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# Energy Use, Exergy Assessment, and Environmental Impacts of Agricultural Production and Agro-Processing Systems in Nigeria: A Systematic Review

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**ABSTRACT**

***Agriculture remains central to Nigeria's socio-economic development, providing livelihoods, food security, and raw materials for agro-based industries. However, the sector is characterised by high dependence on fossil energy, low thermodynamic efficiency, and increasing environmental pressures. Over the past two decades, a substantial body of Nigerian-based research has examined energy use patterns, exergy performance, life cycle environmental impacts, and biomass energy potential across agricultural production and agro-processing systems. This paper presents a comprehensive and integrative review of these studies, synthesising evidence from crop production, irrigation, agro-processing industries, and biomass resource assessments. The review shows that indirect energy inputs, particularly mineral fertilisers, agrochemicals, machinery manufacture, and diesel fuel, dominate total energy consumption in most farming systems. Exergy analyses consistently reveal high irreversibilities associated with combustion processes, fertiliser use, and inefficient thermal operations, especially in steam boilers and dryers used in agro-processing. Life cycle assessment studies identify fossil fuel use and agrochemical application as the main environmental hotspots, contributing significantly to greenhouse gas emissions, acidification, and eutrophication. In contrast, Nigeria possesses substantial biomass energy resources that could partially displace fossil fuels and improve system sustainability. The review concludes that meaningful sustainability gains will require integrated energy, exergy, and environmental optimisation across entire value chains, supported by coherent policy frameworks and targeted technological interventions***

## INTRODUCTION

Agriculture, a cornerstone of Nigeria's economy, significantly contributes to employment, food security, and the supply of raw materials for its agro-industrial sector (Jekayinfa, 2008). However, the sector grapples with challenges such as inefficient energy use, limited mechanization, environmental degradation, and fluctuating productivity (Jekayinfa, 2006; Edoja *et al.*, 2024; Ozigbu *et al.*, 2025). These issues are further compounded by a growing population, increasing demand for food in urban areas, climate change impacts, and rising fossil fuel costs (Abubakar, 2025; Balogun, 2024). Addressing these multifaceted problems requires a thorough understanding of energy dynamics and environmental impacts within Nigerian agricultural and agro-processing systems.

Efficient energy use is crucial at every stage of agricultural production, from land preparation and planting to harvesting, processing, and transportation (FAO, 2021). The types of energy inputs are diverse, including direct sources like human labor, diesel fuel, and electricity, and indirect sources embodied in fertilizers, agrochemicals, and machinery (Jekayinfa, 2006.;

Woods *et al.,* 2010). Inefficient energy use not only escalates production costs but also exacerbates environmental problems, contributing to greenhouse gas emissions, soil degradation, and water contamination (Olaniran et al., 2016; 2017).

Over the past two decades, substantial research has been conducted on energy use, exergy performance, environmental impacts, and biomass energy utilisation in Nigerian agricultural production and agro-processing systems. Studies by Jekayinfa (2006), Jekayinfa and Bamgboye (2007, 2008), Mohammed *et al*. (2013), Ohijeagbon *et al.* (2012, 2013), Olaniran *et al.* (2016, 2017), Fadara *et al.* (2019), Ola *et al.* (2019), Sanusi *et al.* (2020, 2024), Adeleke *et al.* (2022), Ndukwu *et al.* (2021), and other researchers have examined energy consumption patterns, thermodynamic performance, life cycle environmental impacts, and biomass resource utilisation across a wide range of agricultural systems. Collectively, these studies indicate that diesel fuel, mineral fertilizers, machinery operations, and thermal processing are major contributors to energy consumption and environmental burdens, while agricultural biomass resources offer considerable opportunities for improving energy sustainability. However, most of these investigations have focused on specific crops, processing operations, or individual analytical approaches, resulting in a fragmented body of knowledge. Consequently, there remains a need for an integrated synthesis that brings together evidence from energy analysis, exergy assessment, environmental impact evaluation, and biomass resource studies to provide a comprehensive understanding of sustainability challenges and opportunities in Nigerian agriculture.

This review aims to bridge this gap by providing an in-depth synthesis of the current state of knowledge on energy use, exergy performance, and environmental impacts in Nigerian agriculture, with a particular focus on agro-processing value chains and the potential for sustainable transitions. It will explore the following key areas:

1. Energy consumption patterns and efficiencies across diverse crop production systems, considering factors such as tillage practices, irrigation methods, and fertilizer application strategies (Sanusi *et al.,* 2024, Ola *et al.,* 2019).
2. Exergy analyses of agricultural and agro-industrial systems, highlighting areas of thermodynamic inefficiency and opportunities for improvement (Jekayinfa *et al.,* 2022; Ohijeagbon et al., 2012).
3. Environmental impacts of agricultural production and agro-processing, based on life cycle assessment (LCA) studies that quantify emissions, resource depletion, and other environmental burdens (Olaniran *et al.,* 2017; Olaniran *et al.,* 2016).
4. Assessment of Nigeria's biomass energy potential, evaluating the feasibility of utilizing agricultural residues and other biomass resources to displace fossil fuels in agricultural operations and rural energy systems (Jekayinfa and Scholz, 2013; Jekayinfa *et al*., 2020).

By integrating these dimensions, this review seeks to provide a holistic understanding of the sustainability challenges and opportunities facing Nigerian agriculture, offering a foundation for developing more efficient production systems, improving environmental outcomes, and supporting the transition toward cleaner energy sources. To ensure that the conclusions are supported by robust scientific evidence, this review primarily synthesises peer-reviewed studies reporting original research on Nigerian agricultural production and agro-processing systems, while authoritative reports from international organisations are used only to provide broader policy and global context.

## SYSTEMATIC REVIEW METHODOLOGY

This study adopts a systematic review approach guided by PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) to ensure transparency, reproducibility, and methodological rigor in synthesising literature on energy use, exergy performance, environmental impacts, and biomass energy potential in Nigerian agricultural and agro-processing systems.

### Literature Search Strategy

A comprehensive literature search was conducted across major scientific databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar. The search covered publications from 2000 to 2024 in order to capture both early foundational studies and recent developments.

Search queries were developed using combinations of keywords related to energy analysis, exergy analysis, life cycle assessment, environmental impact, biomass energy, agriculture, agro-processing, and Nigeria. Boolean operators were applied to refine the search and ensure adequate coverage of relevant themes. In addition, the reference lists of selected articles were examined to identify further studies not captured in the initial search.

### Study Selection and Eligibility

The selection of studies followed a structured screening process aligned with PRISMA principles. Initially, all records retrieved from the databases were compiled, and duplicate entries were removed. Titles and abstracts were then screened to eliminate studies that were clearly unrelated to Nigerian agricultural systems or the thematic focus of the review. Full-text articles of the remaining records were subsequently assessed against predefined eligibility criteria. Studies were retained if they addressed energy use, exergy performance, environmental impacts, or biomass energy potential within Nigerian agricultural production or agro-processing systems and provided sufficient methodological detail. Preference was given to peer-reviewed journal articles and authoritative institutional reports, while non-scholarly web sources were excluded from the analytical evidence base and used only where necessary for contextual background. A summary of the study selection process is presented in Figure 1 in the form of a PRISMA flow diagram.

| | |
|---|---|
| Identification<br>Records identified (n = 312)<br>Records after duplicates removed (n = 226) | Records excluded (n = 142) |
| Screening<br>Records screened (title/abstract)<br>(n = 226) | |
| Eligibility<br>Full-text articles assessed<br>(n = 84) | Full-text articles excluded (n = 31)<br>Reasons:<br>- Not Nigeria-specific<br>- Insufficient methodology<br>- No quantitative results<br>- Weak sources |
| Included<br>Studies included in qualitative synthesis<br>(n = 53) | |

Figure 1. PRISMA Flow Diagram

### Study Selection Results

The database search yielded a total of 312 records across Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar. After removal of 86 duplicate records, 226 unique records remained for screening.

Following title and abstract screening, 142 records were excluded due to lack of relevance to Nigerian agricultural systems or absence of energy, exergy, environmental, or biomass-related analysis. This resulted in 84 articles being retained for full-text assessment.

During full-text review, 31 studies were further excluded for reasons including insufficient methodological detail, lack of quantitative results, duplication of previously reported findings, or reliance on non-scholarly sources. Ultimately, 53 studies met the inclusion criteria and were included in the final synthesis.

**Data Extraction and Classification**

Relevant information was systematically extracted from each included study to enable comparison across different agricultural systems and analytical approaches. The extracted data included study characteristics, system boundaries, methodological approach (energy, exergy, life cycle assessment, or biomass resource analysis), key input variables, performance indicators, and principal findings.

The selected studies were then organised into four thematic groups corresponding to the core analytical dimensions of the review: energy use analysis, exergy assessment, environmental impact assessment, and biomass energy potential. This classification provided a coherent structure for synthesis and interpretation.

**Quality Appraisal of Included Studies**

To improve the reliability and transparency of the review, all included studies were subjected to a qualitative methodological appraisal before inclusion in the final synthesis. The appraisal focused on four criteria that were considered particularly relevant to studies of agricultural energy systems:

1. Methodological transparency, including the clarity of objectives, analytical procedures, and reporting of assumptions.
2. Definition of system boundaries, assessing whether the limits of the energy, exergy, environmental, or biomass assessment were clearly specified.
3. Data completeness and reporting quality, including the adequacy of input data, performance indicators, and presentation of results.
4. Analytical rigour, evaluated according to the accepted methodological standards for each analytical approach. For example, life cycle assessment studies were assessed with reference to the ISO 14040 and ISO 14044 framework, while energy and exergy studies were evaluated based on the consistency of energy accounting procedures and thermodynamic analysis.

Each study was assigned an overall quality rating of High, Moderate, or Low according to its performance across these criteria. Studies classified as High or Moderate quality formed the principal evidence base for the synthesis, whereas studies of lower methodological quality were used only to provide contextual information and were interpreted cautiously. Because of the substantial methodological heterogeneity among the included studies, particularly with respect to system boundaries, functional units, and analytical assumptions, a quantitative meta-analysis was not considered appropriate. Consequently, the findings were synthesised using a qualitative comparative approach.

The evidence synthesis prioritised peer-reviewed journal articles reporting original research. Authoritative reports from international organisations, including the Food and Agriculture

Organization (FAO), the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA), and the Intergovernmental Panel on Climate Change (IPCC), were used primarily to provide policy context and global comparisons. Non-peer-reviewed web sources were excluded from the analytical evidence base.

