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Enhancing circular economy and sustainable environmental practices: opportunities and challenges of tyre pyrolysis in Africa

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Enhancing Circular Economy and Sustainable Environmental Practices – Opportunities and Challenges of Tyre Pyrolysis in Africa

Abstract

Studies estimate that Africa's urban population is expected to triple over 40 years, from 395 million in 2010 to 1.339 billion in 2050. Challenges associated with increasing urbanisation and the rise of large cities in the African sub-region have potentially catastrophic consequences for the environment and the rich ecosystem. The growing population, particularly in most cities in Africa, has resulted in increasing demand for non-degradable consumable waste products, changes in lifestyle and consumption patterns, and rising demand for transportation and associated solid waste disposal problems, especially tyre waste. However, few studies have examined circular economy practices such as tyre pyrolysis to attenuate Africa's ever-increasing waste disposal challenges. Moreover, most of these studies failed to account for specific risk-based decision-making attributes in an integrated way, such as technology readiness, risk identification, carbon footprint analysis, supply chain and procurement factors, and financial risk quantification. As a result, to the best of our knowledge and understanding, research-based tyre recycling feasibility practices are limited and scattered. We contribute to the literature by providing systematic literature on tyre pyrolysis in Africa from 2008-2022 inclusive, covering 16 African countries. To address tyre waste in Africa, this chapter provides a 10-point strategy on how pyrolysis can be integrated into production plants and associated businesses to minimise tyre waste in Africa.

Keywords

Pyrolysis, tyre waste, circular economy, sustainable practices, Africa

1. Introduction:

With the increasing growth, studies forecast that the global population will increase significantly to around 12.3 billion by 2100 (Seto, 2010). The overuse of natural energy resources, particularly non-renewable ones, is one of several unsustainable practices linked to global overpopulation. Also, the global-north economic growth surge vis-a-vis the social-economic inequalities and environmental degradations in the global-south (north-south dichotomy) continue to exacerbate the global warming and climate change challenges (Seto et al., 2015). Overpopulation also accelerates the pace of urbanisation, consumption, transportation, and waste (Steffen et al., 2015). If economic development continues to base on a linear trend, it has been estimated that the world will need at least 30% more fresh water, 50% more food and 50% more energy (World Economic Forum, 2011; Albrecht et al. 2018), and society will demand unprecedented levels of natural resources and produce an extremely high volume of waste (Di Maio & Rem, 2015).

Africa is already facing more severe climate change than the rest of the world, despite bearing the least responsibility for the problem of climate change. With nearly one-fifth of the world's population today, Africa accounts for less than 3% of the world's energy-related carbon dioxide (CO₂) emissions and has the lowest emissions per capita of any region (Senyagwa, 2022). Nevertheless, Africans are already disproportionately experiencing the adverse effects of climate change, including water stress, reduced food production, increased frequency of extreme weather events and lower economic growth – all fuelling mass migration and regional instability.

Besides, while the world population is projected to grow to approximately 12.3 billion by 2100, the highest percentage of this growth will come from the Global South, particularly in Africa, Asia and Latin America (Abuzukhar, 2021; Ullah et al., 2021). Rapid population growth is usually associated with increasing urbanisation, demand, productivity and

consumption, and the like (Mokoele, 2018; Abuzukhar et al., 2021; Asma et al., 2021). These phenomena exacerbate the challenges faced by Africa in areas such as waste disposal, environmental degradation, and global warming. Since most of Africa's inhabitants continue to migrate to the cities in search of work and a better standard of living, transportation has become a necessity, not a privilege. Most Average and middle-income workers are now buying cars as their primary means of transport. Those who cannot afford to buy cars are now using public transport such as buses, motorbikes, and others. Therefore, Tyre waste disposal is a critical challenge facing most African cities, towns, councils, and individuals.

Despite these issues, accepted circular economy practices have proven to reduce wastes from food production, transportation, industrial, manufacturing, electronics, automobiles, construction, and design (Benachio et al., 2020; EMF, 2017; Jia et al., 2020) is lacking. In addition to these challenges, Africa has been used a dumping ground for electronic and industrial wastes. These antecedents have meant that several African governments continue to grapple with the challenges arising out of unsustainable practices of local and foreign businesses (Adams at al., 2018).

The main aim of this chapter is to discuss a circular economy practice that has been recognised in developing countries as plausible solutions to waste management in the transport sector. Whilst the widely used waste management programmes in China to recycle batteries and the use of e-buses is popular (EMF, 2019), the Western Cape Industrial Symbiosis Programme in South Africa (EMF, 2020) and water recycling practices in Indian companies (Sohal et al., 2022) are among few of the best practices Africa can learn from. To address tyre waste in Africa, this chapter answers the question of how pyrolysis can be integrated into production plants and associated businesses to minimise waste in Africa. Though there are multiple challenges, risks, and impacts for investors and stakeholders, pyrolysis presents the best pathway for dealing with tyre and transport waste in Africa.

The rest of the chapter is organised and proceeds as follows: the next section presents a systematic literature review to delineate what a pyrolysis production plant business entail. The subsequent sections would demonstrate how to implement pyrolysis by converting waste into alternative by-products and the associated challenges. A discussion of implications and areas for future research concludes the chapter.

1.1 Circular Economy

Circular economy is opposite to the linear economy with the fundamental logic of "make-use-throw" (Lacko et al., 2021). The critical premise of circular economy is "*the products of today are the materials of tomorrow at yesterday's price*" (Stahel, 2016, p. 437). Circular economy aims to reduce waste, maximise the use of natural resources, and regenerate economic systems (EMF, 2017). Recent development in circular economy specified the concept into 4R principles: reduce the consumption of primary energy and raw materials (Reduce), use by-products and waste as production inputs (Reuse), recycle water (Recycle) and redesign business models (Renew) (Vasiljevic-Shikaleska et al., 2017). In other words, it is an overall strategy of changing business models, management approaches and managerial mindsets to realise economic benefits with less reliance on drawing resources from natural resources (Murray, Skene, & Haynes, 2017). Adopting a circular economy can help firms and countries to meet better responsible production and consumption goals (i.e. Sustainable Development Goal 12).

