure and waste LDPE	High-pressure batch reactor	HZSM-5	400	4.5, 6.5, 7	-	40.3% for waste LDPE and 43.5% for pure LDPE	[61]
Used PPE gowns made of PP	-	ZnO/CNT hybrid nanocomposite, ZSM-5 catalyst	300 °C, 465, 550	-	60 min	Char, Oil and Syngas	[96]
A. Biodegradable plastics: PLA and PHBH B. Common petroleum-based plastics: HDPE, PP, and PS	Batch reactors	-	Decomposition of PLA and PHBH occurs at 273–378 °C, while HDPE, PP, and PS decompose at 386–499 °C	-	-	Pyrolyzates	[129]
LDPE	Fluidized bed reactor (FBR)	Fluid catalytic cracking (FCC)	500, 550, 600	-	-	Olefins, waxy oil	[130]
PS, PP, and LDPE	Microwave reactor	Iron in different forms (powder and coil)	500	-	30	Oil waxy and viscous	[84]
Pelletized PP	Bubbling Fluidized Bed (BFB) reactor	-	512 to 551	-	-	Oil contained low (C1–C12) and middle (C13–C22) carbon number, Syngas and Char	[131]
PE, PP, PS, and PET	Two-stage fixed bed reactor	Ni/Al ₂ O ₃ (nickel on alumina)	-	-	-	PS yielded the highest solid carbon (32.24 wt%), PE produced the most gas (39.45 wt%) and least liquid (28.95 wt%), while PE and PP formed high-purity MWCNTs, and PET's oxygen content hindered CNT growth.	[132]

5. Benefits of Pyrolysis in the African Context

Plastic pyrolysis presents a promising solution with which to mitigate plastic pollution and contribute to a cleaner environment by converting non-degradable plastic waste into valuable fuels and chemicals. This thermochemical process involves the decomposition of plastic waste at high temperatures in the absence of oxygen, resulting in the production of pyrolysis oil, solid wax, and non-condensable gasses [133]. The process is advantageous over traditional waste management methods like incineration and landfilling, which are costly, inefficient, and environmentally harmful due to emissions of pollutants and GHGs [133]. Pyrolysis not only reduces the volume of plastic waste but also recovers energy and materials, aligning with the principles of a circular economy [26,122]. Recent

advancements in pyrolysis technology, such as microwave co-pyrolysis and catalytic pyrolysis, have improved the efficiency and quality of the products. For example, the microwave co-pyrolysis of polystyrene and polypropylene has achieved high oil yields with significant heating values, demonstrating its potential for high-quality fuel recovery [134]. Catalytic pyrolysis, using catalysts like HZSM-5, enhances the conversion of plastic waste into valuable chemicals such as BTEX (benzene, toluene, ethylbenzene, and xylene), which are crucial for industrial applications [68,118]. To address Africa's unique challenges, recent advancements in catalyst design have prioritized the use of locally available materials, such as agricultural residues and industrial byproducts, to develop eco-friendly and cost-effective catalysts [59–61]. These innovations enable operation under milder conditions, reducing energy demands and adapting to regions with limited resources, thereby aligning with Africa's ecological and economic context. Moreover, the integration of depth filtration techniques can further purify pyrolysis oils, making them suitable for use in petrochemical processes [135]. The production of MWCNT and hydrogen through pyrolysis–catalysis also highlights the potential to generate high-value materials and energy carriers, contributing to sustainable development [26]. Overall, plastic pyrolysis offers a viable pathway to reduce plastic pollution, recover resources, and support environmental sustainability, although challenges such as catalyst optimization and process scalability remain areas for future research [72,104].

