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Optimization of Co-pyrolysis Process for Sustainable Distributed Power and Industrial Development in Nigeria: A Pathway Analysis

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Abstract

This paper analyzes existing research to assess the potential of co-pyrolysis for sustainable distributed power generation in off-grid Nigerian communities. A meta-analysis review methodology was used to assess the techno-economic and environmental aspects of co-pyrolysis, focusing on its ability to simultaneously address waste management and energy insecurity, encouraging industrial development. The analysis revealed a promising opportunity to utilize readily available plastic waste and agricultural residues for syngas production. The review identifies key factors influencing energy conversion efficiency and cost-effectiveness compared to traditional waste management methods. The potential sources of revenue from syngas use were explored, and the environmental concerns such as emissions and coal disposal were addressed. Additionally, the review provides a path analysis for stakeholders by highlighting knowledge gaps and suggesting areas for further research and development. The results provide valuable insights for policymakers, engineers, and researchers to develop an optimal, sustainable, cost-effective solution for off-grid electrification in Nigeria and encourage industrialization at various scales.

Keywords: Power generation, Electrification, Waste management, Agricultural residue, Energy management.

1 | Introduction

Energy security and waste management are two of the most pressing challenges facing developing nations, hindering industrial development, economic development, and public well-being [1], [2]. In Nigeria, for instance, millions lack access to reliable electricity, with estimates suggesting that over 80 million people rely

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on polluting and expensive generators [3], [4]. Fossil fuel dependence for power generation exacerbates this issue, while mismanagement of plastic waste creates environmental hazards and public health concerns [5]–[8]. Co-pyrolysis, a thermochemical process where different organic materials are decomposed simultaneously at elevated temperatures in an oxygen-deficient environment [9], [10], presents a promising solution for sustainable distributed power generation in off-grid Nigerian communities. This technology offers a two-pronged approach, addressing energy insecurity by producing syngas, a combustible gas usable for electricity generation, while simultaneously tackling waste management challenges by converting plastic waste and agricultural residues into usable fuel [11], [12]. Using a path analysis approach, this comprehensive analysis aims to bridge the information gap for stakeholders seeking sustainable and cost-effective off-grid electrification options in Nigeria. The insights presented in this study can be invaluable to policymakers, engineers, and researchers who want to create a future where green energy and responsible waste management go hand in hand in improving the lives of Nigerian communities.

1.1 | Energy Insecurity and Waste Management Challenges in Developing Nations

Energy insecurity and inadequate waste management are critical and interrelated challenges for developing countries, hindering economic development, public health, and environmental sustainability [13]–[19]. Access to reliable and affordable electricity is a major barrier, particularly in rural areas. Castellano et al. [20] and Avila et al. [21] emphasize that only in sub-Saharan Africa do more than 600 million people not have access to electricity, limiting economic opportunities and basic living standards. In Nigeria, for example, millions rely on expensive and polluting electricity generators due to inadequate grid infrastructure, especially in remote areas [20]–[22]. This reliance on fossil fuels exacerbates energy insecurity and contributes to greenhouse gas emissions. Rapid urbanization and economic growth in developing countries have led to increased waste generation, often exceeding the capacity for proper collection and disposal [19], [23]. Open dumping and burning waste are common practices, releasing harmful pollutants into the air and contaminating water sources. Pujara et al. [24] documented these practices' harmful environmental and health impacts in Indian open dumping. Plastic waste is of particular concern because its limited recycling options cause it to accumulate in landfills and the environment, causing ecological damage. The combined effects of energy insecurity and poor waste management create a vicious cycle.

Limited access to electricity hinders economic activity and discourages investment and industrialization. Improper waste disposal leads to health risks and environmental degradation, further hindering development. In addition, reliance on fossil fuels to generate electricity contributes to climate change, which can worsen extreme weather events and disrupt agricultural production, an important source of income and livelihood in many developing countries. Therefore, developing solutions that address both energy and waste management challenges simultaneously is crucial. Co-pyrolysis, a thermochemical process that uses biomass and other waste materials to produce fuel, represents a promising approach for developing countries such as Nigeria. By converting readily available plastic waste and agricultural residues into synthesis gas, co-pyrolysis offers the potential for sustainable decentralized power generation in off-grid communities.