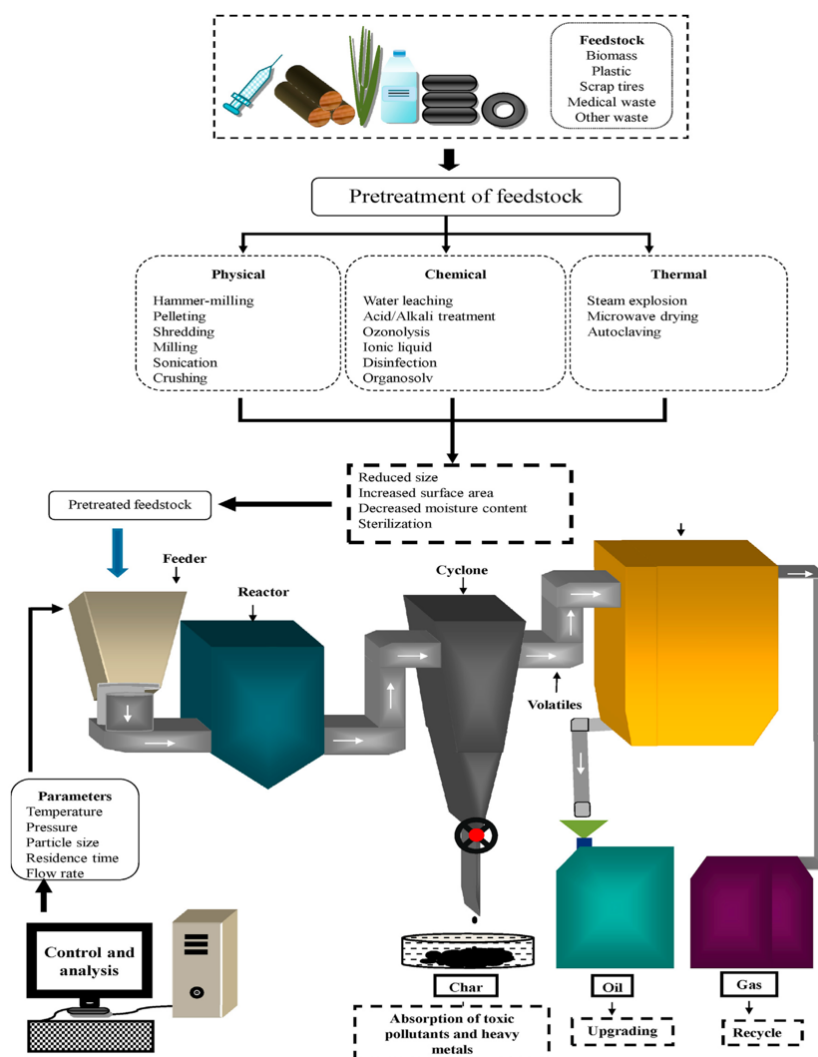
1.2 Waste Tyre Pyrolysis

The pyrolysis-circular economy recycling methodology (albeit a relatively new tyre recycling procedure in Africa) is gaining popularity as an effective measure of dealing with the challenges associated with the tyre waste disposal problems in Africa. Pyrolysis is a thermal decomposition process that converts used tyres into a solid residue (char), liquid oil (pyro-oil) and gas at temperatures between 300 and 900°C (Dick et al., 2020). More importantly, it causes

the feed materials to thermally decompose without using reactive gases, such as oxygen. As a result, its thermal efficiency can be improved from 70% to 90% if pyrolysis oil is further used in the thermochemical process (Nkosi & Muzenda, 2014). We use the conceptual model Zabaniotou et al. (2014) developed to illustrate how pyrolysis is implemented in practice in five key steps: pre-treat raw materials, slow pyrolysis, solid product activation, marketable end-product collection and energy recycling, as shown in Figure 1.

According to Zabaniotou et al. (2014), the pre-treatment of raw materials of end-of-life tyres (ELTs) pertains to steel chord removal and shredding. The primary equipment for preparing feedstocks is divided into two categories: ambient processing and cryogenic processing. Ambient processing of tyres is a common practice for raw material size reduction. Therefore, cryogenic grinding creates fragile, low-elastic particles by utilising liquid nitrogen and a low temperature (190 °C). On the other hand, slow pyrolysis can be made to run in batch or continuous mode. For smaller capacity, a batch pyrolysis system is typically implemented. The process cycle follows the loading of raw materials, pre-heating of the system, pyrolysis, temperature reset (cooling) and collection of end products. Slow pyrolysis often requires significant manual labour. Finally, the row material is processed by solid production activation, distinguished into different categories of marketable products and energy efficiency and optimisation.

Figure 1. Waste Pyrolysis Approach



Source: Chew et al. (2021) and Zabaniotou et al. (2014)

Figure 1 provides a generic view of the application of pyrolysis to waste. As such, the pre-treatment and post-treatment options cover a wide range of wastes. According to the authors, for tyres pyrolysis based on emergent commercial solutions, the following treatment methods are applicable:

Pre-treatment:

- De-wiring
- Washing
- Shredding – typically including wire typically to 20mm-150mm
- Crumbing (de-wired tyres) typically to 1mm – 5mm
- Metals removal (magnets)

Post-treatment:

- Volatiles:
 - Condensation (into 1 or more fractions)
 - Water separation
 - Centrifuge
 - Compression (gases)
 - De-sulphurisation (gases)
- Char:
 - Metals removal (magnets)
 - Milling, beading, and pelletising (if producing recovered Carbon Black).

The volatiles include non-condensing gases. These are typically used to deliver process heat for the pyrolysis reactor and post-treatment of the carbon char. The balance of the products (steel, oil, and carbon char) can be re-used.

As a result, pyrolysis is a circular economy practice that provides a reliable mechanism for dealing with the urgent tyre disposal challenges in the world, including Africa (Sohal et al., 2022), while adding value to potential investors and producing economic growth (employment, GDP, consumption, etc.). Thus, our systematic literature review of twenty-one studies on pyrolysis in 16 African countries from 2008-2022 offers critical references for adopting strategies for dealing with tyre waste disposal and providing decision-making support in Africa.

2. Systematic Literature Review

2.1 Data Sources

At the beginning of December 2022, a search using the Thomson Reuters' Web of Knowledge-based Web of Science, Google Scholar, and EBSCO was undertaken for a multi-year period (2008-2022) across 16 countries in Africa. The initial search criterion used was based on the words ' tyre pyrolysis' (OR ' tyre waste") AND 'circular economy' AND "Africa" in the title of the journal article relating to this multi-year period. Initial searches yielded 125 documents, including published articles, book reviews, editorial materials, and letters to the editor. This initial search was refined to include only published articles and book reviews, excluding

editorial material and editor letters. This search revealed 55 published interdisciplinary journal articles, of which 21 articles were selected after verifying their coverage across African countries (see Table 1).