**Synthesis Approach**

A qualitative comparative synthesis was employed to integrate findings across studies. The analysis focused on identifying recurring patterns in energy use, major sources of exergy destruction, and dominant environmental impact pathways across agricultural value chains. Where possible, findings were interpreted in terms of the number and consistency of supporting studies, while also acknowledging variations arising from differences in system boundaries, assumptions, and methodological approaches.

Rather than treating all studies as directly comparable, the synthesis explicitly considers these differences in order to provide a more nuanced interpretation of the evidence and to avoid overgeneralization.

**Table 1. Characteristics and Principal Findings of Studies Included in the Systematic Review**

| Reference | Agricultural System/Sector | Analytical Approach | System Boundary | Key Indicators / Metrics | Principal Findings |
|---|---|---|---|---|---|
| Jekayinfa (2006) | Mechanised crop farming systems | Energy analysis | Farm-level operations | Energy input, energy ratio | Fossil fuel inputs dominated total energy consumption in mechanised farms |
| Jekayinfa & Bamgboye (2007) | Cassava-based food production | Energy analysis | Processing operations | Thermal energy demand, specific energy | Boiling and drying were the major energy-consuming operations |
| Jekayinfa & Bamgboye (2008) | Palm kernel oil mills | Energy analysis | Processing system | Energy productivity, energy efficiency | Thermal operations contributed most to total energy use |
| Jekayinfa et al. (2018) | Irrigation systems | Energy analysis | Irrigation pumping | Pumping energy requirement | Diesel-powered irrigation significantly increased energy demand |
| Ola et al. (2019) | Melon production | Energy analysis | Field production | Energy ratio, specific energy | Minimum tillage reduced total energy input while maintaining yield |
| Sanusi et al. (2020) | Cucumber production | Energy and economic analysis | Crop production system | Energy balance, economic return | Reduced tillage improved energy efficiency and profitability |
| Sanusi et al. (2024) | Fluted pumpkin production | Energy analysis | Crop production system | Energy productivity, energy use efficiency | Conservation tillage reduced fuel use and improved efficiency |
| Adeleke et al. (2022) | Groundnut production | Exergy analysis | Crop production system | Exergy efficiency, exergy destruction | Diesel combustion and fertilizer use were major sources of exergy loss |
| Jekayinfa et al. (2022) | Soybean production and processing | Energy and exergy analysis | Production and processing chain | Exergy efficiency, energy ratio | Significant exergy destruction occurred during |

| | | | | | |
|---|---|---|---|---|---|
| | | | | | processing operations |
| Ohijeagbon et al. (2012) | Steam boilers | Exergy analysis | Boiler operation | Exergy destruction, exergetic efficiency | Combustion and heat transfer losses caused major inefficiencies |
| Ohijeagbon et al. (2013) | Steam generation systems | Exergy methodology | Thermal systems | Physical and chemical exergy | Developed methodology for exergetic assessment of boilers |
| Olaniran et al. (2016) | Cassava starch production | Life cycle assessment | Cradle-to-gate processing | GWP, acidification, eutrophication | Diesel use and wastewater were major environmental hotspots |
| Olaniran et al. (2017) | Cassava flour production | Life cycle assessment | Production and processing chain | Emissions, environmental impacts | Fuel combustion and agrochemical use dominated impacts |
| Jekayinfa et al. (2013) | Soybean oil production | Life cycle assessment | Production-to-processing system | GHG emissions, resource use | Processing stages contributed heavily to environmental burdens |
| Jekayinfa et al. (2015) | Wheat production and processing | Life cycle assessment | Agricultural and processing chain | Environmental impact indicators | Fertilizer use and processing energy increased emissions |
| Jekayinfa & Scholz (2013) | Crop residue utilisation | Biomass energy assessment | National agricultural residues | Residue-to-product ratio, energy potential | Agricultural residues showed strong renewable energy potential |
| Jekayinfa et al. (2020) | National biomass resources | Biomass energy assessment | National biomass inventory | Technical biomass potential | Nigeria’s biomass potential estimated at approximately 2.33 EJ/year |
| Pecenka et al. (2020) | Woody biomass systems | Biomass energy analysis | Biomass supply chain | Energy demand, fuel quality | Biomass handling and storage influenced fuel quality and efficiency |
| Mohammed et al. (2013) | Biomass resources in Nigeria | Review of biomass systems | National energy systems | Biomass availability | Biomass resources could support rural energy development |
| Oyedepo (2012) | Small- and medium-scale industries | Energy efficiency assessment | Industrial operations | Energy intensity | Efficiency improvements could substantially reduce fuel demand |

**Methodological Approaches in the Assessment of Energy, Exergy, and Environmental Impacts**

The studies examined in this review employ a range of analytical methodologies that provide complementary perspectives on agricultural energy use and environmental performance. These methodologies can be broadly grouped into four main categories: energy analysis, exergy analysis, life cycle assessment (LCA), and biomass energy potential assessment. Together, they offer a structured framework for evaluating efficiency, sustainability, and environmental burdens in agricultural production and agro-processing systems. This section, summarised in Table 1, synthesizes how these approaches have been applied in the literature, with particular reference to studies conducted in Nigeria.

**Energy Analysis**

Energy analysis is the most widely applied methodological approach in studies of Nigerian agricultural systems. It involves quantifying all direct and indirect energy inputs used in agricultural production or processing and expressing them in standardized energy units, typically megajoules (MJ) per hectare or MJ per kilogram of output (Cleveland and Ruth, 1997). This standardization facilitates consistent comparison of energy use across crops, production systems, and management practices.

Direct energy inputs commonly include human labour, diesel fuel, electricity, and irrigation energy, while indirect inputs account for the energy embodied in fertilizers, pesticides, seeds, and machinery (Pimentel, 2004). The embodied energy of machinery is often estimated based on manufacturing energy requirements and allocated over the machine's service life and operating hours (Herendeen, 1974).

From these energy inventories, several performance indicators are typically derived, including: (i) the energy ratio, defined as the ratio of output energy to input energy and used as a measure of overall energy efficiency; (ii) energy productivity, expressed as the quantity of product generated per unit of energy input; (iii) specific energy, which indicates the energy input required per unit of output; (iv) net energy gain, calculated as the difference between output and input energy; and (v) the renewable energy fraction, representing the share of total energy input obtained from renewable sources. These indicators have been widely used to compare tillage systems, evaluate levels of mechanisation, assess input-use efficiency, and identify opportunities for improved resource management in Nigerian crop production systems (Sanusi et al., 2024; Ola et al., 2019).

**Exergy Analysis**

Exergy analysis extends conventional energy accounting by considering not only the quantity but also the quality of energy and by identifying the sources and magnitudes of thermodynamic inefficiencies within a system (Szargut et al., 1988). Unlike energy, exergy is not conserved; it is destroyed due to irreversibilities such as friction, chemical reactions, heat transfer across finite temperature differences, and mixing processes (Dincer and Rosen, 2013). As a result, exergy analysis provides deeper insight into where and how performance improvements can be achieved.

In the Nigerian context, exergy analysis has been applied to crop production systems, agro-industrial boilers, and other agricultural and processing operations (Jekayinfa et al., 2022; Ohijeagbon et al., 2012). These studies typically involve estimating the exergy content of all inputs and outputs, including physical exergy associated with temperature and pressure and chemical exergy related to the composition of fuels, fertilizers, and materials (Kotas, 1995). Exergy efficiency ($\eta_{ex}$) is commonly defined as the ratio of exergy output to exergy input, while exergy destruction or irreversibility is calculated as the difference between exergy input and exergy output.

Applications of this approach to Nigerian agricultural systems have consistently revealed substantial irreversibilities in mechanical operations, fertilizer production, and diesel combustion (Jekayinfa et al., 2022; Adeleke et al., 2022). These findings indicate significant potential for performance improvement through enhanced machinery efficiency, better nutrient management practices, and the adoption of cleaner and more efficient energy sources.

**Life Cycle Assessment (LCA)**

Life cycle assessment (LCA) is a comprehensive methodology for evaluating the environmental impacts associated with a product or service throughout its entire life cycle, from raw material extraction to end-of-life disposal (ISO 14040, 2006; ISO 14044, 2006). By accounting for resource use and emissions across all stages of a product system, LCA provides a holistic perspective on environmental performance, including impacts on climate change, ecosystems, and human health (Rebitzer et al., 2004).

In Nigeria, LCA has been applied to a range of agro-processing and agricultural production systems, including cassava flour production, cassava starch processing, soybean oil extraction, wheat production, and fruit juice manufacturing (Olaniran et al., 2017; Olaniran et al., 2016; Jekayinfa et al., 2015). These studies generally follow the ISO 14040 series framework, which comprises four main phases: (i) goal and scope definition, including specification of the functional unit; (ii) life cycle inventory analysis, involving the compilation of all material and energy inputs and environmental outputs; (iii) life cycle impact assessment, where inventory data are translated into impact categories such as global warming potential, acidification, eutrophication, and human toxicity; and (iv) interpretation, in which results are analysed to identify environmental hotspots and improvement options.

Across these applications, diesel combustion, fertilizer production, steam generation, and agrochemical use are frequently identified as dominant contributors to environmental burdens. Such results underscore the importance of cleaner energy sources, improved fertilizer management strategies, and reduced dependence on synthetic agrochemicals in enhancing the environmental sustainability of Nigerian agriculture.

**Biomass Energy Potential Assessment**

Biomass energy potential assessments are used to estimate the amount of energy that can be sustainably derived from biomass resources within a given region or country (IEA Bioenergy, 2018). These assessments typically consider multiple biomass sources, including agricultural residues, forest residues, energy crops, and organic wastes, and account for factors such as resource availability, residue-to-product ratios, conversion efficiencies, and calorific values.

In the Nigerian context, the assessment by Jekayinfa, Orisaleye, and Pecenka (2020) provides a comprehensive national inventory of biomass energy resources, estimating a technical potential of approximately 2.33 EJ per year. The study integrates agricultural and forestry statistics with assumptions on recoverable fractions and energy content of residues. The results suggest that biomass could play a substantial role in diversifying Nigeria’s energy mix, reducing dependence on fossil fuels, and supporting rural economic development through bioenergy value chains.

**Methodological Heterogeneity and Limitations of Existing Studies**

Although the analytical approaches reviewed provide valuable insights into the energy and environmental performance of Nigerian agricultural systems, comparisons among studies should be interpreted with caution because of considerable methodological heterogeneity. Energy analysis studies differ in their selection of energy-equivalent coefficients, treatment of indirect energy inputs, and definitions of system boundaries, making direct comparison of energy ratios and specific energy values difficult. Similarly, exergy studies employ different reference environments, assumptions regarding chemical exergy, and allocation procedures, which influence reported exergy efficiencies and exergy destruction values (Olayemi and Ayyoob, 2025; Nwanojuo et al., 2025).

