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Circular Economy Adoption in Agriculture: Potential for Sustainable Food Production in Nigeria

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ABSTRACT

Nigeria's vast fertile land and significant agricultural productivity underscore its potential to become a global agricultural powerhouse. With 70.8 million hectares of agricultural land and major crops like cassava, maize, and yam contributing substantially to the economy, Nigeria reached a remarkable milestone as the world's largest cassava producer in 2017. However, these achievements are increasingly threatened by challenges such as inefficient resource utilization, climate change, land degradation, and low technological adoption, emphasizing the urgent need for a transformative shift in agricultural practices. This paper explores the potential of circular agriculture as a sustainable approach to food production in Nigeria. Using a comprehensive literature review methodology, the paper analyzes circular agricultural practices and evaluates its applicability to Nigeria's agricultural landscape. It further highlights existing challenges, assesses the principles, frameworks, and practices of circular agriculture by examining relevant global case studies of successful implementations. Findings from this study suggest that adopting circular agricultural practices can mitigate inefficiencies, enhance resource management, and promote sustainable food production. Additionally, the paper identifies critical gaps in research and policy support and proposes actionable steps, including the development of national frameworks, technological integration, and educational programs to drive the transition toward circular agriculture. Ultimately, this study concludes that the adoption of circular agriculture is essential for ensuring long-term food security, addressing environmental challenges, and supporting sustainable development within the context of Nigeria's growing population.

Keywords: *Circular agriculture, Food Security, Sustainable Agriculture, Circular Economy, Sustainability.*

1.0 Introduction

Agricultural practices are essential for global food security, but many current methods are unsustainable, contributing to land degradation, biodiversity loss, and climate change. The agricultural sector remains a vital part of the global economy, contributing 4% to global GDP and over 25% in some developing countries [7]. However, this dependence on agriculture comes with environmental costs, especially in regions like Africa, where agricultural expansion since the 1960s has accelerated deforestation, biodiversity loss, and greenhouse gas emissions[10] for agriculture account for 18.4% of global emissions [25] and agriculture occupies 50% of the Earth's habitable land, producing 25–30% of global emissions [29]. These figures highlight the urgent need for more sustainable agricultural practices to protect planetary health.

Traditional agricultural methods often rely on heavy inputs of chemical fertilizers and synthetic pesticides, degrading soil quality and depleting natural resources. Global fertilizer use increased from 12 million tons in 1961 to over 110 million tons by 2018 [16]. Similarly, fertilizer use in Nigeria rose significantly from 0.1 kg per hectare in 1961 to approximately 22.6 kg per hectare by 2020[33], despite some fluctuations over the years—including a notable drop to around 7.2 kg/ha in 2022. Although various factors may have contributed to these variations, the overall trend reflects a substantial increase in fertilizer application compared to the previous century.

This linear model of agriculture, based on resource extraction and waste generation, worsens soil depletion, water scarcity, and ecosystem degradation [24].

Intensive farming methods, including monoculture and the use of heavy machinery, lead to soil erosion and the loss of nutrients, which gradually diminish soil fertility [35,36]. Moreso, a shift toward industrial agriculture has led to the destruction of natural habitats, a decline in biodiversity, and a rise in greenhouse gas emissions, all of which have disrupted ecosystem functions [35,37]. With an estimated three billion new middle-class consumers by 2030 and food demand projected to rise by 50% by 2050, continuing current practices could double agriculture-related CO_2 emissions. These projections make it clear that a shift toward sustainable agriculture is not only desirable but essential.

The solution lies in transitioning to a circular economy model that promotes sustainable production and consumption across entire agricultural lifecycles. Circular agriculture focuses on reducing waste, reusing resources, and recycling materials to optimize natural resource use while minimizing pollution [38,39,40]. By moving away from linear practices, circular agriculture offers a regenerative approach that addresses key issues like climate change, soil degradation, biodiversity loss, and deforestation [17,41,42]. Adopting circular agriculture is not just an opportunity but a necessity to meet the rising food demands of a growing global population while safeguarding environmental sustainability for future generations.