Table 1:
Summary of Articles Published Tyres Pyrolysis and Circular Economy in Africa (2008-2022)

Authors	Focus/Title	Country	Methods	Findings/Conclusion	Limitations
Senthil et al. (2008)	This study reviews the feasibility of using waste tires as chips and fibres of different sizes in concrete to improve, strengthen and protect the environment.	Rwanda	Literature Review	The study shows that reducing compressive and tensile strength can be increased by adding some super plasticisers and industrial wastes as partial cement replacement will increase the strength of waste tyre rubber-modified concrete.	The study did not test for the effects of fire on the product.
Vanessa Linganzi (2008)	This study explores how firms make gains from recycling solid industrial waste, including tyres	Burkina Faso	Survey Response	Tyres can be recycled into making footwear tyre sandals which provide income to many low-income families	Some of the tyre-footweares eventually end up in a scrap causing further waste
Sanneh, et al. (2011)	This study examines the recycling system in the Gambia to enhance sustainable municipal solid waste management.	Gambia	Literature Review	Open burning of solid waste, including vehicle tyres, is common in the cities of Gambia. These represent significant harm to humans.	The prevailing open dumping and open burning constitute a significant challenge for the government
Eldred et al. (2012)	The study examines the effects of toxic air pollutants of solid waste, such as the burning of car tyres and its impact on human health	Sierra Leone	Simulation of sample data	The concentration levels, health risks and seasonal variation of polycyclic aromatic hydrocarbons pose a significant threat to humans in Freetown	Another solid waste was included in the analysis
Felix et al. (2012)	This study explores the application of activated recycled rubber from used tyres in oil spill clean-up.	Nigeria	Experimental Research	The carbonisation and activation of recycled carbon from scrap tyres resulted in particles of different and higher surface areas. In addition, activated carbon particles exhibit higher oil removal efficiency when compared with non-activated particles.	Limited sample in the experiment. The research appears to be about the 'carbonisation' of rubber, i.e. its pyrolysis. This means the material then being activated is carbon, not rubber.
Pilusa et al. (2014)	This study a PFD to potentially evaluate the viability of pyrolysis technology as a treatment process for waste tyres intending to produce alternative fuel and other high-value products	South Africa	Processed Flow Diagram	It was discovered that pyrolysis technology becomes more viable when there is a guarantee on the product offtake at a given price. Further processing of the crude tyre oil and carbon black is essential to produce consistent quality products	The study concentrated on the financial feasibility of pyrolysis technology with minimal focus on environmental sustainability
Dodoo-Arhin et al. (2015)	The study explores discarded Rubber Car Tyres as Synthetic Coarse Aggregates in Light Weight Pavement Concretes	Ghana	Experimental Research	This study shows that it is possible to use recycled rubber tyres in concrete construction as a partial replacement for coarse aggregates.	Limited sample sizes were used in this analysis
Ahmed and Negm (2015)	The study assesses the Life Cycle of Vehicles Tyres on the Egyptian Road Network	Egypt	Life Cycle Impact Assessment	Egyptian road tyres contribute mainly to global warming problems and human health.	Limited data used in the study
Tara and Reza (2016)	The study examines the Economic benefits of extended producer responsibility initiatives in tyre waste in South Africa	South Africa	General Equilibrium Model	Findings from the study show that extended producer responsibility initiatives for waste tyres will lead to positive economic benefits and new jobs that favour lower-skilled people	The environmental benefits associated with recycling were not quantified and hence accounted for
Jimoda et al. (2017)	The study assesses the environmental impact of open burning of scrap tyres on ambient air quality	Nigeria	Experimental Research and Simulation	The study significantly established gaseous pollutants (CO, NO ₂ and SO ₂) are present at varying concentrations in all categories of tyres which causes a significant threat to human health.	No beneficial recycling method is provided
Khavharendwe et al. (2017)	The study explores the Mechano-chemical approach in the synthesis of activated carbons from waste tyres, including hydrogen storage applications	South Africa	Mechano-chemical Structural Analysis	The synthesis of carbon materials from waste tyre solid char following the mechanochemical strategy was successful. Compared to the conventional activation method, the application of the compactation method was observed to lead to an increase in surface area between 3 and 24%.	Limited sample sizes were used in this analysis
Sulaymon et al. (2018)	Examines Toxicity potential of the emitted aerosols from open burning of scrap tyres	Zimbabwe	Experimental Research	This study has shown that open-burning scrap tyres (OBST) could increase aerosols' concentration in an environment with significant toxic effects on humans.	Limited dataset used in the experiment
Rekhaye and Jeetah (2018)	Assessing Energy Potential from Waste Tyres in Mauritius	Mauritius	Experimental Research	Findings from the study show that direct combustion will increase CO ₂ emission	Limited sample used for the experiment. Some

Authors	Focus/Title	Country	Methods	Findings/Conclusion	Limitations
	by Direct Combustion, Pyrolysis and Gasification			by 26% if shredded waste tyres as a replacement for coal. Pyrolysis gave 35% char, 33% heavy pyrolytic oil, 17% light pyrolytic oil and 15% gas by mass per cent. Thus, gasification is not best to waste to energy conversion technology	analysis and conclusions cannot be extrapolated to gasification as it is a different thermal process
Dorr et al. (2019)	The study examines the effects of recycled tyre steel fibres and palm kernel shells on the compressive, splitting tensile and flexural strengths of lightweight structural concrete, using recycled tyre steel fibres for reinforcement and palm kernel shells as partial replacement of coarse aggregates	Uganda	Experimental Research	The results of this study show that an increase in recycled steel fibres from 20-80 aspect ratios increases the compressive strength and splitting tensile strengths of normal-weight concrete.	Other solids waste materials were included in the analysis
Quaicoe et al. (2020)	This study sought to examine how to transform waste vehicle tyres into fuel which invariably minimises or eliminates its environmental impact.	Ghana	Experimental Research	Treated pyrolysis oil could be used as blended with other diesel fuels in cars	Limited sample sizes were used in this analysis
Okafor et al. (2020)	This paper review discussed challenges and opportunities offered by post-consumer management of end-of-life tyres in Nigeria. End-of-life tyres (ELTs) cause a multi-faceted problem in Nigeria	Nigeria	Literature Review	Circular management of post-consumer product such as tyres are essential to the economic sustainability	Substantial scarcity of data and methodological challenges in differentiating the economic impacts
Kumar and Siagi (2021)	The study examines the Optimisation of Liquid Fuel Production from Microwave Pyrolysis of Used Tyres	Kenya	Experimental research using Microwave Pyrolysis	The liquid fuel properties obtained from the experiment meet the required international standards and can be used as an alternative to diesel fuel.	Research is still needed to refine the liquid fuel used directly in internal combustion engines.
Munir (2021)	The paper examines waste tyre problems and sustainable waste management in the Tunisian context	Tunisia	Mixed methods analysis	Strict legislation coupled with sustainable finance for waste disposal is imperative in dealing with the problems of tyre waste disposal in Tunisia.	Limited data on tyre disposal.
Sakri et al. (2021)	The study examines the potential production and utilisation of refuse-derived fuel (RDF) from MSW to be used as a substitute fuel in cement kilns in Algeria	Algeria	Experimental research	The results show that refused-derived fuel (RDF) and cement can be produced from municipal solid waste such as car tyres	The study did not examine in detail if the use of RDF in cement manufacturing is cost-beneficial and environmentally friendly
Bwalya et al. (2022)	The study examines used tyres as a resource for concrete production	Zambia	Experimental Research	There is potential for rubber-modified concrete products in Zambia, which in turn mitigates adverse impacts resulting from over-exploitation of natural aggregates and disposal of used rubber tires	However, in this research, a replacement of coarse aggregates was used to determine the suitability of using rubber aggregates in concrete production