5.1. Economic Potential of Pyrolysis

Pyrolysis presents significant economic potential through job creation, energy production, and reduced waste management costs. The process of pyrolysis, which involves the thermal decomposition of waste materials in the absence of oxygen, is increasingly recognized for its ability to convert waste into valuable energy resources, thereby addressing both environmental and economic challenges. For example, in rural India, pyrolysis-based bioenergy development has been shown to be economically feasible, with potential profitability reaching up to 90% and a benefit–cost ratio of 1.35–1.75, while also reducing the global warming potential by 350 kg of CO₂-eq per capita annually [136]. In Australia, the pyrolysis of waste plastics can achieve a 54% return on investment, highlighting its economic viability when waste is collected and processed efficiently [137]. Similarly, in South Africa, a waste tire pyrolysis plant is projected to be sustainable, with a payback period of approximately five years, emphasizing the importance of stable product markets [138]. The economic feasibility of pyrolysis is further supported by studies in Brazil, where the production of biofuels from municipal waste shows promising financial metrics such as a net present value and an internal rate of return, indicating investment viability over a ten-year horizon [139]. Additionally, the use of microwave vacuum pyrolysis for processing waste plastic and used cooking oil has demonstrated low production costs and the potential for producing cleaner liquid fuels, which are economically competitive with conventional diesel [140]. These examples illustrate that pyrolysis not only contributes to energy production and waste reduction but also offers substantial economic benefits, including job creation in the construction and operation of pyrolysis plants, and reduced costs associated with waste management by diverting waste from landfills and generating revenue from energy and material recovery [72,141,142]. Overall, the integration of pyrolysis into waste management systems can significantly enhance economic sustainability while addressing pressing environmental issues.

5.2. Social Benefits of Plastic Pyrolysis

Plastic pyrolysis offers several social advantages, notably in improving public health and enhancing community awareness and participation. By converting plastic waste into

valuable fuels and chemicals, pyrolysis addresses the pressing issue of plastic pollution, which poses significant environmental and health risks due to its non-biodegradable nature and potential to release harmful substances into ecosystems [143,144]. The process of pyrolysis not only reduces the volume of waste in landfills but also mitigates the pollution of oceans and other natural habitats, thereby contributing to a cleaner environment and reducing health hazards associated with plastic waste [72,145]. Moreover, the production of fuels such as gasoline, diesel, and kerosene from waste plastics through pyrolysis provides an alternative energy source, which can alleviate the dependency on fossil fuels and contribute to energy security [145,146]. This transition to a CE model, where waste is transformed into resources, promotes community engagement and awareness as individuals and organizations become more involved in sustainable waste management practices [122]. Additionally, the economic benefits of pyrolysis, such as job creation in recycling and energy sectors, can enhance community participation and support for environmental initiatives [147]. The integration of pyrolysis into waste management systems also encourages educational programs and public awareness campaigns, promoting a culture of sustainability and responsible consumption [102]. Overall, plastic pyrolysis not only offers a technical solution to waste management but also serves as a catalyst for social change, encouraging communities to participate actively in environmental conservation efforts.

6. Challenges and Limitations

6.1. Technological Barriers

Plastic pyrolysis, a promising technology for converting waste plastics into valuable products, faces several challenges related to efficiency, scalability, and maintenance. One significant challenge is the economic viability of pyrolysis plants, which is heavily influenced by economies of scale. Larger plants can reduce costs, but they require consistent feedstock quality and availability, which is often difficult to secure due to the heterogeneous nature of plastic waste [148,149]. The quality of the pyrolysis oil is another concern, as it often contains contaminants that exceed industrial specifications, necessitating extensive upgrading processes such as dechlorination and hydro-processing to make the oil suitable for use in steam crackers and other applications [150,151]. Technological challenges also include optimizing the pyrolysis process to achieve high yields of liquid fuels with good quality, which is complicated by the need for advanced catalysts and process conditions [152,153]. The presence of certain plastics, like polyvinyl chloride, can introduce harmful byproducts such as chlorine gas, which can corrode equipment and complicate maintenance [154]. Moreover, the integration of pyrolysis units into existing industrial frameworks requires the significant pre-treatment of waste plastics, including sorting and dehalogenation, to ensure a stable and predictable feedstock [150]. The development of predictive modeling tools, such as those based on CFD-DEM, is still in its infancy for plastic pyrolysis, posing additional challenges in understanding and optimizing the process [155]. Finally, the high energy consumption associated with conventional pyrolysis methods limits economic feasibility, although emerging techniques like induction heating show potential for reducing energy use and improving process efficiency [69]. Overall, while plastic pyrolysis offers a pathway to a circular economy, overcoming these challenges is crucial for its successful commercialization and widespread adoption.