Life cycle assessment studies also exhibit methodological differences in functional units, system boundaries (e.g., cradle-to-farm gate versus cradle-to-processing gate), inventory data sources, impact assessment methods, and allocation procedures for co-products. These differences can significantly influence estimates of greenhouse gas emissions, acidification, eutrophication, and other environmental indicators. Likewise, biomass resource assessments vary in their assumptions regarding residue-to-product ratios, recoverable fractions, moisture content, competing uses of residues, and conversion efficiencies, leading to considerable variation in estimates of technical biomass energy potential (Liu et al., 2024). These methodological differences do not diminish the value of the existing studies; rather, they highlight the need for greater harmonisation of analytical methods and reporting standards.

**Table 2. Summary of Methodological Approaches for Energy, Exergy, and Environmental Assessment in Agriculture**

| Methodological Approach | Purpose / What It Measures | Key Metrics & Indicators | Typical Data Required | Application in Nigerian Studies |
|---|---|---|---|---|
| **Energy Analysis** | Quantifies all energy inputs and outputs in crop production or agro-processing; evaluates efficiency | Total energy input; Output energy; Energy ratio; Energy productivity; Specific energy; Renewable vs. non-renewable share | Quantity of fuel, electricity, machinery hours, fertilizer and agrochemical use, labor hours, yield data | Used extensively for cucumber, melon, pumpkin, cassava, soybean, wheat, and fruit systems |
| **Exergy Analysis** | Evaluates the *quality* of energy; identifies thermodynamic irreversibilities and improvement potential | Exergy input; Exergy output; Exergy efficiency; Exergy destruction/irreversibility | Temperature, pressure, chemical composition of fuels, boiler data, process temperatures and flows | Applied in analysis of boilers, fruit juice plants, groundnut and soybean farming, steam generation systems |
| **Life Cycle Assessment (LCA)** | Assesses environmental impacts of a product or process from cradle-to-grave | Impact categories such as GWP, acidification, eutrophication, human toxicity, resource depletion | Inventory of all inputs, emissions, wastes, energy use, materials | Used for cassava flour, cassava starch, soybean oil, wheat systems, fruit juice processing |
| **Biomass Energy Potential Assessment** | Quantifies available biomass resources and their energy potential | Biomass resource availability; Residue-to-product ratio (RPR); Calorific value; Technical potential | Crop production statistics, forest data, residue generation rates | Applied in national biomass energy studies and renewable energy planning |

Future studies would benefit from the adoption of standardised system boundaries, transparent reporting of assumptions, and internationally recognised methodological frameworks to improve comparability and facilitate more robust evidence synthesis.

**Synthesis of Key Findings from Nigerian Studies**

This section synthesises empirical evidence from the studies included in this review and places these findings within the broader international literature on agricultural sustainability. Rather than assuming complete agreement among studies, the synthesis highlights the principal areas of convergence while acknowledging methodological differences and variations among agricultural systems.

**Energy Use Patterns in Crop Production Systems**

Among the crop production studies reviewed, the majority identified indirect energy inputs, particularly mineral fertilizers, agrochemicals and machinery manufacture, as the dominant contributors to total energy consumption, although the relative contribution varied with crop type, production system and level of mechanisation. This pattern mirrors global trends in modern agriculture, where embodied energy increasingly exceeds direct human and animal labour inputs (Pimentel, 2004; Woods et al., 2010). Early investigations of mechanised farming systems in southwestern Nigeria showed that fossil fuel–based inputs accounted for more than half of total energy consumption even at moderate levels of mechanisation (Jekayinfa, 2006). Subsequent crop-specific analyses across cereals, legumes, tubers, and horticultural crops have confirmed that fertilizer application and land preparation remain the principal energy sinks in Nigerian farming systems (Jekayinfa & Bamgboye, 2008; Jekayinfa et al., 2012; 2013).

Comparative studies on melon, cucumber and fluted pumpkin production all reported improvements in energy use efficiency under reduced or minimum tillage, although the magnitude of these improvements differed among cropping systems (Ola et al., 2019; Sanusi et al., 2020; 2024). Similar trends have been reported for plantain, mango, pineapple, soybean, and cassava production, suggesting that conservation-oriented tillage practices offer a practical pathway to energy savings without yield penalties (Jekayinfa et al., 2012; 2013).

The limited number of irrigation studies included in this review identified pumping operations as one of the largest consumers of on-farm energy (Jekayinfa et al., 2018). This observation is consistent with reports from other developing regions, where irrigation can account for 30–50% of total on-farm energy use (FAO, 2021). Collectively, these findings underscore the importance of energy-efficient irrigation technologies, including solar-powered pumping and improved water management strategies.

**Energy and Exergy Performance of Agro-Processing Systems**

Most agro-processing studies reviewed reported higher energy intensity than primary crop production, reflecting the dominance of thermal operations such as boiling, steaming, drying, roasting, and evaporation. Energy analyses of cassava-based foods, palm kernel oil processing, fruit juice production, poultry processing, bread baking, and cashew nut processing identify thermal energy as the principal contributor to total energy demand (Jekayinfa & Olajide, 2007; Waheed et al., 2008; Jekayinfa, 2007; 2008; Jekayinfa & Bamgboye, 2006).

The development of predictive energy requirement models for palm kernel oil mills and related processing systems represents an important step towards process optimisation and scale-up analysis in small- and medium-scale agro-industries (Jekayinfa & Bamgboye, 2007; 2008). Similar modelling approaches are widely recognised in the international literature as essential tools for benchmarking industrial energy performance and identifying efficiency improvement opportunities (Cleveland & Ruth, 1997).

Beyond conventional energy accounting, exergy-based studies provide deeper insight into energy quality degradation and system inefficiencies. Methodological and modelling work on oil-fired steam boilers commonly used in Nigerian agro-industries demonstrates that steam generation units are the dominant sources of exergy destruction, primarily due to combustion irreversibilities and heat transfer losses (Ohijeagbon et al., 2012; 2013; 2014; 2015). Applications of exergy analysis to crop production and processing systems further confirm substantial exergy destruction associated with diesel combustion, fertilizer production, and inefficient machinery operation (Adeleke et al., 2022; Jekayinfa et al., 2022). These results are consistent with international findings, which emphasise that improving exergy efficiency requires not only reducing energy consumption but also better matching energy quality to process requirements (Dincer & Rosen, 2013).

**Environmental Impacts and Life Cycle Hotspots**

The life cycle assessment studies included in this review generally identified fossil fuel consumption and agrochemical inputs as the dominant contributors to greenhouse gas emissions, acidification, and eutrophication, although the relative importance of each impact category varied among production systems (Olaniran et al., 2016; 2017). LCAs of cassava flour and cassava starch production systems identify diesel combustion and fertilizer-related emissions as dominant contributors to global warming potential, acidification, and eutrophication (Olaniran et al., 2016; 2017). Comparable environmental hotspots have been reported for wheat, soybean oil, and sweet orange production systems, where agro-processing stages often contribute more than half of total life cycle emissions due to energy-intensive thermal operations (Jekayinfa et al., 2013; 2015; Ogunlade et al., 2020).

These patterns are consistent with international LCA evidence, which indicates that downstream processing frequently dominates environmental impacts when inefficient energy systems are employed (Rebitzer et al., 2004). Consequently, improvements in the environmental performance of Nigerian agriculture cannot rely solely on farm-level interventions but require integrated, value-chain-wide optimisation strategies.

**Biomass Energy Resources and Renewable Energy Opportunities**

The biomass resource assessments reviewed indicate that Nigeria possesses considerable agricultural biomass resources; however, estimates of technical energy potential differ because of variations in assumptions regarding residue availability, competing uses, recoverable fractions, and conversion efficiencies (Jekayinfa & Scholz, 2009; 2013). This line of research was subsequently expanded into a comprehensive national assessment, which estimated Nigeria's technical biomass energy potential at approximately 2.33 EJ per year, underscoring the strategic role of biomass in diversifying the national energy mix (Jekayinfa, Orisaleye & Pecenka, 2020).

Comparable assessments by IEA Bioenergy (2018) likewise identify agricultural residues as key renewable energy resources in developing economies. Complementary studies on wood chip production from poplar, willow, and black locust further show that tree species selection, harvesting methods, and storage conditions strongly influence energy demand and fuel quality, with important implications for the sustainability and efficiency of biomass supply chains (Pecenka et al., 2020).

**Critical Evaluation**

Although the reviewed studies provide valuable information on energy use in Nigerian agriculture, direct comparison among them remains challenging because of differences in system boundaries, energy-equivalent coefficients, crop management practices, and reporting units. Most studies focus on individual crops or production systems within specific regions, limiting the generalisability of their findings to the national level. Furthermore, relatively few investigations have incorporated uncertainty analysis or sensitivity analysis to evaluate the robustness of reported energy performance indicators. Future studies should adopt harmonised methodologies and standard reporting protocols to facilitate meaningful comparison across agricultural systems.

**Integrated Interpretation of Energy, Exergy, and Environmental Dynamics in Nigerian Agriculture**

Evidence from Nigerian studies on energy use, exergy performance, and environmental impacts shows that sustainability challenges in agriculture are shaped by closely linked technical, agronomic, and infrastructural factors. Although many of the studies reviewed earlier focus on one analytical angle at a time, taken together they show that energy use, thermodynamic efficiency, and environmental performance are strongly connected. This means that improvements in agricultural production and agro-processing cannot be achieved by addressing these issues separately. They need to be considered together.

**Interactions among Energy Use, Exergy Efficiency, and Environmental Outcomes**

Patterns of energy use in Nigerian agriculture have clear effects on both thermodynamic performance and environmental impacts. Diesel plays a central role in this relationship. It is the main source of energy for land preparation, irrigation, and many agro-processing activities. However, diesel engines often operate at low exergy efficiencies, in many cases below 35 percent (Adeleke et al., 2022). The losses that occur during combustion appear in exergy studies as high exergy destruction and, at the same time, in environmental studies as high emissions of carbon dioxide, nitrogen oxides, and particulate matter (Olaniran et al., 2017).