2.2 Tyre Pyrolysis and Sustainable Practices in Africa

The compendium of studies presented in Table 1 illustrates that many disposal routes either have detrimental environmental impacts (e.g. combustion) or questionable viability (e.g. use in concrete). Six of the papers focus on pyrolysis and support this route as a reasonable and sustainable means of solving Africa's increasing tyre-waste disposal problem. It is a circular economy route that uses thermal methods of recycling tires. At the same time, the associated project can give the project owners and stakeholders monetary value on the products obtained (pyrolysis oil, char, and metals). Many of these studies have investigated if using activated recycled rubber from old tyres in fuel and carbon charcoal is possible. For example, Aisien &

Aisien (2012) conducted an experiment that involved recycling waste car tyres into oil in Nigeria. They discovered that recycling rubber from discarded tyres and carbonising and activating it produced particles with various and more significant surface areas. They further emphasised that, compared to carbon particles that have not been activated, activated rubber-derived carbon particles demonstrate better effectiveness in oil removal.

Dodoo-Arhin et al. (2015) conducted an experiment in Ghana that discovered that disposable car tyres could be recycled to produce synthetic coarse aggregates in lightweight pavement concretes. They demonstrated that it is feasible to substitute coarse aggregate in concrete buildings with recycled rubber tyres. Moreover, Abuzukhar (2021) conducted a study in Tunisia to investigate if the waste tyre can be used for oil, cement for construction, and the like. The findings from the survey show that pyrolysis can yield a sustainable result of producing oil, cement, and carbon charcoal from waste car tyres. However, the study underscores the need for tight laws and long-term waste financing in addressing the tyre disposal challenges and their associated environmental problems in Tunisia. Other studies, including Asma et al. (2021), argue that cement and refused-derived fuel (RDF) may be made from municipal can be extracted from recycled automobile tyres. Their study shows that pyrolysis represents a sustainable means of recycling the many waste automobile tyres that pollute the environment in most Algerian cities. They demonstrated how fuel could be extracted from recycled car tyres or used in the manufacture of cement.

Circular economy approaches have been emphasised as sustainable solutions to the tyre waste challenges in African countries. Senthil et al. (2008) acknowledged the problem associated with tyre waste in Africa. They examined the possibility of incorporating scrap tyres in concrete as chips and fibres to reinforce concrete for construction work in Rwanda. Their research demonstrates that adding certain super plasticisers and industrial waste as a partial

cement replacement can boost the strength of waste tyre rubber-modified concrete while reducing compressive and tensile strength degradation. The study did not, however, examine how the fire might affect the product. By utilising a study in Burkina Faso, Linganzi (2008) investigated how businesses profit from recycling solid industrial waste, including tyres. He discovered that tyres could be recycled to create footwear called tyre sandals and give many disadvantaged people an income. To improve sustainable municipal solid waste management, Sanneh et al. (2011) assessed the recycling system in the Gambia. They suggested that the open burning of solid garbage, including car tyres, be practised often in the country's towns. However, these pose severe risks to people and complex problems for the administration.

Also, using simulation data from Sierra Leone, Taylor & Nakai (2012) investigated the effects of toxic air pollutants from solid waste, such as burning car tyres, and their impact on human health. They discovered that the concentration levels, health risks, and seasonal variation of polycyclic aromatic hydrocarbons in Freetown pose a significant threat to people's health. Moreover, Elkafoury & Negm (2015) evaluated the life cycle of automobile tyres on the Egyptian road network and discovered that they are primarily responsible for the mid-point effect of global warming problems, as well as for the harm caused by terrestrial acidification and nitrification, including adverse effects on human health. Finally, to assess the economic advantages of the expanded producer responsibility initiative in tyre trash in South Africa, Caetano & Daniels (2016) used a computational general equilibrium model. According to their results, expanded producer responsibility programmes for discarded tyres will have a positive economic impact and create up to 1448 net new full-time equivalent (FTE) employment that is more favourable to those with lower skill levels.

Therefore, Jimoda et al. (2017) evaluated the environmental effects of open burning of waste tyres using process modelling and found that gaseous pollutants (CO, NO₂, and SO₂)

are present in all kinds of tyres at variable amounts, posing a serious hazard to human health. In an experiment conducted in Zimbabwe, Sulaymon et al. (2018) demonstrated how open-burning scrap tyres (OBST) might increase the environment's aerosol concentration, which has harmful consequences for people. Khavharendwe et al. (2017) employed mechanochemical structural analysis to investigate if the mechanochemical approach to producing carbon compounds from waste tyre solid char was effective. Thus, the compaction process improved the surface area by between 3% and 24% compared to the standard activation method. The problems and possibilities presented by post-consumer management of end-of-life tyres (ELTs) in Nigeria are reviewed by Chukwueka et al. (2020). They stated that ELTs and other post-consumer products require circular management to be sustainable.