6.2. Economic Constraints

The financial challenges associated with the plastic pyrolysis process are multifaceted, primarily revolving around high initial investment costs and the necessity for subsidies or incentives to ensure economic viability. The initial investment in pyrolysis plants is substantial due to the need for robust and scalable technology to handle complex plastic

waste streams, such as those from automotive sources, which often yield lower quality pyrolysis oil compared to standard thermoplastics [149]. Economies of scale play a crucial role in reducing costs, with larger plants benefiting from lower cost-covering minimum sales prices for pyrolysis oil. However, these large-scale operations face challenges in securing consistent and affordable feedstock, maintaining feedstock quality, and ensuring the quality of the pyrolysis oil produced [149]. The high cost of waste plastic feedstock and operational expenditures, such as skilled labor and utility fees, further exacerbate the financial burden, making the process economically unsustainable without external financial support [156]. Subsidies and incentives are critical to offset these costs and make pyrolysis competitive with traditional fossil fuels. For example, additional revenue streams, such as gate fees or subsidies, are necessary to achieve positive business case, with required additional revenues varying significantly depending on plant capacity [149,156]. The economic feasibility of pyrolysis is also sensitive to factors like feedstock costs, pyrolysis gas sales, and waste disposal costs, which can significantly impact profitability [157]. Moreover, the development of advanced catalysts and process optimization through machine learning could potentially reduce costs and improve the economic outlook of pyrolysis [153]. Despite these challenges, the potential for pyrolysis to contribute to a circular economy by converting plastic waste into valuable resources remains significant, provided that financial hurdles are addressed through strategic investments and policy support [152].

6.3. Regulatory and Policy Issues

The regulatory landscape in African countries significantly impacts the implementation of plastic pyrolysis technology, primarily due to the challenges associated with existing waste management systems and policy enforcement. Africa generates approximately 17 million tons of plastic waste annually, with ineffective regulations and poor governance contributing to the mismanagement of this waste [6,29]. While some African nations have introduced plastic bans, the success of these measures varies widely, with countries like Rwanda seeing positive outcomes, whereas others struggle with enforcement and a lack of alternatives [8]. The continent's waste management infrastructure is often inadequate, which complicates the adoption of advanced technologies like pyrolysis. Pyrolysis offers a promising solution by converting plastic waste into valuable products, such as the use of fuel and raw materials for new plastics, and is seen as an environmentally sound alternative to incineration and landfilling [121,158]. However, the technology's implementation in Africa faces hurdles due to the need for processes that are safe, robust, efficient, and low-cost, which are essential in regions where the average daily wage is less than USD 3. Moreover, the lack of comprehensive and holistic legislation, as seen in countries like Cameroon, further hinders the effective regulation of plastic pollution and the adoption of innovative solutions like pyrolysis [159]. Despite these challenges, there is potential for pyrolysis to complement existing recycling methods, particularly for plastics that are difficult to recycle physically [121]. To enhance the implementation of pyrolysis technology, African countries need to develop specific regulations that support recycling initiatives and address the socio-economic and environmental challenges associated with plastic waste management [158]. This requires international collaboration, increased public awareness, and investment in infrastructure to create a conducive environment for sustainable waste management solutions [6].

6.4. Public Perception About Pyrolysis

Public perception in Africa regarding plastic waste and pyrolysis waste-to-energy technologies is shaped by a combination of environmental concerns, technological potential, and socio-economic factors. Africa faces significant challenges with plastic waste manage-