2.0 Agricultural Situation in Nigeria

Nigeria boasts a vast expanse of fertile land, with 70.8 million hectares dedicated to agricultural purposes. The country's major crops include maize, cassava, guinea corn, yam, beans, millet, and rice [12]. In 2017, Nigeria produced 59 million tons of cassava, making it the world's largest producer, accounting for approximately 20% of global production [12]. Similarly, Nigeria's rice production increased from 3.7 million metric tons in 2017 to 4.0 million metric tons in 2018 [12]. Moreso, other major crops produced in Nigeria include guinea corn, yam beans, millet, and rice, amongst others. This remarkable productivity highlights Nigeria's significant economic potential in agriculture. However, Nigeria's Agricultural prospects face substantial threats due to persistent challenges due to unsustainable practices in the sector and looming environmental challenges.

Despite agriculture's crucial contribution to Nigeria's economy, it faces inefficiencies, particularly in resource utilization. Fertilizer application, for example, poses severe environmental consequences [22,28]. [12] underscores that agricultural practices in Nigeria contribute significantly to environmental degradation and advocate for an urgent balance between productivity and sustainability. According to the [12], Nigeria's agricultural sector faces numerous challenges, including poor land tenure systems, limited irrigation farming, climate change impacts, land degradation, low technological adoption, high production costs, inefficient input distribution, limited financing, significant post-harvest losses, and inadequate market access. Inefficient agricultural practices are further exacerbated by the low education levels among Nigerian farmers [28]. Again, rising temperatures and unpredictable rainfall negatively impact both crop productivity and livestock well-being [47]. With the population projected to reach 400 million by 2050, enhancing agricultural productivity through the adoption of new technologies and innovations is imperative to ensure food security and nutrition [12]. The challenges posed by current agricultural practices highlight the need for Nigeria to transition towards a more sustainable farming model to fully realize its agricultural potential.

While increasing productivity remains essential, it is equally critical to address the environmental consequences of conventional methods. Adopting sustainable agricultural practices that promote environmentally responsible food production is vital for meeting the needs of a growing population while maintaining ecological balance and ensuring long-term agricultural resilience.

2.1 Understanding Circular Agriculture

The concept of circular agriculture is closely related to climate-smart agriculture and other sustainable farming methods; however, it is fundamentally rooted in the principles of the circular economy. Circular economy aims to eliminate waste and regenerate natural systems by optimizing products and materials, addressing environmental challenges such as climate change, biodiversity loss, waste, and pollution [10,43,44,45]. When applied to agriculture, these principles promote the efficient and sustainable use of materials and natural resources, maximizing output while minimizing resource consumption.

Circular agriculture is also referred to as climate-smart, resilient, regenerative, or conservation agriculture, and represents a food system that works in harmony with nature while fulfilling societal needs [17]. Regenerative and circular agricultural practices help lower greenhouse gas emissions, enhance climate resilience, and create economic opportunities [46]. This approach contrasts with conventional, linear agriculture, which has long dominated global food production but is associated with significant environmental impacts.

The Koronivia Joint Work on Agriculture, established at COP23 in 2017, underscores the need for improved soil and water management, optimized nutrient use, and effective livestock practices to reduce emissions while safeguarding food security [20].

Historically, circular agricultural practices have existed in many parts of the world since the pre-industrial era. These practices naturally aimed to reduce reliance on external inputs, restore ecosystems, and minimize environmental impacts. For instance, circular agriculture helps reduce pressure on agricultural land, preventing deforestation and lowering carbon emissions by reducing transportation needs in food distribution [29]. Additionally, the increasing scarcity of phosphorus (P), an essential component of inorganic fertilizers, underscores the urgency for agricultural systems that prioritize nutrient recycling and reduce reliance on finite resources [30].

The growing threat of natural resource depletion, coupled with rising global food demands, has accelerated the adoption of circular economy principles in agriculture as a strategic approach to sustainable development [24,48]. Many authors emphasize the concept of circular agriculture as a sustainable agricultural practice that ensures nature regeneration, a closed nutrient loop, reduces environmental leakages, and maximizes circularity of value, while ultimately enabling minimal environmental impacts on biodiversity loss, soil degradation, and climate change [32,1,7,30,18]. In essence, this circular agriculture is simply a process of practicing agriculture that minimizes resource use, prevents waste generation, and promotes economic, social, and environmental benefits.

2.2 Principles of Circular Agriculture

Circular agriculture distinguishes itself from conventional agricultural practices by emphasizing sustainable and resource-efficient approaches grounded in the principles of the circular economy [49]. Although various authors have proposed principles to guide circular agriculture, some have been criticized for lacking a comprehensive, holistic perspective. For instance, three phases of circular agriculture have been introduced, sustainable production, sustainable use, and efficient recycling, emphasizing the integration of reuse and recycling within both production and consumption processes [16]. Their approach advocates for practices such as repurposing animal manure as organic fertilizer and utilizing wastewater for irrigation, rather than treating recycling as a distinct and separate step. Similarly, [1] highlighted the importance of leveraging natural processes and limiting harmful inputs. They focused on resource efficiency by promoting the cycling of nutrients, energy, and water while transforming waste streams into valuable inputs within the food production chain to minimize losses.