2.3 Tyre Pyrolysis into Oil and Charcoal for Sustainable Energy

While energy efficiency is recognised as one cost-effective way to meet sustainable development demands, most African countries are still saddled with acute energy problems. With the need for energy services in Africa snowballing, exploring new avenues for securing more affordable and sustainable energy sources is imperative. Besides, increased energy efficiency is essential for economic growth since it reduces fuel imports, eases strains on existing infrastructure and reduces production costs. Furthermore, studies show that the pyrolysis-circular economy approach can provide a more sustainable and partially renewable source of cheaper energy and alleviate energy problems.

The circular economy ideas should also be applied better with the support from thermal technologies. For example, Pilusa et al. (2014) formulated a process flow diagram using South African data. They evaluated the viability of pyrolysis technology as a treatment process for waste tyres to produce alternative fuel and other high-value oil products for energy. They discovered that pyrolysis technology could produce oil and carbon black and be a reliable

energy source but also, critically, identified that the resultant products needed further treatment to achieve a quality that would sustain a project. Similarly, Quaiocoe et al. (2020) argue that treated pyrolysis oil could be blended with diesel fuel for cars and other vehicles. Kumar & Siagi (2021) developed microwave pyrolysis and argued that the liquid fuel properties obtained from their experiment meet the required international standards and can be used as an alternative to diesel fuel.

Pyrolysis is a promising chemical solution to manage waste effectively, energy deficits and material recovery (Nkosi et al., 2020) and turn waste into renewable energy sources (Adeniyi et al., 2019; Ighalo & Adeniyi, 2019; Adeniyi et al., 2018). It is one circular economy practice to create a sustainable society and encompasses all operations, from garbage recycling to recovering components from worn goods (Ighalo et al., 2021). Examples include the recycling of textile wastes (Shirvanimoghaddam et al., 2020), the production of bioenergy from food wastes (Ingrao et al., 2018), the use of olive pomace for renewable energy (Nunes et al., 2020) and the conversion of waste into biogas (Kapoor et al., 2020). In addition, pyrolysis offers many key benefits, including the ability to reduce water pollution through alternative pollutant conversion, the potential to reduce reliance on imported energy resources, cost savings over landfills and the provision of public health benefits through cleaned-up wastes (Ighalo et al., 2021).

Besides, Zabaniotou et al. (2015) demonstrated the possibility of bridging the divide between agriculture and the circular economy while focusing on converting agricultural leftovers to liquid fuel, gas fuel, and biochar. Vaskalis et al. (2019) adopted an experiment employing fluidised bed gasification systems that combined the production of heat and power and were fuelled using wastes obtained from the processing of rice. The results demonstrated that the suggested model might be used to properly exploit waste flows from various rice value chains by using wastes as fuels. Somoza-Tornos et al. (2020) studied the recovery of ethylene

monomers through the pyrolysis of polyethene. They found that polyethene pyrolysis might close the ethylene manufacturing operations' loop. The findings also demonstrated the necessity for additional research on pre-treatment polyethene waste to obtain more accurate environmental assessments, and the opportunity to lower hazardous emissions into the environment is provided by waste pyrolysis.

Finally, Pilusa et al. (2014) studied the financial feasibility of pyrolysis technology with minimal focus on environmental sustainability. Although pyrolysis has been proposed as promising in existing literature, we still lack a comprehensive understanding of how waste tyre pyrolysis is implemented and, more importantly, what the challenges are associated with pyrolysis implementation in African countries.

Although circular economy is impactful in developing sustainability, emerging economies still need more successful examples in waste collection, recycling, repair and refurbishment (Murray, et al., 2017). For instance, evidence suggests that circular economy has primarily remained a vague concept in African countries where the most emphasis has been placed on economic development and natural resource maximisation (Desmond & Asamba, 2019). However, research-based feasibility projects still need to produce more consistent findings for decision-making support (investors, stakeholders, and government representatives). As a result, developing a circular economy is even more difficult in a developing country.

Similarly, establishing a waste tyre pyrolysis plant in practice has many challenges that discourage adoption and implementation. So, analysts, researchers, and decision-makers need to identify critical project drivers and link them to actionable strategies, plans, and decision support. For example, (a) technology readiness (technical maturity of pyrolysis technologies at the implementation phase), (b) risk identification (detection of potential risks that adversely

affect projects and business performance), (c) carbon footprint analysis (generation or reduction of greenhouse gases, including carbon dioxide and methane), (d) supply chain and procurement factors (processes of getting and transforming tyres feedstock into products and distributing them to customers), and (e) financial risk quantification (practice for creating, quantifying, protecting economic value under risk and uncertainty).

3. Findings and Discussions

3.1 Current Limitations and Contributions of Tyre Pyrolysis Research

Table 2 shows that most of the literature reviewed underscores the environmental sustainability arguments in pyrolysis in Africa. However, significant and rapid progress has been made in other parts of the world. Critically the progress encompasses: uses for both recovered Carbon Black (tyre manufacturers) and tyre pyrolysis oil (refiners producing fuel and plastics manufacturers); regulations (e.g. waste status and legislation) and incentives (mainly biofuels). These factors have massively increased the focus on tyre pyrolysis as a solution.

In doing these have also highlighted the many issues that need to be addressed to realise tyre pyrolysis projects. The decision-makers must advance such projects to support tyre pyrolysis as one solution for a more circular and long-lasting solution for tyres disposal needs to cover product quality and end-use, investment, project management, technological challenges, risk management, supply chain management, and the like. Besides, pyrolysis is only beginning to gain popularity in Africa. Nonetheless, the existing research streams on tyre pyrolysis still need to identify other critical project drivers, including carbon footprint analysis, risk management, and techno-economic requirements, in an integrated way to satisfy project owners and stakeholders. These drivers can help scholars fill research gaps in future studies. Furthermore, it could be supported by working and interviewing engineering specialists about the challenges in tyre pyrolysis projects and potential managerial implications.