ment due to inefficient waste collection systems and limited recycling capabilities, which exacerbate pollution problems across the continent [160]. Despite these challenges, there is growing awareness and engagement among the youthful population in Africa, who are increasingly adopting technologies aimed at improving quality of life and environmental sustainability [160]. Pyrolysis, a thermochemical process that converts plastic waste into energy, is seen as a promising solution to these challenges. It offers a way to manage plastic waste effectively while producing valuable energy resources, such as pyro-oils, which have properties similar to those of conventional fuels like diesel [72,161]. The potential for pyrolysis to contribute to a circular economy is particularly appealing in Africa, where there is a strong push towards sustainable waste management practices [13,160]. However, the success of such technologies depends heavily on public acceptance, which is influenced by factors such as social trust and health consciousness. Studies have shown that while social trust does not directly correlate with public support for waste-to-energy projects, it affects acceptance through attitudes, and health consciousness is positively associated with public approval [162]. In Ghana, for example, the integration of pyrolysis into a hybrid waste-to-energy facility has been proposed as a viable solution for urban waste management, highlighting the economic and environmental benefits of such technologies [163]. Overall, while there is a positive trend towards embracing waste-to-energy technologies in Africa, the implementation of these solutions requires the careful consideration of public perception, policy support, and technological adaptation to local contexts [13,160].

7. Policy Recommendations and Strategic Actions

7.1. Policy Framework

To support the adoption of plastic pyrolysis, several policy changes and frameworks are necessary, focusing on technological, economic, and environmental aspects. Firstly, regulatory frameworks should incentivize the development and deployment of pyrolysis plants by providing subsidies or tax breaks for companies investing in this technology, as it offers a viable alternative to traditional waste management methods like landfilling and incineration [164,165]. Policies should also encourage research and development in catalytic pyrolysis, which has shown promise in enhancing the efficiency and output quality of pyrolysis processes, thereby supporting the circular carbon economy [114]. Moreover, the standardization of feedstock preparation, such as sorting and cleaning of waste plastics, is crucial to optimize the pyrolysis process and ensure consistent product quality [66,122]. Governments could establish guidelines for the collection and sorting of plastic waste to facilitate its conversion into valuable products like fuels and chemicals [146]. Additionally, creating a market for pyrolysis-derived products by setting minimum recycled content requirements in new plastic products could drive demand and improve the economic viability of pyrolysis [165,166]. Environmental regulations should also be updated to recognize the lower emissions profile of pyrolysis compared to incineration, thus promoting its adoption as a cleaner alternative [164,167]. Finally, public-private partnerships could be promoted to build the necessary infrastructure and share the financial risks associated with scaling up pyrolysis technologies [165,168]. By implementing these policy changes, the adoption of plastic pyrolysis can be significantly accelerated, contributing to sustainable waste management and energy production.

7.2. Incentives and Funding

To encourage investment in pyrolysis technology, a combination of financial incentives, subsidies, and funding mechanisms can be strategically implemented. One effective approach is the introduction of tax credits, such as the Cellulosic Biofuel Producer Tax Credit (CBPTC), which has been shown to significantly enhance the Internal Rate of Return

(IRR) for pyrolysis facilities by offsetting production costs and increasing profitability [169]. Additionally, subsidies that support the development of large-scale pyrolysis plants can help to achieve economies of scale, thereby reducing the cost-covering minimum sales prices of pyrolysis oil, which is crucial for economic viability, especially when dealing with complex waste streams like automotive plastics [149]. Implementing gate fees for waste management can also provide an essential revenue stream, making pyrolysis more competitive with traditional fossil fuels [149]. Moreover, funding mechanisms that support research and development can address technological barriers and improve the scalability and efficiency of pyrolysis processes, as seen in the roadmap for catalytic pyrolysis, which aims to integrate this technology into biorefinery networks [114]. Investment in mobile pyrolysis units can also be incentivized to reduce transportation costs and improve the business case for agricultural and forestry residue conversion. Moreover, aligning pyrolysis projects with waste management policies that prioritize circular economy principles can enhance their environmental and economic viability, as demonstrated by the potential of pyrolysis to convert municipal solid waste into valuable energy sources [142,170]. Finally, public–private partnerships and government-backed loans can provide the necessary capital for initial investments, ensuring that pyrolysis technology can be effectively integrated into existing waste management and energy systems [171]. These combined strategies can create a conducive environment for the widespread adoption and commercialization of pyrolysis technology, ultimately contributing to sustainable waste management and energy production.