However, it was argued that existing principles of circular agriculture often concentrate on agricultural production and environmental sustainability, without fully addressing the broader dimensions of agricultural systems [7]. To bridge this gap, they proposed a more comprehensive framework encompassing technical, economic, social, and environmental aspects across the entire agri-food value chain. Their principles include eco-friendly technology application, resource efficiency, and waste valorization, offering a more integrated and holistic perspective.

Building on existing research, a synthesized set of principles for circular agriculture has emerged, drawing from the contributions of various scholars and institutions [32,11].

These principles include three core strategies: designing out waste and pollution, keeping products and materials in use, and regenerating natural systems. They provide a solid foundation for building environmentally friendly, resource-efficient, and sustainable agricultural systems, collectively forming a unified framework that tackles key environmental, social, and economic challenges in agriculture, fostering long-term resilience and sustainability.

2.2.1 Designing out waste and pollution

This principle focuses on minimizing the excessive use of harmful inputs, such as synthetic chemicals, which can contaminate soil, especially in developing countries. [7] expand on this by emphasizing the role of eco-friendly technologies and sustainable farming practices to enhance agroecosystem resilience and reduce reliance on synthetic inputs. Supporting this, [32] highlight the effectiveness of integrated systems like crop-livestock production in reducing chemical usage, which aligns with broader efforts to reduce pollution and improve farm sustainability.

2.2.2 Keeping products and materials in use

This second principle underscores the importance of efficient resource utilization across the entire agri-food supply chain. This involves efficient use of agricultural resources, co-products, and by-products to avoid waste. Both [32,7] advocate for resource efficiency through practices like organic farming, agroforestry, and circular aquaculture. Advances in technology further support this principle by enabling the conversion of organic waste into valuable outputs, such as bioenergy, soil amendments, and bio-fertilizers, ensuring resources remain useful rather than wasted.

2.2.3 Regenerating Natural Systems

This third principle focuses on enhancing ecosystem health and resilience through regenerative agricultural practices. These practices, as outlined by [32], contribute to minimizing greenhouse gas emissions by capturing carbon in soils while improving soil fertility and ecosystem performance. [7] similarly stress the ecological benefits of circular agricultural methods, which promote the conservation and restoration of natural systems. Circular agriculture fosters a robust agro-ecosystems that reduce dependency on external inputs like chemicals while promoting nutrient cycling and reducing food waste by reusing by-products.

2.3 Frameworks of Circular Agriculture

Circular agriculture, rooted in the principles of the circular economy, follows a similar conceptual framework. Numerous contemporary studies have proposed robust frameworks for circular agriculture. For instance, [16] reviewed existing literature and advocated for a more comprehensive approach. [3] introduced a circular model based on a 6R framework including rethink, refuse, reduce, reuse, recover, and repair, drawing inspiration from the Ellen MacArthur Foundation's butterfly model, which integrates economic, social, and environmental dimensions. Similarly, [6] expanded the concept by prioritizing each level of circularity through an ambitious 9R framework.

[4] synthesized existing frameworks into a holistic 10R framework encompassing rethink, repurpose, refuse, reduce, reuse, repair, refurbish, remanufacture, recycle, and recover. This framework focuses on minimizing the consumption of natural resources while maximizing the utilization of waste materials. While acknowledging these frameworks, [16] emphasized the importance of aligning them with agricultural development strategies. They also highlighted the need to enhance efforts in resource recovery, including land, water, climate, and biological resources. These frameworks, derived from the principles of circular economy, are critical for promoting uniform and sustainable practices globally.

3.0 Nigeria's Current Position on Circular Agriculture

Circular agricultural practices have long existed in Nigeria, often embedded in traditional systems and referred to by various terminologies. However, the most significant recent governmental effort to institutionalize circular economy principles within the agricultural sector is the launch of the *Nigeria Circular Economy Roadmap* [29]. This roadmap identifies agriculture as a priority sector and aims to catalyze governance support for enabling a circular transition in agriculture and food systems. Its objectives include promoting the adoption of circular business models in agriculture, encouraging investments and technological advancements, and supporting the development of indigenous circular innovations and solutions [9,50]. The roadmap emphasizes applying circular economy principles across multiple agricultural subsectors, including livestock, forestry, and fisheries, and extends to processing and waste management along the agri-food value chain. To the best of current knowledge, this marks the first national policy in Nigeria that holistically prioritizes a circular approach to agriculture, moving beyond a narrow focus on food production alone.