1.2 | Challenges of Fossil Fuel Dependence for Power Generation and Plastic Waste Mismanagement

Reliance on traditional fossil fuels to generate electricity comes with several limitations, which include:

I. Environmental impact: burning fossil fuels releases greenhouse gases, contributing greatly to climate change. Studies by Guillaumont and Simonet [25] highlight the increasing vulnerability of African nations to climate extremes related to global warming. This can have devastating consequences, including disrupted weather patterns, reduced agricultural productivity, and rising sea levels.

II. Resource depletion: fossil fuels are finite, and their continued dependence raises concerns about long-term energy security. In addition, exploration and production activities can have negative environmental and social impacts [26].

III. Economic dependence: the price of fossil fuels can be volatile, exposing countries to fluctuations in the global market. Furthermore, dependence on imported fossil fuels leads to an outflow of funds that could be invested in local renewable energy solutions [27].

Rapid urbanization and economic growth have led to a surge in plastic waste generation, exceeding the number of proper collection and disposal systems [28], [29]. Alabi et al. [30] documented the air and soil pollution associated with these practices:

I. Problems with landfills: due to the quantity of plastic waste, landfills quickly overflow. This can lead to land shortages and pollution.

II. Incineration concerns: burning plastic releases harmful pollutants such as dioxins and furans into the atmosphere, posing a health risk to surrounding communities.

III. Plastic pollution in the ocean: incorrectly disposed plastic waste often finds its way into the waterways and, ultimately, into the ocean, posing a major ecological threat.

1.3 | Co-Pyrolysis: Potential for Addressing Both Energy and Waste Issues

In developing countries like Nigeria, co-pyrolysis represents a sustainable and integrated solution that considers waste management and energy needs. Co-pyrolysis can utilize a variety of raw materials, including plastic waste and agricultural residues. Nigeria's abundance of poorly managed plastic waste provides a readily available raw material for co-pyrolysis [31], [32]. Studies by Mo et al. [9] and Ryu et al. [33] show the potential of co-pyrolysis to convert various types of plastic into valuable synthesis gas. Nigeria's agricultural sector generates significant crop residues such as rice straw and corn stalks. These residues can be effectively converted into syngas through co-pyrolysis, providing a valuable waste management strategy while creating a clean energy source [34].

The co-pyrolysis process offers several advantages over traditional waste management methods, which include:

I. Syngas production: co-pyrolysis produces synthesis gas, a gas mixture of hydrogen, carbon monoxide, methane, and other hydrocarbons. These syngas can be used for a variety of purposes, including:

- *Syngas is particularly suitable for decentralized power generation in off-grid communities because it uses internal combustion engines or gas turbines to generate electricity [35], [36].*
- *Heat generation: the direct combustion of syngas is possible for industrial or domestic heating applications.*
- *Electricity generation: internal combustion engines or gas turbines can use synthesis gas as fuel to generate electricity. This is particularly beneficial for distributed energy systems in remote, off-grid communities in Nigeria, where expansion of the national grid may be impractical.*
- *Syngas can be further processed to produce valuable chemicals such as methanol or synthetic fuels [37], [38].*

II. Waste diversion: co-pyrolysis diverts plastic waste and agricultural residues from landfills and incineration, reducing environmental pollution and associated health risks.

III. Renewable energy source: using agricultural residues as a raw material provides a renewable energy source and reduces dependence on fossil fuels.

1.4 | Co-Pyrolysis Technology

A key advantage of co-pyrolysis is its ability to convert plastic waste and agricultural residues into a valuable gaseous product called synthesis gas. Syngas, also called synthesis gas or production gas, is a blend of different gases, including hydrogen (H_2), carbon monoxide (CO), methane (CH_4), carbon dioxide (CO_2), and other hydrocarbons. The materials used as starting materials and the co-pyrolysis process determine the synthesis gas composition [39]. Several factors that influence the efficiency and quality of syngas production through co-pyrolysis need to be considered to optimize syngas production. The factors include:

I. Raw material composition: the type and ratio of plastic waste and agricultural residues can significantly influence the syngas composition and energy content. Research has highlighted how different plastic types co-pyrolyzed with biomass can influence syngas yield and calorific value [40]–[43]. Finding optimal raw material combinations is crucial for maximizing syngas quality for specific applications.

II. Operating conditions: temperature, presence of a catalyst, heating rate, pressure, and residence time in the co-pyrolysis reactor have a significant impact on the synthesis gas yield and composition. Optimization of these parameters is essential for maximizing desired gas components and minimizing unwanted by-products [44]–[48].