7.3. Capacity Building: Training and Knowledge Sharing Initiatives

Capacity-building initiatives in Africa, particularly in the realm of plastic pyrolysis, are crucial for addressing the continent's pressing environmental and economic challenges. The need for such initiatives is underscored by the growing problem of plastic waste pollution, which is exacerbated by the inadequate waste management infrastructure in many African countries [12]. Plastic pyrolysis, a promising technology that converts plastic waste into valuable fuel, offers a sustainable solution but requires significant capacity development to be effectively implemented in the Global South [172,173]. Training programs and knowledge sharing are essential components of capacity-building efforts, as they equip stakeholders with the necessary skills and understanding to manage and optimize pyrolysis processes [174]. The Chem4Energy consortium exemplifies successful capacity building through its collaborative research and training programs, which have advanced renewable energy applications and cross-disciplinary expertise [175]. However, the success of such initiatives also hinges on addressing mindset challenges, as a transformative mindset is critical for the effective implementation and sustainability of capacity-building programs in Africa [176]. Moreover, overseas scientific capacity-building programs, while beneficial, must be complemented by local efforts to retain expertise and ensure that the benefits are realized within African industries [177]. Ultimately, capacity-building initiatives must be comprehensive, incorporating training, mindset transformation, and infrastructure development to enable Africa to harness the full potential of plastic pyrolysis and contribute to sustainable development [178].

7.4. Strategies for Engaging the Public in Plastic Waste Management and Pyrolysis

To increase public awareness and engagement in plastic waste management and pyrolysis in Africa, a multifaceted approach is necessary, leveraging both technological advancements and community involvement. Africa's youthful population, which is open to adopting new technologies, presents a unique opportunity to test and implement innovative solutions for plastic waste management, such as pyrolysis, which is recognized for

its potential to convert plastic waste into valuable chemicals and energy [102,160]. Public participation is crucial, as demonstrated by studies in Lagos, Nigeria, where community engagement in waste management activities significantly reduced illegal waste disposal [179]. Providing information and resources, such as dumpsters and educational programs, can enhance community involvement, particularly among women and less educated households, who have shown a willingness to participate in cleanup activities [179]. Additionally, integrating waste management into a circular economy framework can optimize resource use and waste valorization, addressing socio-economic and infrastructural barriers [180,181]. Policies should focus on removing barriers to waste valorization by redistributing value within the business ecosystem, thus incentivizing stakeholders to engage in sustainable practices [35]. Moreover, the adoption of pyrolysis as a waste-to-energy technology can be promoted by highlighting its environmental benefits over traditional methods like incineration and landfill, as well as its ability to produce eco-energy [72,102]. The use of AI to optimize pyrolysis processes can further enhance its efficiency and appeal [102]. By combining these strategies, Africa can effectively increase public awareness and engagement in plastic waste management and pyrolysis, contributing to a more sustainable future.

8. Future Research Directions

8.1. Innovative Technologies: Future Research Directions in Pyrolysis

Future research in improving plastic pyrolysis technology and its applications should focus on several key areas. Firstly, the development of advanced catalyst systems, such as tandem catalysis, is crucial for enhancing the efficiency of halogen removal and the selective conversion of targeted products, which can facilitate the upcycling of halogen-containing plastics into high-value materials [112]. Additionally, optimizing the co-pyrolysis of plastics with biomass can improve the hydrogen-to-carbon effective ratio, leading to the production of higher-quality fuels and chemicals, such as aromatics and olefins, while reducing coke formation [66,182]. Research should also explore the potential of thermo-catalytic pyrolysis for scaling up liquid fuel production from polyolefins and polystyrene, focusing on optimizing parameters like temperature, residence time, and catalyst type to maximize energy recovery and product yield [105]. Moreover, the integration of innovative processes such as induction heating could enhance pyrolysis efficiency and yield, offering a promising route for converting plastics into valuable resources like batteries and nanomaterials [183]. The conversion of plastic waste into high-value carbon materials for applications in energy storage and water treatment is another promising area, necessitating the further exploration of pyrolysis routes and influence factors [88]. Moreover, the techno-feasibility of catalytic pyrolysis for producing high-value products like jet fuel and lubricants should be critically analyzed to bridge existing research gaps and facilitate commercialization [184]. Finally, collaborative efforts between governments, industries, and research institutes are essential to establish supportive regulatory frameworks and drive the development of sustainable plastic waste management technologies [185]. Overall, these research directions aim to enhance the efficiency, scalability, and environmental benefits of plastic pyrolysis, contributing to a more sustainable and circular economy.