Agrochemical use, especially nitrogen fertilizer, follows a similar pattern. These fertilizers contain large amounts of embodied energy and high chemical exergy because of the natural gas used in their production (Pimentel, 2004). When they are applied in excess or at the wrong time, they lead to nitrous oxide emissions and nutrient losses to water bodies. These have been identified as major environmental problem areas in Nigerian life cycle assessment studies (Olaniran et al., 2016; 2017). In this way, the same weaknesses identified by energy and exergy analysis also appear as key hotspots in environmental assessments.

**Systemic Sources of Inefficiency across Agricultural Value Chains**

The literature points to several recurring operational and technological problems that explain energy and exergy inefficiencies in Nigerian agriculture. At the farm level, intensive tillage and the use of old or poorly maintained tractors lead to high fuel use and low mechanical efficiency. Studies on melon, cucumber, cassava, and vegetable production show that repeated ploughing and harrowing increase energy input and exergy losses without giving matching increases in yield (Ola et al., 2019; Sanusi et al., 2024). Diesel powered irrigation pumps show similar weaknesses, with a large share of the input energy lost as heat (Jekayinfa et al., 2018).

The situation is often worse in agro-processing. Many cassava, palm oil, rice, and fruit juice processing plants rely on old boilers, inefficient steam generators, and poorly insulated dryers. Exergy studies of these systems report very high destruction levels, sometimes as high as 60 to 70 percent. These losses are mainly due to incomplete combustion, poor air fuel mixing, and heat losses through uninsulated surfaces (Ohijeagbon et al., 2012; Jekayinfa and Olajide, 2007). These technical weaknesses also show up in life cycle studies as high greenhouse gas emissions, particulate pollution, and heavy use of fuelwood (Olaniran et al., 2017). Because similar problems appear across many crops and processing chains, inefficiency seems to be a general feature of the system rather than a problem of a few isolated operations.

**The Role of Biomass Resources in Balancing Energy and Environmental Concerns**

Nigeria's agriculture produces large amounts of crop residues, and the areas with the most residues often overlap with areas that depend heavily on diesel and suffer large energy losses. Materials such as cassava peels, rice husks, maize cobs, sorghum stalks, and palm residues are common in the same regions where inefficient thermal processes and high fuel use are found (Jekayinfa and Scholz, 2013). This overlap suggests a clear opportunity to use biomass to reduce both energy and environmental problems.

Technologies such as briquetting, gasification, and anaerobic digestion can convert these residues into useful energy more efficiently than traditional firewood or diesel based systems. For example, gasifiers can reach exergy efficiencies above 55 percent, compared with about 20 to 30 percent for many conventional boilers (IEA Bioenergy, 2018). Studies on residue based energy systems in cassava, rice, and palm oil value chains show that replacing diesel or fuelwood with processed biomass can reduce greenhouse gas emissions, lower particulate pollution, and reduce pressure on forest resources (Jekayinfa et al., 2020). In addition, biochar produced from some of these processes can help improve soil quality and store carbon in the long term (Lehmann and Joseph, 2015). All these points suggest that biomass can help balance energy needs with environmental goals when it is properly integrated into agricultural systems.

**Implications for Future Transitions in Nigerian Agriculture**

The evidence reviewed here shows that improving sustainability in Nigerian agriculture will require combined efforts in energy use, thermodynamic performance, and environmental protection. Reducing dependence on diesel, improving soil and input management, upgrading thermal equipment, and making better use of agricultural residues should be treated as parts of one broad strategy. The studies suggest that real progress is more likely when renewable energy options are combined with better farming practices, improved processing technologies, and smarter residue management. This kind of integrated approach provides a sound basis for guiding future research, investment, and policy in the sector.

Although the reviewed evidence demonstrates strong interactions among energy use, exergy performance, and environmental impacts, relatively few Nigerian studies have evaluated these dimensions simultaneously within a single analytical framework. Consequently, many conclusions presented in this review are derived by integrating findings from separate studies rather than from comprehensive multi-criteria assessments. Future research should increasingly combine energy, exergy, life cycle assessment, and techno-economic analysis to provide a more holistic evaluation of agricultural sustainability.

**Energy Use Patterns in Nigerian Agricultural Production Systems**

Energy is a key input in crop production and plays an important role in shaping productivity, production costs, and environmental performance. In Nigeria, where farming ranges from smallholder systems to moderately mechanised commercial operations, patterns of energy use reflect differences in crop type, farming practices, labour availability, and access to technology. Building on the integrated view developed in the previous section, the literature reviewed here shows how energy is used across production activities and how these patterns affect both efficiency and sustainability in the sector.

**Dominant Energy Sources and Their Distribution**

Nigerian agriculture relies on a mix of human labour, fossil fuels, fertilizers, electricity, and biomass. The importance of each source varies across regions and farm sizes. Human labour remains a major source of energy in many smallholder systems, especially for crops such as cassava, maize, and vegetables where planting, weeding, and harvesting are largely done by hand (Fadara et al., 2019). Although this form of energy has little direct environmental impact, it often accounts for a large share of total energy use in low mechanisation settings.

Fossil fuels, especially diesel, are widely used for ploughing, harrowing, irrigation, transport, and threshing. As a result, diesel is one of the main contributors to total production energy in semi mechanised and mechanised farms (Ozigbu, Ezekwe, and Morris, 2025). This heavy reliance on diesel also exposes farmers to fuel price changes and adds to greenhouse gas emissions.

Fertilizers make up a large part of indirect energy input, particularly in cereal and legume systems where nitrogen application is common. Because nitrogen fertilizers require natural gas during production, their embodied energy is high. This makes fertilizer use an important part of the total energy budget in crops such as maize, soybean, and rice (Jekayinfa, 2008). Electricity plays a smaller role because grid supply is unreliable in many rural areas. Where it is available, it is mostly used for irrigation pumping and postharvest operations. In many cases, farmers rely on diesel generators instead, which further increases fossil fuel use (Uwaezuoke, and Nwulu, 2026).

Biomass energy is used more in agro-processing than in field production. Crop residues such as maize cobs and fuelwood are sometimes used for drying or heating in small scale operations. When these resources are not managed properly, their use can lead to local deforestation and air pollution, especially when harvesting exceeds natural regeneration rates (Bioenergy Potential in Nigeria, 2019).

**Crop Specific Energy Consumption Patterns**

Energy use differs widely among crops because of differences in cultivation methods, labour needs, irrigation, and fertilizer use. Rice, especially in lowland systems, requires a large amount of energy for land preparation and water management. Irrigated rice also uses considerable diesel for pumping, which makes it one of the more energy intensive crops in Nigeria (CABI, 2013). Cassava production depends heavily on manual labour for planting and harvesting, but even more energy is used after harvest because of the high moisture content of the roots and the need for peeling, grating, and drying (Jekayinfa and Olajide, 2007).

Maize production usually combines manual and mechanised operations, with land preparation and fertilizer application taking the largest share of energy. Vegetable crops such as tomato and pepper often require frequent irrigation and pest control, which increase both direct and indirect energy inputs (Veriv Africa, 2025). These differences among crops show the diversity of Nigerian agriculture and point to the need for energy management strategies that are suited to specific production systems.

**Table 3. Energy sources in Nigerian agriculture and associated environmental implications.**

| Energy Source | Application | Environmental Impact |
|---|---|---|
| Human Labor | Land preparation, planting, weeding, harvesting | Low, but can be physically demanding |
| Fossil Fuels | Tractors, irrigation pumps, transportation | High greenhouse gas emissions, air pollution |
| Fertilizers | Crop nutrition | High embodied energy, water pollution, soil degradation |
| Electricity | Irrigation, processing, storage | Depends on source of electricity generation (fossil fuels, hydro, renewable) |
| Biomass | Heating, drying | Deforestation, air pollution (if not sustainably sourced and efficiently combusted) |

The Role of Tillage Practices

Tillage practice has a strong influence on energy use in crop production. Conventional tillage, which involves repeated ploughing and harrowing, requires much more fuel and labour than conservation-based methods. Studies on melon, cucumber, and fluted pumpkin production show that minimum tillage reduces fuel use and total energy input while giving yields similar to those of conventional systems (Ola et al., 2019; Sanusi et al., 2024). Conservation tillage also helps improve soil structure and moisture retention, which can further lower energy needs in later farming seasons.

These results agree with findings from other countries, where reduced soil disturbance is linked to lower erosion, better soil organic matter, and higher energy productivity (Sadiq et al., 2025). In Nigeria, where many soils are already under pressure, conservation tillage offers both agronomic and energy related advantages.

6.4 Opportunities for Improving Energy Efficiency

There are several practical ways to improve energy efficiency in Nigerian agriculture. Wider use of conservation tillage can cut fuel consumption and support better soil health. More efficient irrigation methods, such as drip and sprinkler systems, can reduce the energy needed for vegetable and fruit production. Solar powered irrigation pumps also offer a way to reduce dependence on diesel and provide a more reliable energy source, especially in regions with high solar potential (Vijayakumar et al., 2023).

Better fertilizer management, including soil testing, more precise application, and greater use of organic inputs, can lower the embodied energy of crop production and reduce emissions linked to poor nutrient use (Graham et al., 2017). Agroforestry systems, which combine trees with crops, can improve soil fertility, provide shade, and supply biomass for energy. In this way, they support more sustainable production systems (Hans-Martin et al., 2025). When used together, these measures offer realistic paths to reducing both the energy intensity and the environmental impact of agriculture in Nigeria. These interrelated strategies for improving sustainability in Nigerian agriculture are illustrated schematically in Figure 1. When used together, these measures offer realistic paths to reducing both the energy intensity and the environmental impact of agriculture in Nigeria. The integrated relationship among conservation tillage, renewable energy use, improved nutrient management, and agroforestry systems is illustrated in Figure 2.