**Table 2:
Project Drivers in Tire Pyrolysis and Circular Economy Literature in Africa (2008-2022)**

Authors	Focus of Study	Country	Environmental Benefits	Technology Readiness	Risk Identification	Carbon Footprint	Supply Chain & Procurement	Risk Quantification
Senthil et al. (2008)	Waste tyre for cement chips for concrete	Rwanda	Y	Y	Y	Y	Y	N
Vanessa Linganzi (2008)	Recycling industrial waste tyres in footwear sandals	Burkina Faso	Y	Y	Y	Y	Y	N
Sanneh, et al. (2011)	Examine waste disposal problems, including car tyres	Gambia	Y	Y	Y	Y	Y	N
Eldred et al. (2012)	Examines the effects of burning car tyres and its toxic effects on humans	Sierra Leone	Y	Y	Y	Y	Y	N
Felix et al. (2012)	This study explores the application of activated recycled rubber from used tyres in oil spill clean-up.	Nigeria	Y	Y	N	Y	N	N
Pilusa et al. (2014)	This study evaluates the viability of pyrolysis technology as a treatment process for waste tyres	South Africa	Y	Y	N	Y	Y	N
Dodoo-Arhin et al. (2015)	The study explores discarded Rubber Car Tyres as Synthetic Coarse Aggregates in Light Weight Pavement Concretes	Ghana	Y	Y	N	Y	N	N
Ahmed and Negm (2015)	The study assesses the Life Cycle of Vehicles Tyres on the Egyptian Road Network	Egypt	Y	Y	N	Y	Y	N
Tara and Reza (2016)	The study examines the Economic benefits of extended producer responsibility initiatives in tyre waste in South Africa	South Africa	Y	Y	N	Y	N	N
Jimoda et al. (2017)	The study assesses the environmental impact of open burning of scrap tyres on ambient air quality	Nigeria	Y	Y	N	Y	N	N
Khavharendwe et al. (2017)	The study explores the mechanochemical approach in the synthesis of activated carbons from waste tyres and their hydrogen storage applications	South Africa	Y	Y	N	Y	N	N
Sulaymon et al. (2018)	Examines Toxicity potential of the emitted aerosols from open burning of scrap tyres	Zimbabwe	Y	Y	Y	Y	N	N
Rekhaye . and Jeetah (2018)	Assessing Energy Potential from Waste Tyres in Mauritius by Direct Combustion, Pyrolysis and Gasification	Mauritius	Y	Y	Y	Y	Y	N
Dorr et al. (2019)	The study examines the effects of recycled tyre steel fibres and palm kernel shells on concrete	Uganda	Y	Y	N	Y	N	N
Quaicoe et al. (2020)	It examines how to transform waste vehicle tyres into fuel	Ghana	Y	Y	Y	Y	N	N
Okafor et al. (2020)	It discusses the challenges and opportunities offered by a waste tyre in Nigeria.	Nigeria	Y	Y	Y	Y	Y	N
Kumar and Siagi (2021)	The study examines the optimisation of Liquid Fuel Production from Microwave Pyrolysis of Used Tyres	Kenya	Y	Y	N	Y	N	N
Munir (2021)	It examines waste tyre problems and sustainable waste management in the Tunisian context	Tunisia	Y	Y	Y	Y	Y	N
Sakri et al. (2021)	It examines the potential production of refuse-derived fuel (RDF) from used car tyres	Algeria	Y	Y	N	Y	N	N
Bwalya et al. (2022)	The study examines used tyres as a resource for concrete production	Zambia	Y	Y	N	Y	Y	N

3.2 Other Challenges in Tyre Pyrolysis, from Industry to Academia

This chapter draws on OSL’s (2021) consulting project report on Tyre pyrolysis. In this report, along with the systematic literature review, we have identified other critical criteria for installing a waste tire pyrolysis plant through consultation and collaboration with engineering experts in the UK, the US, Europe, and Africa. The underlying recommended topics, complemented with literature, should be considered in any research-based feasibility study,

financial decision, front-end engineering design, construction, or project risk management analysis. Otherwise, they may hinder the acceptance and implementation of pyrolysis projects and, consequently, have potential implications for business performance; for example, operational costs, technological assurance, end-product quality, shareholder integration, project management and execution, risk management, hazardous and environmental assessment, plant optimisation, process modelling, and regulatory framework.

a) *Operational costs:* developing and operating pyrolysis plants, firms often have a heavy burden of operational costs of establishing proper infrastructure and ensuring a safe working environment (Kozub et al., 2021). Many expenses derive from the reactor systems, condensers and heat exchangers, burner and furnace systems, oil loading stations and pumps, oil storage, water system, thermal oil system, and carbon-black silos. Apart from tangible equipment, contractor's fees, commissioning, testing and training costs also constitute high costs and are expected to grow. For African firms, overcoming the higher costs of adopting such a circular economy business is a big concern to be considered as part of the risk quantification process.

b) *Technological assurance:* it is evident that waste tyre pyrolysis requires advanced technologies, and these must be ready to deploy at a commercial scale – i.e., have achieved Technology Readiness Level 7 (process proven at commercial scale). Such a level of development presumes the technology employs stringent control mechanisms, suitable automation systems and reliable safety circuits. Managers and engineers must also consider alternative designs to cope with unplanned disruption, such as a gas evacuation system. Therefore, high-quality materials and standards must be ensured in reactor systems, storage tanks, assembly and mechanical equipment for blowers and pumps (Martines, 2021). All these require evaluating superior manufacturing techniques and technical expertise to judge, support and enable obtaining crucial data for system design and maintenance. To strengthen the confidence in the technology, the pyrolyser suppliers should provide adequate and verifiable

technical descriptions of all plant components, including functional descriptions, flow diagrams, operational instructions, mass and volumetric flow rates, pressure and temperature profiles and emissions.

It has also been advised to test and identify reliable pyrolysis technologies before purchasing and verifying the supplier's information. Note that pyrolysis plants consider experimental data to support the process' nominal operating characteristics and aid in more accurately developing the business model. Another crucial factor to consider is the demonstration of facilities, which helps reduce technical ambiguity and build up the confidence of prospective customers in the technology and the qualities of end-products. Establishing and demonstrating an appropriate technology also need to include well-designed plans for corrective, preventive, and predictive maintenance and be dependable throughout the medium and long term in a regular manner. These characteristics contribute to increased trust in providers of pyrolysers and enhance better project outcomes.