III. Reactor design: the design and configuration of the co-pyrolysis reactor play a critical part in the efficiency of syngas production. Advanced reactor designs can improve heat and mass transfer, producing higher syngas yields and cleaner product gas [49], [50].

Optimization of co-pyrolysis technology for efficient syngas production tailored to the specific waste feedstocks available in Nigeria, creating lower-cost reactors, and finding ways to treat feedstocks before their use can make co-pyrolysis even more technologically and economically viable for distributed power generation in Nigeria. To fully exploit their potential and ensure responsible implementation, a comprehensive review of co-pyrolysis's techno-economic and environmental aspects is required. This critical assessment will facilitate the optimization of benefits and mitigate potential risks.

2 | Methodology

A rigorous research review was employed to assess the potential of co-pyrolysis for sustainable distributed power generation in off-grid Nigerian communities.

2.1 | Systematic Literature Search

A comprehensive search strategy was implemented to identify relevant studies in well-known academic databases. The search terms included keywords related to co-pyrolysis, plastic waste management, agricultural residue utilization, syngas production, distributed power generation, and rural electrification in the Nigerian context. In addition, conference proceedings have been included to capture recent discoveries in this field.

2.2 | Inclusion/Exclusion Criteria

In order to direct the analysis to the most relevant research, strict inclusion and exclusion criteria were established.

2.2.1 | Inclusion criteria

To be included in the review, the following criteria were met:

I. Focus on co-pyrolysis: the study investigates the co-pyrolysis process, particularly the thermal decomposition of mixed raw materials.

II. Relevant raw materials: the co-pyrolysis process utilizes at least one of the materials: plastic waste (various types) and agricultural residues (e.g., rice straw, corn stover).

III. Syngas production: the study presents data on syngas yield or quantifies the ability to produce syngas from the selected raw materials.

IV. Application to power generation: the study considers using syngas for power generation, particularly in a distributed energy system suitable for off-grid communities.

V. Publication type: the research is published in a peer-reviewed journal or a reputable conference on relevant subject areas (engineering, environmental science, etc.).

2.2.2 | Exclusion criteria

Exclusion was based on the following criteria:

I. Focus on other waste raw materials: studies that investigated co-pyrolysis exclusively with raw materials other than plastic waste or agricultural residues were excluded.

II. Irrelevant applications: research that did not consider using syngas for decentralized power generation was not included.

III. Studies with limited data: studies that lacked sufficient quantitative data on feedstock composition, operating conditions, syngas yield, or energy conversion efficiency were excluded.

2.3 | Qualitative Analysis

A thematic analysis was conducted for qualitative data on economic considerations and environmental concerns. This included identifying recurring themes and patterns in the extracted information to understand the economic feasibility and potential environmental challenges associated with implementing co-pyrolysis in Nigeria.

3 | Discussions

The findings from the literature survey are highlighted and discussed in this section.

3.1 | Suitability of Plastic Waste and Agricultural Residues for Co-Pyrolysis: A Technical Assessment.

Research efforts focused on optimizing raw material selection and pretreatment can unlock the full potential of this technology for sustainable distributed power generation. The technical feasibility of co-pyrolysis for distributed power generation in Nigeria depends on the suitability of readily available raw materials such as plastic waste and agricultural residues. The potential of these feedstocks for co-pyrolysis is as follows.

I. Plastic waste:

- *Abundance: Nigeria faces a significant challenge in the disposal of plastic waste as a large portion is poorly managed through landfilling, incineration, or open burning [28], [51], [52]. Co-pyrolysis offers a promising way to divert plastic waste from these harmful practices and use it for energy production.*
- *Syngas production potential: studies have shown that co-pyrolysis improves the quality and yield of valuable products, such as syngas, when converting various plastics [9]. Muzyka et al. [53] revealed that co-pyrolysis of Poly-Ethylene (PE), Poly-Propylene (PP), and Poly-Styrene (PS) with biomass offers a promising method for converting waste plastics and low-quality biomass into valuable synthesis gas. This study identified the optimal co-pyrolysis conditions (550°C with 32% waste plastic addition) to maximize the syngas' hydrogen, hydrocarbon, and calorific value, demonstrating minimal dependence on specific feedstock types.*
- *Challenges: the heterogeneous nature of plastic waste requires careful pretreatment and sorting to optimize co-pyrolysis efficiency. In addition, certain plastics, such as Polyvinyl Chloride (PVC), can form harmful byproducts during co-pyrolysis [53]–[55].*