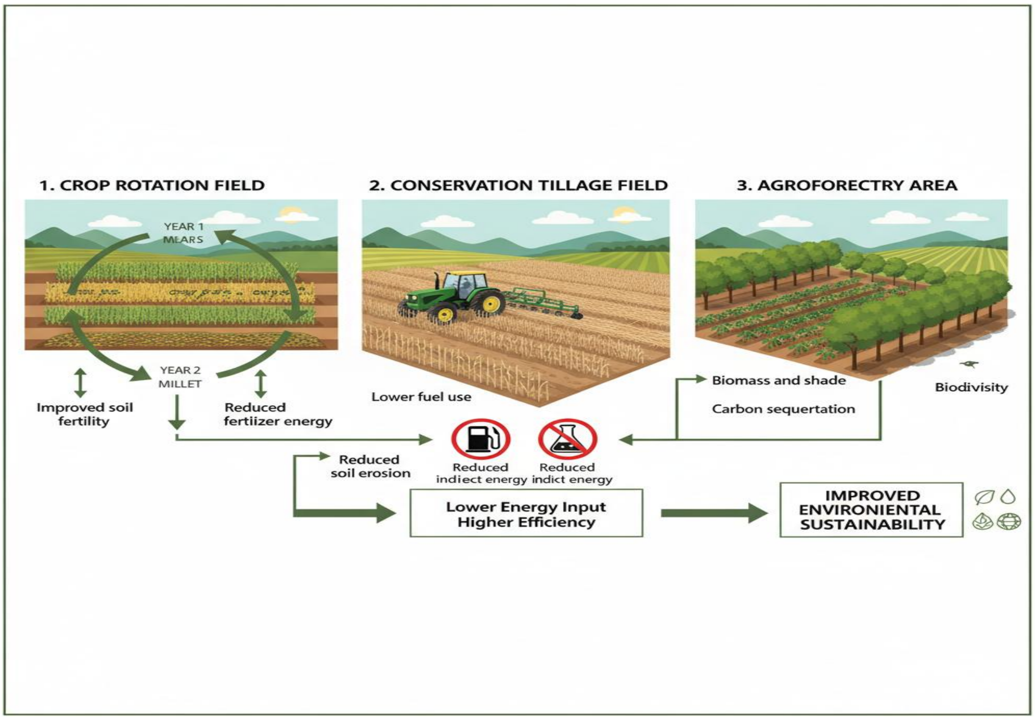


**Figure 2. Integrated sustainable farming practices for improving energy efficiency and environmental performance in Nigerian agriculture**.

The Path Forward: Towards Sustainable Agricultural Production

The current patterns of energy use in Nigerian agriculture show a sector that still depends heavily on fossil fuels, manual labour, and inefficient production methods. At the same time, the evidence reviewed here points to clear opportunities for improvement. By adopting conservation-based farming practices, modernising irrigation systems, expanding the use of renewable energy, and improving nutrient management, Nigeria can move towards a more energy efficient and environmentally sustainable agricultural sector. Reaching this goal will require joint efforts from farmers, researchers, policymakers, and development partners. The potential benefits for productivity, rural livelihoods, and environmental quality make this transition both necessary and worthwhile.

Most available studies focus on annual field crops, while relatively little information is available for perennial crops, livestock systems, protected cultivation, and integrated farming systems. In addition, many investigations are based on relatively small sample sizes or individual case studies, limiting the representativeness of reported energy indicators. Expanding research to a wider range of production systems and agroecological zones would improve understanding of national energy-use patterns.

**Exergy Analysis of Agricultural and Agro-Industrial Systems in Nigeria**

Exergy analysis has become an important tool for understanding energy quality and for assessing the real thermodynamic efficiency of agricultural systems. Traditional energy analysis shows how much energy is used in crop production or agro-processing, but it does not explain how effectively that energy is converted into useful work. Exergy analysis addresses this limitation by focusing on the useful work potential of energy inputs and by identifying where and how losses occur. This approach is especially relevant in Nigeria, where many agricultural operations depend on ageing machinery, inefficient thermal systems, and resource-intensive processes. The studies reviewed show that exergy analysis offers clearer insight into the sources of energy waste and provides more focused guidance for improving sustainability across agricultural value chains.

**Conceptual Basis for Exergy Assessment in Agricultural Systems**

Exergy refers to the maximum useful work that can be obtained from a system as it moves towards equilibrium with its surroundings. In agriculture, the concept can be applied to mechanical, chemical, and thermal processes, which makes it useful for assessing both farm operations and processing activities. Exergy analysis has long been used in engineering fields to identify inefficiencies in engines, combustion systems, and thermal plants. Its application to agriculture in Nigeria has grown steadily over the past two decades (Dincer and Rosen, 2013).In crop production systems, the main sources of exergy input include diesel fuel, fertilizers, agrochemicals, machinery, and human labour. Exergy losses occur through combustion losses in tractor engines, mechanical friction during field operations, heat losses in thermal processes, and inefficient use of fertilizers. Several studies show that diesel combustion alone accounts for a large share of total exergy destruction in farming operations (Adeleke et al., 2022). In addition, nitrogen fertilizers involve high embodied exergy because of the energy-intensive nature of their production, and poor use efficiency on farms leads to further losses through volatilisation and leaching.

**Exergy Flows in Crop Production Systems**

Studies on soybean, cassava, groundnut, maize, and vegetable production systems in Nigeria provide a clear picture of how exergy moves through different farming operations. Reported exergy efficiencies in these systems usually fall between about 45 and 65 percent, which means that a large fraction of the input exergy is lost through mechanical and thermal processes. The size of these losses depends on the type and condition of machinery, the intensity of tillage, and the level of fertilizer use. Tractor operations are among the largest sources of exergy destruction. Many tractors used in Nigerian agriculture are old and poorly maintained, which leads to low thermal efficiency and high losses from friction, heat dissipation, and incomplete combustion. Diesel powered irrigation pumps show similar behaviour, with much of the input energy ending up as waste heat rather than useful pumping work (Jekayinfa et al., 2018). Fertilizer production also contributes greatly to exergy input, but it is linked to high exergy losses when fertilizers are applied inefficiently in the field (Adeleke et al., 2022). These results suggest that better machinery performance, improved tillage practices, and more efficient fertilizer use could reduce exergy losses in crop production systems.

**Exergy Assessment of Agro-Industrial Processes**

Exergy analysis is even more important in agro-processing, where thermal operations account for a large share of total energy use. Nigerian agro-industries such as cassava processing plants, palm kernel oil mills, rice mills, and fruit juice factories depend heavily on boilers, dryers, steam generators, and mechanical equipment that often operate well below their optimal efficiency.

**Boiler inefficiencies**

Boilers used in cassava and palm kernel processing are among the main sources of exergy destruction. Studies by Ohijeagbon et al. (2012) and Olaniran et al. (2016) show that poor combustion control, weak insulation, heat losses through pipes, and unsuitable air to fuel ratios can lead to exergy destruction levels above 60 percent of the input. These losses not only waste fuel but also increase pollutant emissions.

**Cassava processing operations**

Cassava processing includes energy-intensive steps such as peeling, grating, dewatering, fermentation, and drying. Flash dryers and rotary dryers, which are common in small and medium scale factories, have been shown to produce large exergy losses because of high temperature differences and the lack of heat recovery systems (Jekayinfa and Olajide, 2007). The poor performance of these dryers adds greatly to fuel use and environmental impact. The major exergy streams and destruction pathways in a typical cassava processing plant are illustrated in Figure 3.

**Table 4: Typical Exergy Efficiencies for Major Nigerian Crops**

| Crop | Exergy Efficiency (%) | Key Sources of Exergy Loss | Reference |
|---|---|---|---|
| Cassava | 50 to 62 | Machinery friction, weeding operations | Jekayinfa and Olajide, 2007 |
| Soybean | 52 to 59 | Fertilizer production and diesel combustion | Adeleke et al., 2022 |
| Groundnut | 48 to 55 | Diesel combustion during land preparation | Jekayinfa, 2008 |
| Wheat | 45 to 50 | Irrigation pumping and intensive tillage | Sanusi et al., 2024 |
| Vegetables | 55 to 65 | Pumping inefficiencies and fertilizer application losses | Ola et al., 2019 |

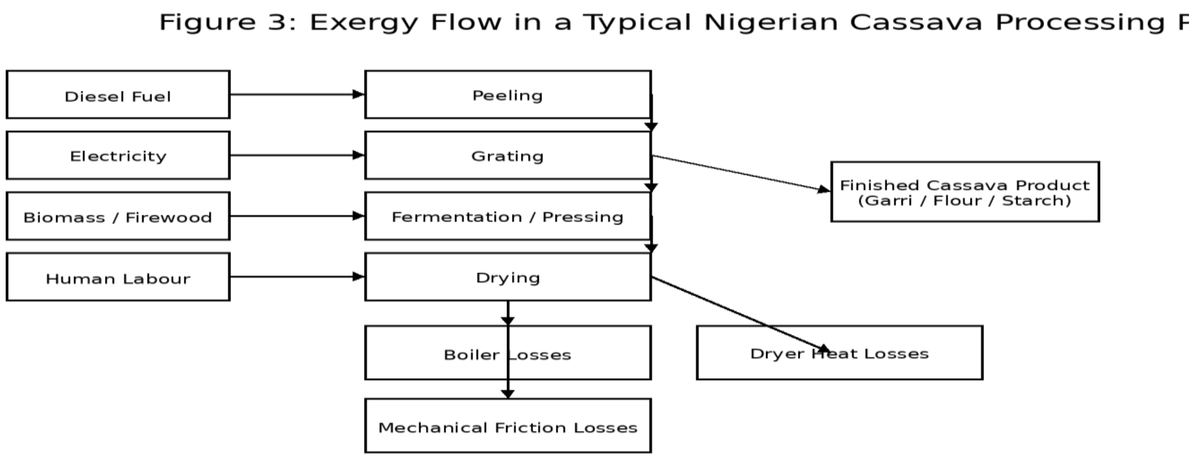


**Figure 3. Exergy flow diagram showing major exergy inputs, useful outputs, and destruction points in a typical Nigerian cassava processing plant.**

Fruit juice processing relies heavily on pasteurisation and sterilisation, both of which involve high heat input. Many plants use old steam generators and poorly insulated heating chambers, which results in large heat losses and low exergy efficiency (Olaniran et al., 2017). Other industries, such as rice milling, also show high exergy losses during parboiling and drying, mainly because of large temperature differences and inefficient heat transfer.

**Table 5: Exergy Performance of Selected Nigerian Agro-industries**

| **Industry** | **Exergy Efficiency (%)** | **Dominant Sources of Exergy Destruction** |
|---|---|---|
| Cassava processing | 18 to 32 | Flash drying, steam generation, fermentation heat losses |
| Palm kernel oil extraction | 25 to 40 | Boiler inefficiencies and mechanical friction in screw presses |
| Fruit juice processing | 20 to 30 | Pasteurization, sterilization, and temperature gradient related losses |
| Rice milling | 30 to 45 | Parboiling and drying operations |

**Exergy Based Environmental Implications**

Exergy losses in agricultural and agro-industrial systems have clear environmental effects. High exergy destruction in diesel engines leads to increased emissions of carbon dioxide, particulate matter, and nitrogen oxides. Inefficient boilers and dryers raise the demand for firewood and crop residues, which contributes to deforestation and indoor air pollution in many rural areas. Exergy losses linked to fertilizer use also cause environmental problems through nitrous oxide emissions, eutrophication, and soil acidification (Olaniran et al., 2016). These links show that improving exergy performance can reduce environmental impacts while also cutting fuel use and production costs.