Furthermore, industrial-scale pyrolysis facilities must be fitted with desulphurisation abatement systems, primarily because of the sulphur (H_2S) entering the gas portion. The ability to prove that a supplier's technology complies with specific regulatory air emissions criteria, especially those related to occupational health, is mandatory. Technological consideration and standard regulations need to be established to make sure that no plant employees should come into touch with potentially harmful chemicals like fumes and vapours. Pyrolysis plants need to identify all elements involved, including intermediates, byproducts, and effluents, for their hazardous characteristics (physical, chemical, and health). Each material should be categorised using a banding system that connects the substance's dangers to the required engineering controls. The process's dangers (exothermic reaction, gas evolution, etc.) should be recognised, quantified, and recorded to recommend the degree of control corresponding to each hazard. The pyrolysis facility must be risk-free for workers and guests and should not violate

environmental, health, and safety regulations. All these technological insurance considerations are complex and resource-demanding for African firms but help to address the gap between expenditures and sales in reality (ETRMA, 2018).

c) End product quality: it is worth noting that pyrolysis technologies and products in African countries are still in the early stages of development. The technological maturity of the pyrolyser significantly impacts the quality of end products, including chemical properties, which may be caused by various reasons, such as lacking the technical tools to guarantee safe operating circumstances. A slight difference in inputs and materials used in pyrolysis can significantly change end-product quality, aspects associated with supply chain management. For example, different types of tyres contain different grades and reliability of materials. Note that all pyrolysis techniques and types of machinery can produce end products with other chemical characteristics and qualities. For example, one end-product of all recovered carbon black (rCB) comprises numerous CB grades (Martinez et al., 2019) and both inorganic and carbonaceous components. Therefore, ensuring the same qualities in a virgin CB (Mastral et al., 1999) is difficult. As one of the end products, tyres pyrolysis oil (TPO) is a viable replacement for petroleum-derived goods, such as heating oil, valuable chemical compounds, and motor fuels. This discrepancy in the properties of TPO and rCB has undermined a reputation and given urgency for pyrolysis manufacturers to improve.

To make TPO meet the fuel criteria, applications in the plants need to establish further upgrading steps (Schmitt et al., 2019). Moreover, more rigorous refinement techniques, such as milling and acid treatment, are required to enhance the characteristics of other end-product rCBs and improve the intended use (Ighalo et al., 2022). All the technological and chemical demonstration indicates how crucial it is to have appropriate safety data sheets and regulations for both TPO and rCB. Safety data sheets also need to be enacted during shipping and handling. The development of established certifications and standards, as is happening with bio-oil,

biochar, and bio-oil from biomass pyrolysis, are recommended to support the market acceptability of these products (ETRMA, 2018). Therefore, standardisation prevents traditional methods' performance limitations and attracts investors and entrepreneurs (Zabaniotou et al., 2014).

To accurately forecast how the pyrolysis process functions in detail by using new characterisation techniques based on structure, surface area, sieve residue, pellet characteristics, and concentrations of ash and sulphur (ASTM, 2018). However, it has also been observed that TPO and rCB made with their pyrolysers may be sold as virgin CB and diesel-like fuel, establishing a negative reputation with prospective interested parties. Proofs-of-concept enables tackling this difficulty by small-scale testing in goods and processes and is often conducted in cooperation with possible end markets to confirm the practicality of the pyrolysis product. As a result, the TPO and/or rCB must be set based on the clients' requirements of quality and options provided by the pyrolyser. As a solution, some ELT pyrolysis providers have customised their solution to meet the qualities required by the clients to substitute rCB for virgin CB in tyres and automobile components (Prnewswire, 2018).

d) Stakeholder integration: pyrolysis project execution and business management require convergence among project owners and stakeholders. Collaborating with multiple stakeholders, such as product clients, investors, technicians, researchers in the subject, type and rubber enterprises, tyre collectors, national and local environmental entities and government, is difficult. These stakeholders can support the effective implementation of ELT pyrolysis facilities but also have their interests. As we discussed above, pyrolysis is a resource-intensive business. It often requires substantial financial support to handle the high plant construction and commissioning expenses and to ensure development and environmental compliance.

Also, persuading investors and guaranteeing a quick break-even is a challenge for shareholders, which are aspects to be considered during the scenario analysis for risk quantification. Therefore, joint venture agreements between seasoned businesses involved in designing and installing industrial-scale plants, waste-to-energy (WtE) processes, and petroleum and chemical products can improve the project deployment and the marketability of the products produced through pyrolysis. How to carry out collaborative activities related to research institutes and universities is also challenging. How to manage suppliers and clients to ensure a resilient and sustainable supply chain is a general concern in African countries. The promotion or subsidies of recycling goods by governments and other authorities can have a favourable impact on pyrolysis but requires social network support (Yang, et al., 2021). The marketability barriers for end products tend to be diminished if external stakeholders involved in recycling, clean production, and environmental protection do not recognise these products as alternative energy sources and sustainable value-added outputs in line with sustainable production.

e) *Project management and execution:* in addition to the technical system, various project management procedures should be considered during the project implementation stage, such as FEED, detailed design, procurement, installation/construction and plant commissioning. They have relevant cost, schedule, and financial risk implications that need to be analysed during the risk quantification process.

For instance, it has been suggested that the Front End Engineering Design (FEED) be assigned to a single engineering design firm that would continue to develop the facility's design. The FEED contractor will be in charge of developing the engineering design to a degree of specificity enough to eliminate any sizable uncertainty about the facility's technical needs. Get vendor quotes, improve the cost estimates and help manage long lead equipment items to be prepared in conjunction with the design. Due to the nature of the reactor systems, it could be

necessary to initiate a distinct contract to develop their design further, give the details required for the facility's overall design, and establish the costs of the reactor systems. The major FEED contract should be reimbursed against a target cost, although fixed price arrangements are possible based on a scope correctly specified (Yussef et al., 2018).

In a pyrolysis project, the project owner can choose an EPCm (Engineering, Procurement, Construction, and Management) business with the expertise and experience necessary to complete the project effectively. The EPCm contractor will ensure that the project's engineering and design adhere to its technical and functional requirements. Its primary duty is to oversee, manage, and coordinate the construction interface following a de-risked timetable. The EPCm contractor can negotiate contracts with other contractors, suppliers, subcontractors, and sub-vendors through a tendering procedure. They will also oversee the management of the equipment delivery orders from order placement to equipment delivery to guarantee that suppliers' technical and commercial responsibilities are met.

Finally, construction must also be supervised by the EPCm contractor under an EPCm contract. They are responsible for creating the construction scope, choosing the most qualified installation contractor(s), and managing these firms throughout the building process. Due to the diverse extent of the installation, there may be more than one installation contractor, including civil/structure; mechanical/piping; and electrical/instrumentation.

f) Risk management: This topic is highly related to risk identification and quantification. Note that decision-makers can only manage risk events if they quantify their impacts. So, a quantitative cost-risk analysis helps identify, simulate, quantify and analyse the primary cost-risk variables and risk drivers should be organised and conducted (WBCSD, 2019). At the same time, risk management requires a consistent and well-defined phase of Design Verification and Engineering (including FEED) to facilitate risk quantification on costs, asset integrity, safety,

operability, maintainability, availability and procurement, construction, and commissioning (Del Cano & De la Cruz, 2002).