II. Agricultural residues:

- *Availability: the Nigerian agricultural sector produces significant crop residues such as rice straw, corn stover, and bagasse. These residues often pose problems for disposal and can contribute to air pollution through* *combustion processes. Co-pyrolysis offers a valuable waste management strategy while simultaneously converting these residues into a usable energy source [56], [57].*

- *Synergistic effects: co-pyrolysis of plastic waste with agricultural residues can provide synergistic benefits. The cellulose content in biomass can increase syngas yield from plastic waste, while the plastic component can improve the overall energy density of the syngas [58], [59].*
- *Challenges: the amount of water and ash in agricultural waste can affect how well co-pyrolysis works and requires special pretreatment methods to function optimally.*

3.2 | Factors Affecting Energy Conversion Efficiency during Co-Pyrolysis

Optimizing energy conversion efficiency in co-pyrolysis requires careful consideration of various raw material properties, operating conditions, and reactor designs. Further research is required to develop robust models that predict syngas yield and quality based on specific feedstock mixtures and operating parameters. This will be critical for developing and operating co-pyrolysis systems for efficient syngas production tailored to distributed power generation in Nigeria. For decentralized power generation to work effectively, co-pyrolysis must convert the raw materials into usable synthesis gas as quickly as possible. Below are the key factors affecting energy conversion efficiency during the co-pyrolysis process.

3.2.1 | Raw material properties

The ratio of plastic waste to agricultural residues significantly influences the synthesis gas yield and quality [54]. Irawansyah et al. [60] found that increasing the amount of plastic in the raw material mixture can improve the thermal efficiency of syngas. Still, excessive plastic content can lead to slagging problems in the reactor. In order to find the optimal ratio, the synthesis gas quality must be brought into line with the reactor performance [61].

The moisture content of agricultural residues can negatively impact energy conversion efficiency. High moisture content reduces the heating value of the feedstock and consumes energy for water evaporation during the pyrolysis process [62]. Pretreatment techniques such as comminution, drying, or dechlorination can improve the suitability of these raw materials for co-pyrolysis [9], [53], [63].

How plastics and agricultural wastes break down at different temperatures affects the co-pyrolysis process. It is important to figure out how each part of the feedstock decays quickly to ensure that process variables such as temperature and residence time work best for syngas production [53], [64]–[67].

3.2.2 | Operating conditions

The reaction temperature is a critical parameter in co-pyrolysis. Sufficiently high temperatures are required for the thermal degradation of the raw materials and the production of synthesis gas. However, temperatures that are too high can promote undesirable reactions such as cracking, leading to lower synthesis gas yield and increased formation of undesirable byproducts [42], [68]–[71].

Adequate residence time allows for complete decomposition of the starting material and maximizes syngas yield. Residence time refers to the time the starting material spends in the pyrolysis Reactor. However, excessively long residence times can lead to secondary reactions that degrade the quality of the syngas [64], [71]–[75]. The addition of catalysts during co-pyrolysis can help convert raw materials into syngas more quickly [9], [69], [76], [77].

3.3 | Balancing Costs and Benefits

Assessing the economic feasibility of co-pyrolysis for waste management in Nigeria requires a comparison with the costs associated with traditional practices such as landfilling and incineration.

3.3.1 | Economic considerations for traditional waste management

Landfilling is Nigeria's most common waste management method, but often lacks adequate infrastructure and management [78], [79]. While initial setup costs may be lower compared to co-pyrolysis plants, landfills incur ongoing land acquisition, operation, and maintenance costs. Environmental pressures associated with leachate management and potential methane emissions may also increase long-term costs [80]. Incineration allows a reduction in waste volume but requires significant capital investments for plant construction and pollution control equipment. The operating costs associated with fuel combustion and maintenance can be high [81]. In addition, strict air emissions regulations are required to minimize health concerns from combustion byproducts [82]. By diverting waste from landfills or incineration, co-pyrolysis can result in cost savings in landfill or incineration fees. Depending on implementation and regulatory framework, co-pyrolysis projects that reduce greenhouse gas emissions compared to traditional waste management practices could be eligible for carbon credits, thereby generating additional revenue streams.