**Opportunities for Reducing Exergy Destruction**

The literature points to several practical ways of reducing exergy losses in Nigerian agricultural systems. Better maintenance and proper calibration of tractors and pumps can lower friction losses and improve performance. Upgrading irrigation systems, using solar powered pumps, and adopting efficient electric motors can improve the useful output obtained from energy inputs. In agro-processing, better combustion control, improved insulation, waste heat recovery, and modern boiler designs can greatly reduce thermal losses.

Improved fertilizer management, including more accurate application and greater use of organic inputs, can also reduce chemical exergy losses. Heat integration in processing plants offers further opportunities. For example, warm exhaust air from dryers can be used to preheat incoming wet materials, which would reduce temperature differences and lower exergy destruction. Such improvements are well known in industrial practice and could be applied more widely in Nigerian agro-industries.

Although exergy analysis provides deeper insight into thermodynamic inefficiencies than conventional energy analysis, its application within Nigerian agriculture remains relatively limited. Differences in reference environments, assumptions regarding chemical exergy, and system boundary definitions make comparison of reported exergy efficiencies difficult. Moreover, exergy studies have largely focused on crop production and steam boiler systems, with comparatively little attention given to livestock production, cold-chain operations, postharvest handling, and integrated bioenergy systems. These areas represent important opportunities for future research.

**Environmental Impact Assessment of Agricultural Systems in Nigeria**

Environmental impact assessment has become essential for understanding how agricultural activities influence ecosystems, soil and water quality and greenhouse gas emissions. In Nigeria, where agriculture is both a major livelihood source and a driver of land use change, studies increasingly apply life cycle assessment methods to quantify the environmental implications of crop production and agro processing. The reviewed literature demonstrates that environmental impacts vary across crops and production systems, yet certain patterns appear consistently across value chains. These patterns reflect the influence of fertilizer use, fuel combustion, irrigation practices and biomass extraction on emissions, resource depletion and ecological integrity.

**Greenhouse Gas Emissions from Crop Production**

Fertilizer use and fossil fuel combustion are the major contributors to greenhouse gas emissions in crop production. The application of nitrogen fertilizers generates nitrous oxide, which has a global warming potential far higher than carbon dioxide. Several studies, including those by Olaniran et al. (2016) and Adeleke et al. (2022), report that nitrous oxide emissions represent a significant share of total greenhouse gas output for crops such as maize, rice and vegetables. These emissions are typically associated with poor fertilizer management practices, including excessive application, improper timing and the absence of soil testing. Diesel use in land preparation, irrigation and transportation also contributes significantly to greenhouse gas emissions.

The widespread use of old tractors and inefficient irrigation pumps increases fuel consumption and results in higher emissions of carbon dioxide and nitrogen oxides. Studies that compare manual and mechanised operations show that mechanised farms often have higher per hectare emissions, although this difference narrows when yields are taken into account (Ozigbu, Ezekwe and Morris, 2025). These findings indicate that the environmental footprint of crop production depends not only on energy use but also on the efficiency with which that energy is converted into productive output.

**Soil Degradation and Nutrient Losses**

Soil degradation represents one of the most critical environmental challenges associated with Nigerian agriculture. Intensive tillage, continuous monocropping and poor residue management accelerate the decline of soil organic matter and increase erosion rates. Conservation tillage and crop rotation have been shown to improve soil structure and reduce erosion, yet adoption remains limited in many farming communities (Sustainable Farming Practices in Nigeria, 2025). Nutrient losses from fertilizer misapplication contribute further to soil degradation. Excessive nitrogen and phosphorus application can lead to soil acidification, nutrient imbalance and reduced microbial activity. These problems are particularly pronounced in high input vegetable systems, where farmers often rely on heavy fertilizer use to compensate for poor soil quality (Veriv Africa, 2025). Fertilizer runoff into surface water bodies also contributes to eutrophication, which affects aquatic ecosystems and water quality in farming regions.

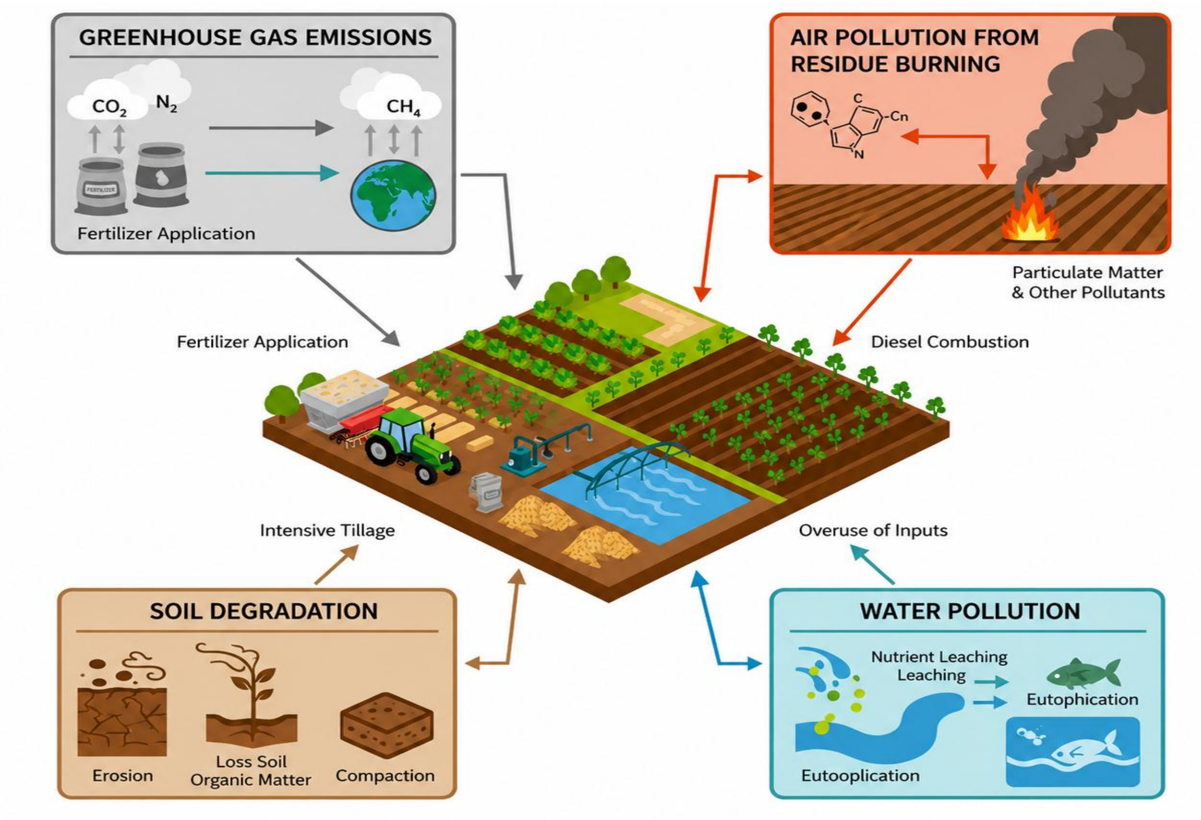


**Figure 4. Major environmental impact pathways associated with energy use in Nigerian agricultural production systems.**

**Table 6: Estimated Biomass Availability from Major Nigerian Crops**

| Crop | Annual Residue Production (Million Tons) | Typical Energy Content (MJ/kg) | Principal Residues | Source |
|---|---|---|---|---|
| Rice | 5.2 | 14–17 | Husk, straw | Jekayinfa and Scholz (2009) |
| Cassava | 55–60 | 16–18 | Peels, stalks | Jekayinfa and Olajide (2007) |
| Maize | 15–20 | 15–17 | Stover, cobs, husks | Olaniran et al. (2017) |
| Sorghum | 10–12 | 14–16 | Stalks, leaves | FAO (2014) |
| Oil Palm | 8–10 | 17–20 | Shells, fibers, empty fruit bunches | Ohimain (2013) |
| Groundnut | 3–5 | 14–16 | Shells, husks | Adeleke et al. (2022) |

The interconnections between fossil fuel use, fertilizer application, emissions, and ecological impacts are summarised in Figure 4. These residues have strong potential for thermal energy generation, briquette production, biogas, syngas, biodiesel, ethanol, and combined heat and power applications in agro-processing communities.

Environmental Impacts of Irrigation and Water Use

Irrigation plays an important role in vegetable and rice production but also generates environmental impacts when not properly managed. Diesel powered pumps release emissions and contribute to noise pollution, while inefficient water application methods lead to waterlogging, salinisation and nutrient leaching. In many northern Nigerian farming communities, irrigation water is extracted from shallow aquifers that are already under pressure due to population growth and climate variability. Over extraction poses long term risks to water security and soil fertility (CABI, 2013).

Recent studies highlight the potential benefits of solar powered irrigation and improved water application techniques. Drip irrigation, for example, not only reduces water use but also lowers nutrient losses and minimizes soil erosion. However, adoption remains limited by initial investment costs and lack of technical knowledge among farmers.

**Biomass Burning and Deforestation Impacts**

Biomass remains widely used as an energy source in rural Nigeria, particularly in small scale processing activities such as cassava drying, palm oil extraction and fish smoking. Firewood extraction contributes to deforestation in many regions, particularly in areas where natural regeneration is slow or land conversion pressures are high. Studies by Olaniran et al. (2017) and Bioenergy Potential in Nigeria (2019) show that unsustainable wood harvesting is a major driver of forest degradation in southwestern and central Nigeria.

Open burning of crop residues is also common and contributes to particulate emissions, carbon monoxide release and nutrient loss from soils. These practices reduce soil fertility, worsen air quality and increase greenhouse gas emissions. Improved residue management strategies such as mulching, composting and biochar production have shown promise in reducing environmental impacts while enhancing soil health.

**Environmental Burdens from Agro-industrial Processing**

Agro-industrial systems such as cassava processing plants, rice mills and palm kernel oil mills contribute significantly to environmental degradation through emissions, wastewater discharge and solid waste generation. Thermal systems in processing plants often operate with low efficiency, resulting in excessive fuel consumption and air pollution. Flash dryers, rotary dryers and boilers release particulate matter and greenhouse gases due to poor combustion efficiency and inadequate air fuel control (Ohijeagbon et al., 2012).