8.2. Life Cycle Assessment: Evaluating Pyrolysis Sustainability

Conducting comprehensive life cycle assessments (LCAs) to evaluate the long-term sustainability of pyrolysis in Africa is crucial, given the continent's potential for biomass utilization and the need for sustainable energy solutions. Pyrolysis, a process that converts biomass into biofuels, biochar, and other valuable products, has been extensively studied for its environmental and economic impacts. For example, the LCA of biomass pyrolysis highlights the importance of considering the entire process, from biomass pre-treatment to

product collection, to assess its sustainability and feasibility [186]. However, the variability in LCA methodologies, such as differences in functional units and system boundaries, complicates the comparison of results across studies [187]. In Africa, where agricultural residues and organic wastes are abundant, pyrolysis could play a significant role in addressing the food–energy–water nexus by producing biochar, which enhances soil fertility and sequesters carbon [188]. The environmental benefits of pyrolysis are further supported by studies showing significant reductions in CO₂ emissions when biochar is used in horticulture or when syngas is processed through chemical looping combustion [189,190]. Despite these benefits, challenges remain, such as the need for efficient feedstock collection and processing, which can be addressed by portable refineries and improved waste management systems [188]. Additionally, the choice of pyrolysis technology, whether conventional or microwave-assisted, impacts the environmental footprint, with conventional pyrolysis generally being more environmentally friendly [191]. To ensure the sustainability of pyrolysis in Africa, it is essential to integrate LCA with CE principles, focusing on the reuse of byproducts and minimizing environmental impacts [187]. Moreover, socio-economic implications, such as job creation and energy security, should be considered alongside environmental assessments to provide a holistic view of pyrolysis's potential in Africa [192]. Therefore, a comprehensive LCA approach, tailored to the specific conditions and resources of African countries, is necessary to evaluate and optimize the long-term sustainability of pyrolysis technologies on the continent.

8.3. Exploring Synergies with Waste and Renewable Energy Solutions

Integrating pyrolysis with other waste management and renewable energy technologies in Africa presents a promising opportunity to address both energy access and waste management challenges. Pyrolysis, a thermochemical process that converts biomass and waste into biochar, bio-oil, and gasses, can be effectively combined with other technologies to enhance energy recovery and environmental sustainability. For example, in Zimbabwe, integrating waste management practices with renewable energy initiatives is crucial for transitioning towards a CE, optimizing energy production, and addressing waste management challenges [193]. The integration of solar energy into pyrolysis units, as explored in the SPEAR project, offers a cost-effective solution for rural communities in Sub-Saharan Africa, producing biochar and electricity from agricultural waste [194]. Additionally, combining pyrolysis with anaerobic digestion can improve energy efficiency and methane production, as demonstrated by studies showing enhanced exergy efficiency in integrated systems compared to standalone processes [195]. In Ghana, a hybrid waste-to-energy facility incorporating solar PV, anaerobic digestion, and pyrolysis is proposed to treat municipal solid waste, potentially generating significant electricity and alternative fuels, thus supporting a CE [163]. Moreover, the use of solar thermal energy in pyrolysis, such as in the pyrolysis of waste tires, can reduce dependency on fossil fuels and improve economic viability [196]. These integrated approaches not only enhance the sustainability of waste management systems but also contribute to energy security and environmental protection, aligning with global sustainability goals [72]. Overall, the integration of pyrolysis with other technologies offers a multifaceted solution to Africa's energy and waste management challenges, requiring supportive policies and investments to realize its full potential.

To advance the effective implementation of plastic pyrolysis technology for managing plastic waste in African Continent and also the whole world, a multi-faceted approach is essential. This approach should integrate supportive policies, economic incentives, technological improvements, and community involvement. Policymakers should develop comprehensive regulatory frameworks, while financial incentives and public–private partnerships would help to mitigate initial investment hurdles. Investments in technological

research, capacity-building initiatives, and community education can further enhance the adoption of waste plastic pyrolysis. Public awareness campaigns must address misconceptions and promote community support. This investigation is proposing a framework for plastic waste management and converting plastic waste into energy, which is depicted in Figure 4. Implementing this framework can significantly reduce improper plastic waste management, contribute to energy production, and promote economic growth. This strategy aligns with the African Union’s recycling targets and can better position the continent for transitioning to a more sustainable and circular economy (CE).