Nonetheless, the roadmap has notable gaps. For instance, it does not comprehensively address aspects such as crop production. Furthermore, the successful implementation of circular agriculture will depend significantly on the integration of core circular economy principles—namely, designing out waste and pollution, keeping products and materials in use, and regenerating natural systems [32,11].

Achieving effective circular agriculture in Nigeria will also require aligning national policies with established frameworks. In particular, the policy integration of the circular agriculture framework proposed by [4], which is compatible with broader national agricultural development strategies suggested by [16], could strengthen implementation and sectoral impact.

4.0 Measuring Circularity in Agriculture: Indicators, Frameworks, and Evolving Perspectives

Circular agriculture depends on quantifiable indicators to assess environmental impact and sustainability. However, inconsistencies in existing indicators pose challenges for researchers, policymakers, and funding agencies. For instance, [2] highlights that investors and public funding bodies increasingly demand quantifiable data to support and validate circular models. In response, various monitoring frameworks have been introduced globally to track material flows and assess circularity at different scales and supply chain levels.

In the Netherlands, a national monitoring framework measures material inputs and outputs, recycling rates, and restorative material flows, including bio-based materials. Similarly, the [8] developed a tool to evaluate circularity by assessing product-level material flows through input and output analysis. Key indicators for circularity in food systems include material loss and food waste reduction, reuse and recycling of bio-based materials, pesticide and fertilizer usage, nutrient balance and cycling efficiency, renewable energy adoption, carbon emissions, and economic benefits from circular business models.

While these indicators effectively capture specific components of circular agriculture, they may be less applicable across all system dimensions. To enhance the understanding of nutrient cycling, [31] introduced two key circularity indicators:

- **Cycle Count (CyCt):** Measures the average number of complete cycles a nutrient input undergoes before being lost through exports or other pathways, providing insight into the contributions of direct and recycled flows to the output/input (O/I) ratio.

- **Use Count (UseCt):** Tracks the number of times a nutrient cohort passes through the highest trophic level producing the intended output, which is particularly useful for assessing nutrient use efficiency in systems with no net product output, such as food systems where humans occupy the top trophic level.

Although circularity indicators offer useful significance, [31] argue that higher circularity does not always translate to greater nutrient use efficiency. Therefore, designing truly sustainable agricultural systems requires integrating additional metrics to reduce environmental impacts, minimize system losses, and enhance the return of external waste flows.

Building on existing arguments, [7] synthesized a broader set of criteria to bridge gaps in existing indicator frameworks, which often overemphasize technical aspects while overlooking social and economic dimensions. They proposed an integrated framework for evaluating circular agriculture that includes:

- **Technical and environmental criteria:** Adoption of environmentally friendly technologies, nutrient and resource recycling, carbon emissions reduction, soil fertility enhancement, biodiversity conservation, and waste minimization.

- **Economic criteria:** Improving productivity, product quality, and financial benefits from circular business models.
- **Social criteria:** Enhancing working conditions, promoting producer and consumer welfare, and preserving cultural heritage.

This integrated approach highlights the need to go beyond circularity-focused metrics by incorporating technical, social, and economic dimensions. Achieving the full potential of circular agriculture requires balancing circularity indicators with complementary metrics to guide decision-making, optimize system performance, and ensure long-term sustainability.

5.0 Circular Agricultural practices

Since circular agriculture holds strong potential for enhancing sustainable food production, understanding its practices is critical to its widespread adoption and scalability globally. A study by [7] classified circular agricultural practices according to their nature and degree of circularity, emphasizing their role in fostering sustainability and supporting circular economy principles within agriculture. This classification, according to them, includes organic farming, mixed farming, agroforestry, and circular aquaculture. [7] assert that these circular economy practices align with circularity principles and contribute to resource efficiency, waste reduction, and ecosystem health, ultimately enhancing both environmental and economic sustainability in the agricultural sector. [7] assertion was buttressed by a [16] study who also states that circular agriculture promotes sustainable development by integrating all stages of the food system, from production to disposal, with a focus on sustainability. According to [16], circular agriculture key components including mixed crop-livestock systems, organic farming, agroforestry, and water recycling, collectively aim to reduce CO_2 emissions, improve resource efficiency, and significantly decrease the reliance on external inputs.