3.3.2 | Challenges and considerations

Construction of co-pyrolysis plants requires upfront investments in technology, reactor design, and infrastructure. Nigeria may need government subsidies or innovative financing mechanisms to encourage co-pyrolysis adoption. The operating costs of co-pyrolysis include raw material procurement, pretreatment, reactor operation, and synthesis gas processing. Optimizing raw material selection and minimizing pretreatment requirements can improve co-pyrolysis economics. Developing a reliable market for syngas produced through co-pyrolysis is critical to economic sustainability. This could include setting up mini-grids for local power generation or identifying industrial uses for the syngas at nearby sites.

3.4 | Techno-economic Assessment of Syngas Utilization: Exploring Potential Revenue Streams

Syngas produced through co-pyrolysis offer a versatile energy resource with the potential to generate revenue through various pathways. Focusing on developing mini-grids for off-grid electrification and exploring industrial applications for process heat and possible syngas upgrading can contribute to the economic sustainability of co-pyrolysis projects in Nigeria. The economic viability of co-pyrolysis distributed power generation projects in Nigeria through potential revenue streams from syngas utilization are explained below.

3.4.1 | Challenges and considerations

Mini-grids can generate electricity by using syngas from co-pyrolysis as fuel in internal combustion engines or gas turbines. This approach is particularly suitable for building mini-grids in off-grid communities in Nigeria and provides a reliable and sustainable source of electricity. Co-pyrolysis plants in areas with existing national grids can feed syngas directly into the grid, contributing to a cleaner and more diverse energy mix [83]–[85]. However, syngas quality and network connection requirements must be carefully examined.

3.4.2 | Industrial applications

Many industries require process heat for various applications. Co-pyrolysis creates synthesis gas, a clean and efficient alternative to fossil fuels for industrial heat generation [86]. Furthermore, Mariyam et al. [87] suggest using syngas to generate electricity for on-site industrial power needs. Syngas from co-pyrolysis can further be converted into chemicals such as hydrogen, methanol, or Fischer-Tropsch as desired. Various industries can purchase these products, generating additional revenue streams [64], [88].

3.4.3 | Factors affecting revenue streams

The economic viability of syngas utilization depends on access to reliable markets for electricity or industrial products generated from there. Developing mini-grids in off-grid communities or establishing partnerships with nearby industries can create stable demand for syngas from co-pyrolysis plants [64], [86].

Government policies and regulations on renewable energy sources, waste management, and carbon Emissions trading can significantly influence the economic attractiveness of co-pyrolysis projects. Supportive measures such as feed-in tariffs for renewable energy or carbon credits for converting waste into energy can incentivize the adoption of co-pyrolysis and improve revenue streams.

3.5 | Life Cycle Analysis

Conducting a Life Cycle Analysis (LCA) is critical for comprehensively assessing the environmental impacts of co-pyrolysis projects in Nigeria. A life cycle assessment considers all process phases, from raw material procurement and pretreatment to synthesis gas production and emissions control. This holistic approach helps to identify potential environmental hotspots and optimize the overall environmental performance of co-pyrolysis projects [89], [90].

3.6 | Mitigating Environmental Impacts: Emissions Control Strategies for Co-Pyrolysis

The co-pyrolysis process can produce air pollutants such as Nitrogen Oxides (NOx), Sulfur Oxides (SOx), Particulate Matter (PM), and Volatile Organic Compounds (VOCs). These pollutants can contribute to respiratory problems, acid rain, and smog formation [91]. Although co-pyrolysis can reduce greenhouse gas emissions compared to traditional waste management practices such as burning fossil fuels, the process still causes some CO_2 emissions. By optimizing the co-pyrolysis process and possible capture of CO_2, the overall greenhouse gas footprint can be further minimized [9], [91].

Implementing effective emissions control strategies is critical to minimize the environmental impact of the process. Co-pyrolysis for distributed power generation in Nigeria can be environmentally friendly by selecting the right raw material, optimizing the process, installing syngas purification systems, and following Best Management Practices (BMPs). LCA can provide valuable insights into optimizing the environmental performance of co-pyrolysis projects in the Nigerian context. While co-pyrolysis represents a promising solution for waste management and power generation, the environmental impacts associated with emissions must be carefully considered. The key emission control strategies to minimize the environmental footprint of co-pyrolysis plants in Nigeria are as follows:

I. Raw material selection and pretreatment: careful selection of raw materials containing few impurities, such as chlorine or sulfur, can significantly reduce the pollution produced by co-pyrolysis. Pretreatment techniques such as washing or size reduction can also improve feedstock quality and minimize emissions [92], [93].