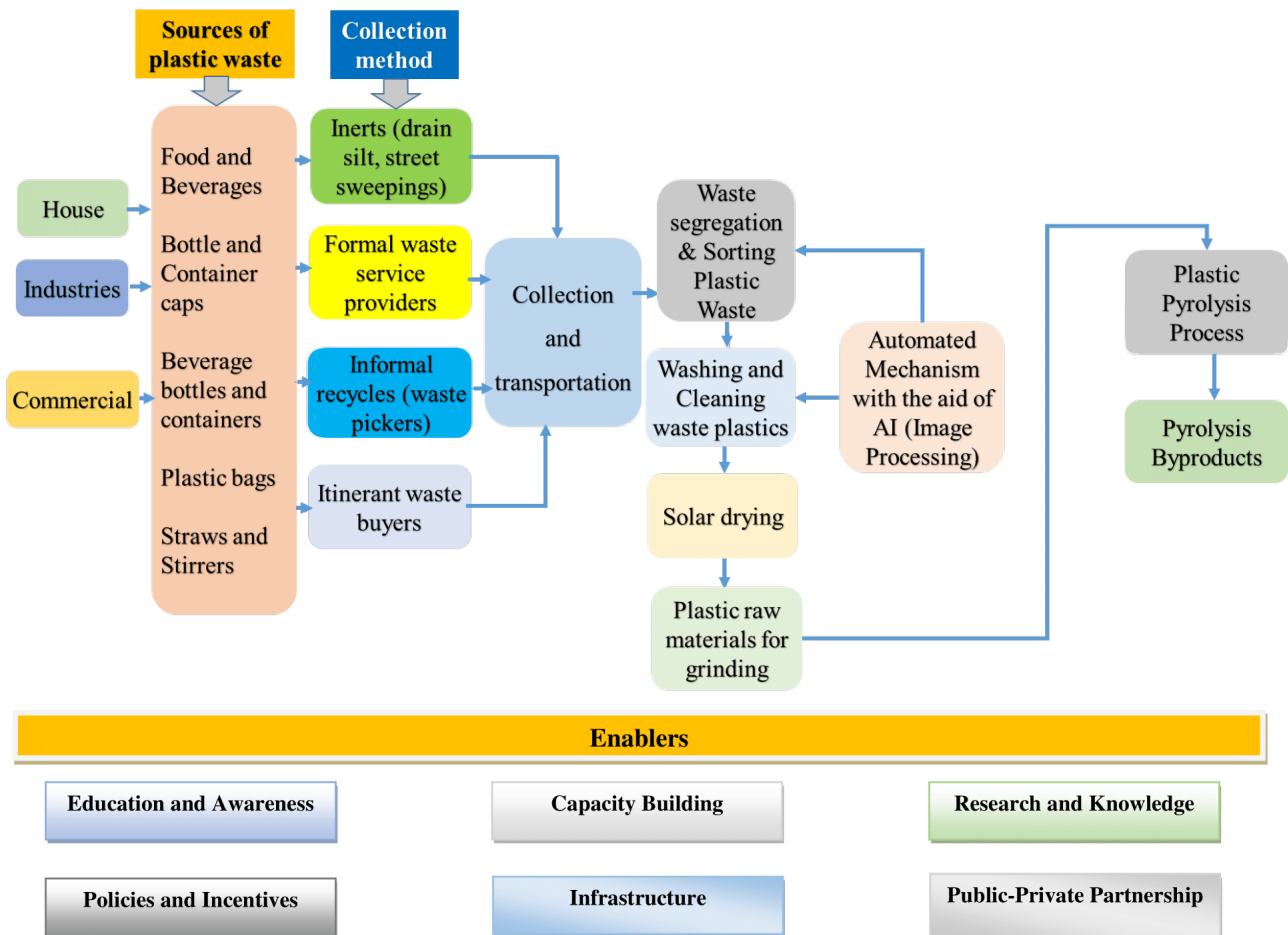


Figure 4. Proposed framework.