Wastewater from cassava processing contains high concentrations of organic matter and cyanogenic compounds, which can contaminate surface and groundwater if not properly managed. Rice mills generate husk residues that are often burned in the open, releasing emissions and creating waste disposal challenges. Palm kernel mills produce large quantities of shell and fibre residues, which are sometimes used inefficiently or burned without emission control systems. These environmental burdens highlight the need for improved waste management and cleaner processing technologies.

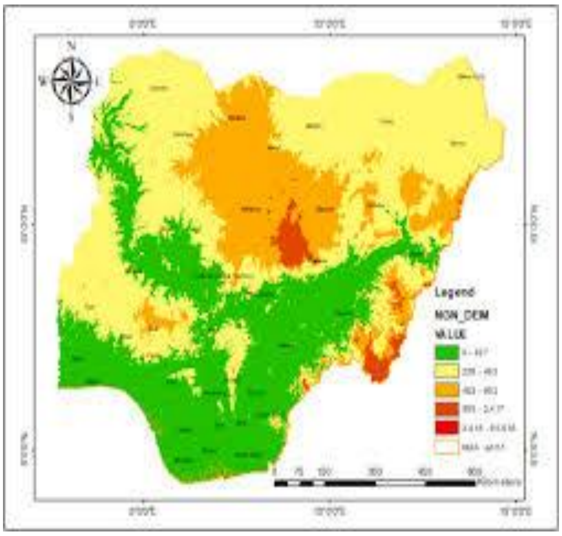


Figure 5: Geographic distribution of major agricultural biomass resources across Nigeria.

Figure 5 is a geographic representation of biomass availability across Nigeria. The map highlights regions with high concentrations of cassava, rice residues, oil palm residues, and livestock manure. It shows the Niger Delta as a major palm biomass zone, the North Central region as high in cassava residues, and the North West as high in cereal residues.

Life cycle assessment studies conducted in Nigeria remain relatively few compared with energy analysis studies, and most employ cradle-to-gate rather than cradle-to-grave system boundaries. Differences in inventory databases, impact assessment methods, and allocation procedures also limit direct comparison among studies. Greater adoption of internationally harmonised LCA methodologies and locally representative life cycle inventory databases would substantially improve future environmental assessments.

**Biomass Resource Potential and Renewable Energy Opportunities in Nigerian Agriculture**

Biomass resources represent one of the most important renewable energy opportunities available to the Nigerian agricultural sector. Large quantities of crop residues, processing by products, and animal wastes are generated each year, yet only a small fraction is effectively used as an energy resource. Much of the remainder is burned in the open, left to decay, or disposed of in ways that create environmental and health risks. Recent studies have increasingly examined how agricultural biomass can be harnessed to reduce dependence on fossil fuels, improve rural energy access, and enhance environmental sustainability. The evidence suggests that, if properly collected, processed, and integrated into local energy systems, agricultural residues could play a central role in supporting cleaner energy transitions in Nigeria (Adeshina, et al., 2024).

**Availability and Distribution of Biomass Resources**

The availability of biomass in Nigeria is closely linked to the spatial distribution of agricultural production. States with high outputs of cassava, rice, maize, sorghum, and oil palm also generate large quantities of residues. Cassava peels, maize cobs, sorghum stalks, rice husks, and palm kernel shells are among the most abundant agricultural biomass resources, and they are produced in significant volumes across the southwest, southeast, and north central regions. Jekayinfa and Scholz (2013) estimate that Nigeria generates tens of millions of tonnes of agricultural residues annually, a quantity sufficient to support a wide range of bioenergy applications.

Residue availability depends on harvest intensity, crop type, and processing practices. For instance, rice mills in major producing states such as Kebbi, Niger, and Ebonyi generate large volumes of husk and bran, while cassava processing centres in Oyo, Ogun, and Kogi produce substantial amounts of peels and fibrous waste. Despite this abundance, many residues remain underutilised because of weak collection systems, high transportation costs, and limited access to suitable biomass conversion technologies.

**Energy Potential of Agricultural Biomass**

Assessments of the energy potential of Nigerian agricultural residues show that these materials have sufficient calorific value to serve as practical substitutes for diesel, firewood, and other conventional fuels. Cassava peels have moderate energy content and can be converted into briquettes or pellets that burn more efficiently than raw biomass. Rice husks, although high in silica, are suitable for combustion and gasification when properly processed. Palm kernel shells have relatively high heating values and are already used in some regions as boiler fuel because of their favourable combustion properties (Bioenergy Potential in Nigeria, 2019).

When aggregated across major crops, the total energy potential of agricultural biomass exceeds the energy demand of many agro industrial operations. This indicates that biomass could significantly reduce fossil fuel use in cassava factories, rice mills, and palm oil mills if effectively integrated into their energy systems. Converting residues into briquettes, biogas, or producer gas also offers opportunities to improve exergy efficiency by promoting more complete combustion and reducing thermodynamic losses.

**Biomass Conversion Technologies and Their Suitability**

Several biomass conversion technologies have been examined in the Nigerian context, with their suitability depending on residue type, local infrastructure, and energy demand. Briquetting and pelletisation are among the most accessible options. These processes produce dense solid fuels that burn more consistently and efficiently than raw residues. Briquettes made from cassava peels, maize cobs, and rice husks have shown good combustion performance and can replace firewood in small and medium scale processing operations (Jekayinfa et al., 2020).

Gasification converts solid biomass into producer gas, which can be used for power generation or thermal applications. Experimental applications in rice mills and cassava drying facilities indicate that gasifiers can achieve higher exergy efficiency than diesel generators and traditional boilers. Anaerobic digestion, which produces biogas from animal waste and organic residues, has also been investigated, particularly in mixed crop livestock systems. However, its adoption remains limited due to technical, financial, and management challenges.

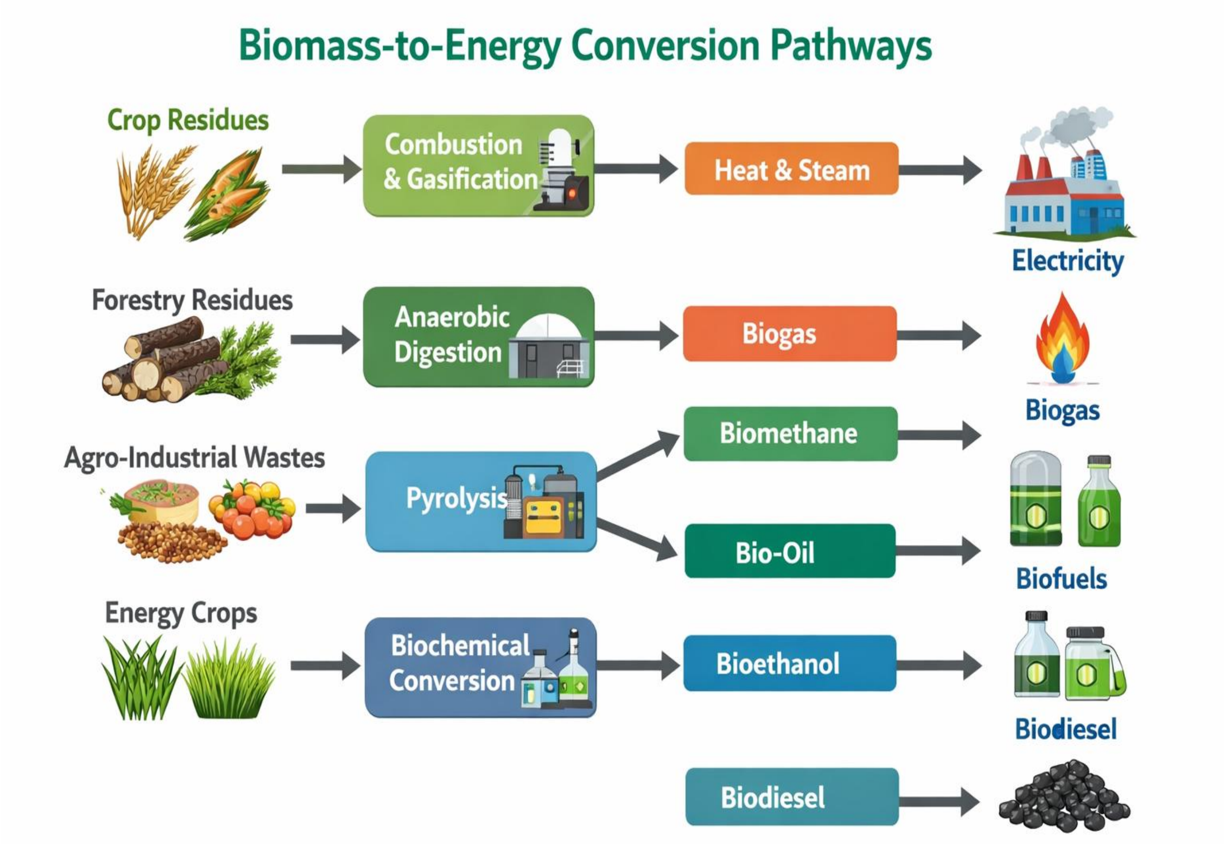


Figure 6. Biomass-to-energy conversion pathways applicable to Nigerian agricultural residues.

The choice of technology depends strongly on feedstock quality, moisture content, and proximity to processing centres. Systems that require steady and uniform feedstock supply, such as gasifiers, are better suited to locations with concentrated residue production, whereas briquetting technologies can be applied more flexibly at different scales. The main technological pathways for converting agricultural residues into useful energy products are presented in Figure 6.

Environmental Benefits of Biomass Energy

The environmental benefits of biomass energy arise mainly from its ability to replace fossil fuels, reduce open residue burning, and lower greenhouse gas emissions. When used in place of diesel, biomass can reduce emissions of carbon dioxide, nitrogen oxides, and particulate matter associated with engine and boiler operation. In thermal applications, briquettes and pellets generally burn more cleanly than firewood, leading to improved indoor and outdoor air quality. In addition, the utilisation of residues helps to curb open burning, a practice that contributes to air pollution, nutrient loss from soils, and greenhouse gas emissions (Olaniran et al., 2017).

Biochar, a by-product of some biomass conversion processes, offers further environmental advantages. When applied to soil, biochar can improve soil structure, enhance nutrient retention, and contribute to long term carbon sequestration. These co benefits make biomass energy an attractive option not only for energy supply but also for soil restoration in degraded agricultural landscapes.