II. Process optimization: optimizing operating conditions such as temperature, residence time, and reactor design improvement can help convert all syngas and reduce the production of waste products and emissions [94], [95].

III. Syngas purification systems: using downstream syngas purification systems to remove pollutants such as particles, tar and sulfur compounds before syngas use. Different syngas purification technologies may be required depending on the chosen application (power generation or industrial use) [96].

IV. BMPs: implementing BMPs for plant operations and maintenance can minimize fugitive emissions and ensure efficient operation of the co-pyrolysis process.

3.7 | Management of Coal Residues-Beneficial Applications versus Safe Disposal

Coal residue management is essential to ensuring the environmental sustainability of co-pyrolysis projects in Nigeria. Research into useful applications such as soil improvement, activated carbon production, or co-firing can provide economic and environmental benefits. Further research is needed to understand biochar's properties fully, determine whether recovery routes are possible, and determine how best to manage biochar within the LCA framework of the co-pyrolysis process in terms of environmental performance. The potential beneficial applications and safe disposal methods for coal produced during co-pyrolysis are highlighted below.

3.7.1 | Characteristics and potential applications of Char

Char properties, such as how much carbon it contains, how much heat it can store, and how much ash it contains, depending on the feedstock and the conditions of the co-pyrolysis process [97]–[101]. Understanding these characteristics is critical to determining appropriate management strategies.

Char can be processed and applied for soil improvement. Biochar has been shown to improve soil fertility and water retention and suppress soil-borne pathogens. However, further research is required to determine the feasibility of using co-pyrolysis coal in Nigerian agriculture, considering the potential presence of heavy metals and other pollutants [102]. Further processing of biochar with a large surface area produces activated carbon. Activated carbon can be used for water and air purification, pollutant removal from industrial processes, and energy storage [103]. However, careful assessment of charring properties and possible air emission problems is required [104].

3.7.2 | Safe disposal methods of char

Co-combustion of char with other fuels in cement kilns can be a viable option for safe disposal while potentially recovering some of the char's energy content [105]–[109]. Proper stabilization techniques can minimize leaching and environmental impact by landfilling Char.

4 | Knowledge Gaps and Pathway Analysis

While research on co-pyrolysis for syngas production for rural electrification in developing countries is promising, knowledge gaps and areas requiring further investigation remain. Addressing these limitations is critical to optimizing the technology's techno-economic and environmental performance in Nigeria.

4.1 | Co-pyrolysis Coal

Further research is required to understand the unique properties of coal produced by co-pyrolysis of various raw materials common in Nigeria. There is also a need to research the technical and financial feasibility of using co-pyrolysis coal for soil improvement, activated carbon production, or co-firing in Nigeria to reduce the overall environmental impact.

4.2 | Raw Material Availability and Sustainability

Research is needed to assess the long-term sustainability of raw material supply for co-pyrolysis plants in rural Nigeria. This requires an assessment of the availability of agricultural waste, considering their primary agricultural use and potential competition from other biomass utilization routes. Research is needed to optimize pretreatment techniques for various raw material combinations in Nigeria. This can improve conversion efficiency, reduce emissions, and improve the overall economics of co-pyrolysis projects [91], [110], [111].

4.3 | Feedstock Optimization

Research on raw material optimization is needed to identify the optimal combinations of plastic waste and agricultural residues commonly available for raw material mix optimization in Nigeria. These studies should investigate how different amounts of feedstock alter the quality (calorific value, composition, and amount of impurities formed during co-pyrolysis) of the synthesized gas produced. Understanding these synergies can maximize syngas production and minimize emissions. Various Nigerian raw materials can be converted more efficiently, emissions reduced, and co-pyrolysis projects can be more financially viable by developing and improving pretreatment methods such as size reduction, washing, or torrefaction [53], [112].

4.4 | Technology Development and Adaptation

There is limited real-world data on the Nigerian context's performance and economic feasibility of co-pyrolysis. Pilot and demonstration projects are essential for validating technology performance, optimizing operating parameters, and generating data for robust techno-economic analysis [56], [113]. Research efforts should explore the potential for local manufacturing of co-pyrolysis technology components in Nigeria. This can help reduce costs, create jobs, and build capacity to operate and maintain co-pyrolysis plants [114].