9. Conclusions

Africa’s plastic waste crisis, marked by the improper management of its plastic waste, underscores the urgency for sustainable solutions. The following are the key highlights of this review:

- This review identifies pyrolysis as a pivotal technology with which to address the growing plastic waste crisis in Africa. By converting plastic waste into valuable products such as pyrolysis oil, syngas, and char, pyrolysis provides a dual benefit of waste reduction and energy recovery. However, its successful implementation requires that critical barriers, including infrastructure deficits, financial constraints, and regulatory challenges, be addressed.
- Pyrolysis has demonstrated the potential to recover up to 85% of plastic waste as reusable byproducts, significantly reducing environmental pollution. Case studies reveal that pyrolysis can generate energy equivalent to conventional fossil fuels while

supporting circular economy (CE) principles and creating economic opportunities in waste management and energy sectors.

- To optimize pyrolysis for the African context, future research should prioritize the development of low-cost, energy-efficient reactor designs tailored to the region's needs. Additionally, life cycle assessments and techno-economic analyses are critical for understanding the long-term sustainability and scalability of pyrolysis technologies.
- Governments, private industries, and academia must collaborate to create enabling environments for pyrolysis. This includes regulatory support, financial incentives, and awareness campaigns to engage stakeholders in adopting pyrolysis as a sustainable waste management solution. Public-private partnerships can play a significant role in scaling pyrolysis infrastructure and fostering innovation.
- This review integrates the diverse literature on pyrolysis in the African context, providing a comprehensive understanding of its potential and challenges. By offering actionable insights and a roadmap for implementation, it contributes to bridging critical knowledge gaps and promoting sustainable plastic waste management in Africa.

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Nomenclature

Nomenclature	Description
PES	polyester
PE	polyethylene
PP	polypropylene
PO	polyolefin
PS	polystyrene
S	sulfur
PET	polyethylene terephthalate
HDPE	high-density polyethylene
LDPE	low-density polyethylene
PTFE	polytetrafluoroethylene
PETE	polyethylene terephthalate
PVC	polyvinyl chloride
SUP	Single-Use Plastic
PUP	Post-Use Plastic
CE	circular economy
Sq km	square kilometer
°C	degrees Celsius
°C/min	degrees Celsius per minute
mm ² s ⁻¹	square millimeters per second
C-O	carbon-oxygen
C-N	carbon-nitrogen
C-C	carbon-carbon

C ₂ H ₄	ethylene
C ₃ H ₆	propylene
HC	hydrocarbons
C(sp ³)-C(sp ³)	carbon–carbon bond where both carbon atoms are sp ³ hybridized
C-H	carbon–hydrogen
CO ₂	carbon dioxide
Ni-AC	nickel-activated carbon
Fe-AC	iron-activated carbon
CNTs	carbon nanotubes
MWCNTs	multi-walled carbon nanotubes
H ₂ /CO	hydrogen/carbon monoxide
Ni	nickel
Fe	iron
Wt%	weight percent
nm	nanometer
MT	million tonnes
mmol	millimole
HZSM-5	Hydrogen-form Zeolite Socony Mobil-5
MgCO ₃	magnesium carbonate
H ₃ PO ₄	phosphoric acid
PHBH	Poly(3-hydroxybutyrate-co-3-hydroxyhexanoate)
PVB	polyvinyl butyral
PLA	polylactic acid
FBR	fluidized bed reactor
BFB	bubbling fluidized bed
Ga	gallium
MSW	municipal solid waste
FCC	fluid catalytic cracking
WPP	Waste Polypropylene
NGOs	non-governmental organizations
WCF	Waste Cotton Fabric
SADC	Southern African Development Community
GC-MS	gas chromatography–mass spectrometry
COREPLA	Consorzio Recupero Imballaggi in Plastica
GHG	greenhouse gas
LCA	life cycle assessment
SPEAR	Solar Pyrolysis for Energy and Rural Development

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