9.5 Barriers to Biomass Energy Adoption

Despite its potential, several factors limit the widespread adoption of biomass energy in Nigerian agriculture. Access to modern biomass technologies such as efficient stoves, briquetting machines, and gasifiers remains limited, particularly in rural areas. High initial investment costs and weak financial support mechanisms further constrain uptake. The collection and transportation of residues also present major challenges, especially for bulky materials like maize stover and sorghum stalks. Poor rural infrastructure and the dispersed nature of smallholder farming systems make residue aggregation difficult and costly.

Institutional and policy barriers also play a role. Current energy policies provide few specific incentives for biomass utilisation, and coordination between agricultural and energy sector institutions remains weak. In addition, limited technical capacity among farmers and processors restricts the operation and maintenance of biomass systems. These constraints point to the need for stronger policy support, targeted financial incentives, and capacity building initiatives.

9.6 Summary

Biomass resources offer substantial renewable energy opportunities for the Nigerian agricultural sector. The country produces large quantities of residues with significant energy potential, and several proven technologies are available for converting these materials into useful energy. The environmental benefits include reduced fossil fuel use, lower emissions, and improvements in soil quality. However, technical, financial, and institutional barriers continue to limit large scale adoption. Overcoming these challenges will be essential for integrating biomass energy into agricultural development strategies and for advancing cleaner and more resilient energy systems in Nigeria. Figure 7 shows a systems diagram showing the relationships among diesel consumption, exergy losses, emissions, residue burning, and biomass availability. Arrows indicate feedback loops that reinforce or weaken sustainability outcomes. Figure 8 shows a bar chart comparing typical exergy destruction in boilers, dryers, tractor engines, rice hullers, cassava processing units, and palm oil digesters. The systemic relationships among diesel use, exergy losses, emissions, residue burning, and biomass potential are illustrated in Figure 7. A comparative analysis of typical exergy destruction across selected agricultural and agro-industrial systems is presented in Figure 8. Although Nigeria possesses substantial biomass resources, estimates of energy potential should be interpreted cautiously because they are based primarily on technical availability. Many studies assume that all crop residues are recoverable for energy production, whereas in practice significant proportions are retained on fields for soil conservation, used as livestock feed, or lost during collection, storage, and transportation. Future assessments should distinguish more clearly between theoretical, technical, economic, and sustainable biomass potential to provide more realistic estimates for energy planning.

**Figure 7. Systems interaction map showing feedback relationships among energy use, exergy destruction, emissions, and biomass availability in Nigerian agriculture.**

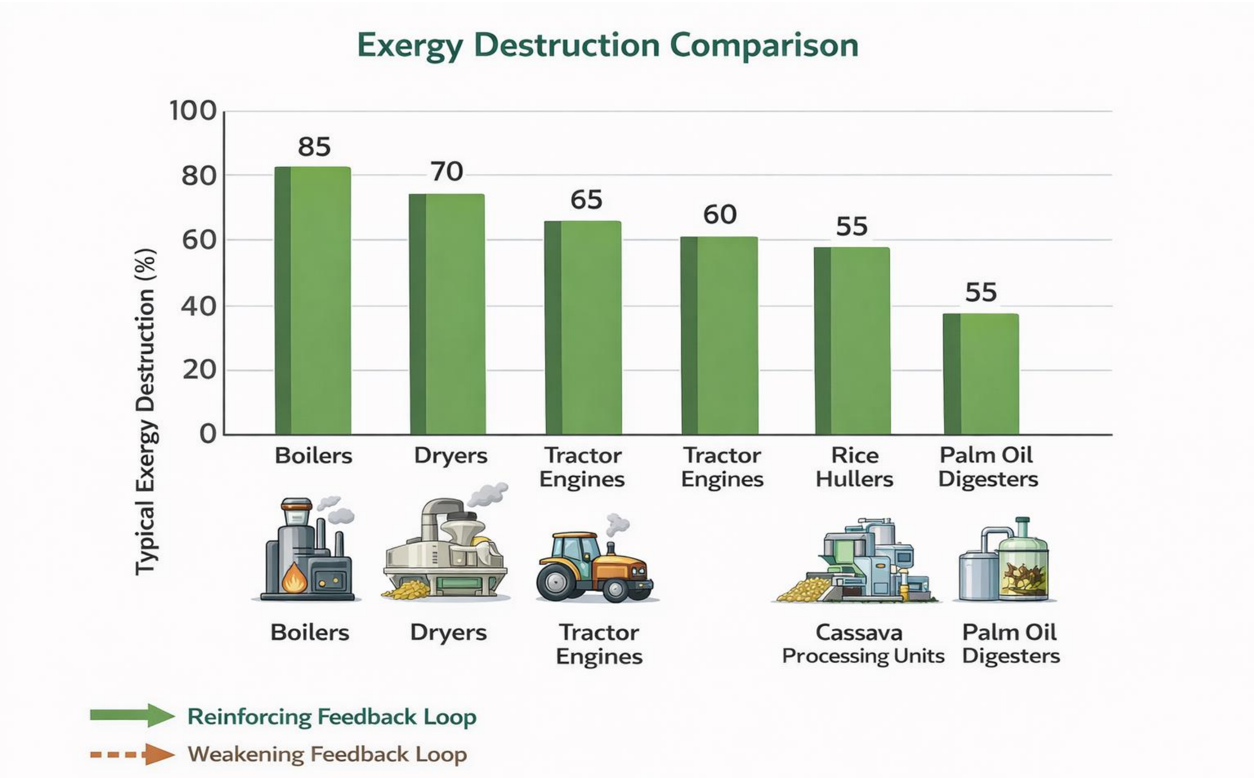


**Figure 8: Exergy Destruction Comparison**

**Socioeconomic Factors Influencing Energy Use and Environmental Performance in Nigerian Agriculture**

Energy use and environmental performance in Nigerian agriculture are shaped not only by technological factors but also by socioeconomic conditions that influence farmers' decisions, resource access and production practices. Rural livelihoods depend heavily on smallholder farming systems, and variations in income, education, land tenure, market access and institutional support exert a strong influence on how energy inputs are managed across value chains. The literature shows that socioeconomic conditions determine the adoption of improved machinery, fertilizer use practices, irrigation technologies and environmental management strategies. These factors collectively govern the sustainability and efficiency of production systems.

**Income Levels and Access to Production Technologies**

Farm income remains one of the strongest determinants of energy use patterns in Nigerian agriculture. Farmers with higher income levels are more likely to adopt mechanised equipment, modern irrigation systems and renewable energy technologies that reduce labour burdens and improve productivity. Studies by Veriv Africa (2025) and Ozigbu, Ezekwe and Morris (2025) show that wealthier farmers adopt tractors, power tillers and improved pumps at significantly higher rates than those with lower incomes. This income-based disparity results in uneven energy efficiency across farming communities. Low income farmers often continue to rely on manual labour and traditional tools, which limit their capacity to scale up production and adopt environmentally responsible practices.

Access to credit also plays an important role. Farmers who have access to loans or cooperative financing are better equipped to invest in efficient machinery, agrochemicals and postharvest equipment. Without credit, many smallholders are forced to rely on outdated or suboptimal methods that increase energy waste and environmental degradation.

**Education, Training and Technical Knowledge**

Education level strongly influences farmers' ability to adopt energy efficient technologies and sustainable farming practices. Farmers with higher education or regular exposure to extension services tend to adopt better fertilizer management, improved irrigation methods and conservation tillage practices. These practices reduce both energy input requirements and environmental burdens.

Lack of technical knowledge is a major barrier to adopting renewable energy systems such as solar powered irrigation pumps or biomass gasifiers. Several studies highlight that even where technologies are physically available, poor understanding of operation, maintenance and repair leads to underutilisation or abandonment (Sustainable Farming Practices in Nigeria, 2025). Training programs offered by agricultural extension agents, universities and development organisations have been shown to improve technology adoption and reduce environmentally harmful practices.

**Land Tenure Systems and Farm Size**

Land tenure arrangements influence both investment decisions and energy use patterns. Farmers with secure land rights are more likely to invest in long term soil conservation methods, improved irrigation systems and efficient machinery. In contrast, farmers with temporary or uncertain access to land often avoid long term investments and rely on short term production strategies that increase soil degradation and energy inefficiency (CABI, 2013).

Farm size also affects energy use. Larger farms tend to adopt mechanisation, which increases fuel use but can reduce overall energy intensity when measured per unit of output. Smaller farms typically rely on manual labour, resulting in lower fuel consumption but also lower productivity. Studies comparing farm sizes indicate that energy efficiency tends to improve in medium sized farms where mechanisation is moderate and fertilizer application is more precise.

**Market Access and Infrastructure**

Access to markets influences farmers' willingness to invest in improved production technologies. Farmers situated closer to urban centres or processing locations are more likely to adopt efficient irrigation systems, improved seeds and better machinery, because reliable markets reduce financial risk and increase returns on investment. Poor rural infrastructure, including dilapidated roads and limited storage facilities, increases transport energy use and postharvest losses, which in turn raises the overall environmental footprint of production (Olaniran et al., 2016).

Market demand also shapes energy use patterns. High value crops such as tomatoes and other vegetables attract more intensive irrigation and fertilizer use, particularly when market prices are favourable. Conversely, low market prices discourage farmers from investing in efficient technologies, leading to continued dependence on low input and low productivity methods.

**Institutional Support, Policies and Governance**

Government policies and institutional frameworks play a critical role in shaping agricultural energy use. Policies promoting mechanisation, fertilizer subsidies and irrigation development directly influence farmers' production choices. However, the absence of coherent renewable energy policies and limited coordination between agricultural and energy ministries restrict the diffusion of cleaner technologies such as solar irrigation and biomass conversion systems (The Role of Renewable Energy, 2025).

Weak extension services also limit the dissemination of best practices related to energy efficiency and environmental management. In areas where extension services are well organised, farmers show higher adoption of conservation tillage, better fertilizer scheduling and improved residue management strategies. Conversely, lack of institutional support perpetuates inefficient production systems and increases environmental impacts.

**Social and Cultural Influences on Energy Use**

Cultural practices and traditional norms continue to influence decisions related to land preparation, residue management and the adoption of new technologies. In many communities, traditional tillage methods are preferred because they are culturally familiar and require no specialised knowledge. These practices often increase energy use and soil degradation. Similarly, open burning of crop residues persists despite environmental and health risks, largely because it is a long established practice and provides a quick means of field clearing.

Gender roles also affect energy use patterns. Women, who often manage small garden plots and household processing activities, rely heavily on manual labour and biomass fuels. Limited access to machinery, credit and training constrains their ability to adopt energy efficient technologies, resulting in higher labour intensity and environmental burdens in gendered agricultural tasks.

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