4.5 | Syngas Purification and Utilization

More research needs to be done on the techno-economic feasibility of various syngas purification methods that can work with the unique syngas composition produced by the co-pyrolysis of Nigerian raw materials. The trade-off between cleaning efficiency and cost must be carefully considered [115], [116]. Exploring the potential for syngas use beyond electricity generation in rural communities is valuable. This could include applications such as producing clean cooking fuels, synthetic natural gas for existing infrastructure, or raw materials for chemical production.

4.6 | Policy and Regulatory Framework

Developing a regulatory framework that promotes sustainable raw material sourcing practices and avoids competition with food security is critical to Nigeria's long-term viability of co-pyrolysis. Government policies that offer financial incentives, such as renewable energy feed-in tariffs or credit guarantees, can encourage investment in co-pyrolysis projects in rural areas. Furthermore, exploring mechanisms to mitigate the risks associated with technology adoption is important for private investors [117]–[119].

4.7 | Social and Environmental Impact Assessment

Studies are needed to assess the potential social impacts of co-pyrolysis projects on rural communities in Nigeria. These include considerations of employment opportunities, community involvement in project development and decision-making, and potential health risks associated with emissions. Developing strategies to maximize positive social impacts (creation of jobs, improvement of livelihoods) and mitigation of potential risks (health risks from emissions) is crucial for successful project implementation. The specific types of raw materials, conditions of the co-pyrolysis process, local waste management practices, and the need for rural electricity access in Nigeria are required.

4.8 | Pilot Scale Studies and Technology Development

Establishing pilot-scale co-pyrolysis plants in Nigeria is critical to generating real data on process performance, emission characteristics, and syngas quality. This data can validate techno-economic models, optimize operating parameters, and guide the design of larger commercial facilities. Pilot studies can also provide valuable insights into potential challenges and opportunities related to raw material logistics, plant operations, and syngas utilization. Exploring the potential for local manufacturing of co-pyrolysis technology components in Nigeria can help reduce costs. Creating jobs and building capacity for the operation and maintenance of co-pyrolysis plants. Locally manufactured components can make the technology more affordable and ensure that labor is readily available to operate and maintain the facility.

5 | Conclusion

Co-pyrolysis has the potential to revolutionize Nigeria's energy and waste management landscape through the collective efforts of policymakers, engineers, researchers, and local stakeholders. This innovative technology can convert waste biomass, such as agricultural residues, into clean energy while reducing the environmental impact of waste disposal. Using co-pyrolysis, Nigeria can significantly reduce its dependence on fossil fuels, reduce greenhouse gas emissions, and achieve a more sustainable future. This review highlights the promise of co-pyrolysis for sustainable distributed power generation in off-grid Nigerian communities. Knowledge gaps in feedstock optimization, syngas cleaning, and life cycle assessment have been highlighted, setting a clear pathway for further research and development. Policymakers can leverage these findings to develop policies that incentivize co-pyrolysis projects through feed-in tariffs or loan guarantees and establish a robust regulatory framework for sustainable feedstock sourcing and plant operation. Engineers can use this knowledge to optimize co-pyrolysis technology for efficiency, cost-effectiveness, and minimal environmental impact and develop and deploy pilot-scale plants to gather real-world data for future commercialization.

Author Contributions

The authors' contributions are: "The Conceptualization, Okwuchi Smith Onyekwere; Methodology, Okwuchi Smith Onyekwere and Adinife Patrick Azodo.; Validation, Okwuchi Smith Onyekwere., Amani David Haruna. and Adinife Patrick Azodo.; formal analysis, Okwuchi Smith Onyekwere and Adinife Patrick Azodo.; investigation, Okwuchi Smith Onyekwere and Adinife Patrick Azodo.; resources, Okwuchi Smith Onyekwere., Amani David Haruna. and Adinife Patrick Azodo.; writing-creating the initial design, Okwuchi Smith Onyekwere.; writing-reviewing and editing, Adinife Patrick Azodo. And Okwuchi Smith Onyekwere.; visualization, Amani David Haruna.; monitoring Amani David Haruna.; project management, Amani David Haruna.; funding procurement, Okwuchi Smith Onyekwere., Amani David Haruna. and Adinife Patrick Azodo. All authors have read and agreed to the published version of the manuscript. All Authors have made a significant contribution to the work reported.

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Data Availability

Some data were obtained from literature, which has been included in the references. No special permission was required to obtain and use the data.

Conflicts of Interest

The authors declare no conflict of interest. No Funders, other than the authors, played a role in the study's design, in the collection, analysis, or interpretation of the data, in the writing of the manuscript, or in the decision to publish the results.

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