To reduce uncertainty on cost and capital expenditure and potential impact across the supply chain and procurement during plan execution, more project risk analysis and quantification is needed in FEED; for example, integrating capital expenditures with the project timeline and variable costs must align with budgeting, capital allocation, and procurement strategies. In pyrolysis projects, it is essential to understand the economic effects of the reactor system and increase expense confidence by considering multiple possibilities early and doing further risk analysis on the incoming energy supply (supplier capacity, building needs, project consequences, etc.) following plant and products specifications.

g) Hazardous and environmental assessment. Consistent with our discussion above, pyrolysis is not always risk-free. Although pyrolysis provides flexibility to convert wastes into economically usable products, feedstock availability tends to emerge as an essential concern. Transporting, storing, and processing feedstock before thermochemical conversion provides additional difficulties (Effendi & Bridgewater, 2008; Zhang et al., 2010) and negative environmental impacts do exist as well. So, Important parameters during the production process must be carefully measured and calibrated to cope with adverse environmental impacts, including particle size, vapour residence time, carrier gas flow rate, moisture content and pressure. However, the process is complex, requiring careful comprehension and in-depth investigation (Chemerys and Baltrunaite, 2018). To cope with potentially hazardous and environmental issues, managers and plants need to accurately plan and structure the process in the refineries. A cleaner production environment and more understanding of the reaction parameters need to be explored in detail to maximise the product, lessen the environmental effect, and achieve economic efficiency.

h) Plant optimisation. Managers also need to consider several issues and options related to future optimisation, including process heat options, onsite power generation, standard equipment sizing, pumped export oil pipeline and heat recovery and utilisation. For example, power or natural gas may provide a more economic source of process heat. Using power may reduce CAPEX, however power rates may still not make this an economic option. Equally product fractionation can be an option as selling light and heavy oil products may deliver a higher economic worth. In addition to pyro-gas and ultralight oil, the heat might also be produced using electricity, but further research is needed in these areas because some options might require changing the entire production process, which is infeasible for a plant manager.

Depending on process location, transferring the oil produced by tyre pyrolysis to a neighbouring oil refinery may be more economic using pipelines than tankers. The drawback is that it limits the plant's commercial flexibility by tying it to supplies to that refinery. However, whenever additional data is easily accessible, a cost-benefit and risk analysis will need to be carried out at the FEED stage.

Regarding heat recovery and utilisation, some tyre pyrolysis process flow diagrams demonstrate that there are options for waste heat recovery and use. For instance, the heat from the flue gas may be recovered and utilised to operate an organic Rankine system or an absorption chiller refrigeration system, which might be used to create energy or replace the electric chillers, lowering the process's electrical power usage. Additionally, there is the potential to use production waste heat to heat office rooms, reducing the need for HVAC power. Using heat recovery in more depth remains a future challenge as well.

i) Process Modelling. Any feasibility study has to provide an accurate heat and material balance report for any particular process (modelling and simulation). In addition, these reports give valuable data to size essential process equipment. Then, high-level heat and material

balance information should be collected and provided to size pieces of process equipment. The entire process's material and energy balance will be completed during the FEED phase. This will be done by carefully modelling and simulating the tyre pyrolysis process in the simulation programme.

As a result, a lot of data and feedback are required for process modelling, such as ultimate and approximate analysis of the tyre feedstock, reactor size, temperature and pressure, product stream flow rate and composition, among other details of the operating parameters, including composition and properties of the pyrolysis gas, ultra-light, light and heavy oils.

j) Regulatory framework. The equipment in pyrolysis must comply with local laws and regulations to be imported and used safely and lawfully. Although they are not required, design standards and codes provide direction to promote the adoption of best practices. Technology and equipment used in pyrolysis plants need to be reviewed at a high level to ensure conformation with applicable regulations (Zabaniotou et al., 2014); for example, pressure systems safety regulations, supply of machinery regulations, provision and use of work equipment regulations, electrical equipment regulations, control of major accident hazards regulations, planning (hazardous substances) regulations, environmental permitting regulations, and town and country planning (environmental impact assessment) regulations, among others.

Moreover, design codes are a special kind of in-depth design advice that adopts best practices to speed up workflows, produce products of higher quality, and promote some degree of industry standardisation. While design codes alone are not required, specific laws stipulate that particular equipment must be built following a globally recognised design code. In addition, all equipment must comply with local regulations following internationally recognised design codes. The institutional environment is fast shifting. Thus, the most recent directives and rules

should be examined to guarantee that the equipment will comply with legislation before ordering.

In summary, research-based feasibility or circular economy pyrolysis projects need to advance in a more long-lasting analysis to address decision-making problems (investment, project management, technological challenges and readiness, risk management, supply chain management, and the like). So, to strengthen the opportunities in Africa, not only project owners and stakeholders do need to be aligned and integrated, but also scholars need to start filling research gaps and answer managerial questions around operational costs, technological assurance, end-product quality, project management and execution, risk management, future optimisation, process modelling, and regulatory framework, and the like.

4. Conclusions

The main message of the findings of this paper has two aspects. The first is that waste tyre pyrolysis research-based applications and feasibility studies have had limited focus within literature in African countries, especially in addressing the multiple challenges, risks, and impacts faced by investors and stakeholders in Africa. Meanwhile the growing population has resulted in increasing demand for non-degradable products, especially tyre waste. So, the circular economy approach that tyre pyrolysis promises require underscoring in environmental sustainability and driving discussions that support decision-makers on more long-lasting solutions (technology readiness, risk identification, carbon footprint, supply chain and procurement, and risk quantification).

Second, research-based literature on pyrolysis projects and associated businesses must consider industry requirements and specifications to support project finance and investments decision around front-end engineering design, operational costs, technological assurance, end-product quality, shareholder integration, project management and execution, risk management,

hazardous and environmental assessment, plant optimisation, process modelling, and regulatory framework.

Although pyrolysis projects, investments and businesses are only beginning to gain popularity in Africa, further insight into circular economy and waste tyres management can also address some of the concerns within the sustainable energy literature, including corporate sustainability, policy-making, risk-based business decisions (i.e., project financing, commercial scale of the technologies selected, product offtake contracts, site planning and conditions, government incentives, engineering and construction services providers, and the like), and environmental management issues.

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