5.1 Organic Farming

Organic agriculture is another approach for practicing circular agriculture. [7] states that organic farming is a circular agricultural system that emphasizes natural processes and resources, avoiding chemicals and genetically modified organisms. This approach enables healthier food production by using organic manure hence reducing unhealthy dependence on chemical fertilizers, pesticides, insecticides, and plastics [34]. Organic farming also preserves soil fertility, naturally manages pests, and protects the environment [7]. Due to the economic hardship in developing countries and the increasing cost of chemical fertilizers, organic farming becomes not only an environmentally friendly farming practice but also an economically smart one. [16] reports that organic farming expanded significantly, from 11 million hectares in 1999 to 72.3 million hectares in 2019. Its increasing adoption is can also boost rural employment and promotes gender inclusion, as pesticide-free practices allow for greater involvement of women in agriculture[16].

5.2 Mixed farming

Mixed farming is a circular agriculture practice where one farm supports multiple activities, such as growing crops and raising animals, leveraging the beneficial interactions between crops, livestock, and aquatic systems [7]. Some examples of mixed farming include multiple cropping, crop-livestock integration, and crop-livestock-fish farming [7]. Mixed farming, which integrates crop cultivation with animal husbandry, enhances circular agriculture by using locally produced feed and manure instead of imports and chemical fertilizers, thereby helping to reduce agricultural CO_2 emissions [16]. This farming approach closely adheres to the principles of circular agriculture by fostering a circular food production system, where resources such as land, water, and waste are efficiently utilized to achieve maximum productivity, thereby significantly benefiting the environment.

5.3 Agro-forestry

Agroforestry, an ancient agricultural practice, is increasingly recognized by circular agriculture studies as a crucial solution to the challenges posed by resource scarcity and a growing global population. This method integrates crops, pastures, livestock, and forestry to restore biodiversity and improve soil fertility through natural organic matter [7]. By utilizing crop residues as animal feed, providing shade and biomass through trees, and maintaining soil cover with organic material, agroforestry reduces ecological impacts. It minimizes dependency on synthetic inputs such as fertilizers and insecticides by naturally enhancing soil fertility and supporting organic pest control methods [27]. Additionally, agroforestry systems mitigate the risks associated with monoculture farming and exhibit greater resilience during shortages or extreme climatic events [27]. By reducing the need for chemical fertilizers and pesticides, agroforestry aligns with the principles of circular agriculture, contributing to sustainable resource use and ecological balance [16]. These multifaceted benefits highlight the critical role of agroforestry as an integral component of circular agriculture and sustainable development.

5.4 Circular Aquaculture

Circular aquaculture is a sustainable farming method based on circular agricultural principles, where waste is repurposed into resources for new production [7]. This practice includes polyculture, in which different aquatic species are co-farmed, using their ecological interactions to improve efficiency, minimize waste, and support ecosystem functions[7]. Circular aquaculture emphasizes optimizing the use of water and feed resources while converting aquaculture waste into valuable outputs. This approach enhances efficiency, minimizes waste, and supports more sustainable practices, enabling operators to achieve greater value through resource optimization. It has been gaining traction in Asia, Europe, and the US, where integrated farming systems are employed to recycle and reuse nutrients effectively [15]. In the context of circular agriculture, the system of circular aquaculture plays a crucial role in efficiently utilizing waste and maximizing resource use, making it an essential component of circular agricultural practices.

6.0 Nature-Based Solutions and Circular Agriculture

Circular agriculture and Nature-Based Solutions (NbS) share a strong connection. Many NbS practices align with circular agriculture principles, promoting sustainability. Both NbS and circular agriculture are increasingly recognized as critical strategies for tackling environmental challenges, particularly in addressing resource management, climate change, and sustainable development [19,21]. These approaches emphasize the integration of natural processes into agricultural systems to promote resilience and sustainability. As noted by [21], NbS in agriculture provide a sustainable means of enhancing productivity while simultaneously addressing significant environmental issues. [21], further highlight that NbS can mitigate trade-offs between food production, climate mitigation, and biodiversity conservation. Achieving carbon neutrality in rural areas through NbS involves strategies such as managing land use and human activities, re-establishing ecological feedback loops, and adopting practices like carbon farming, carbon sink management, climate-smart agriculture, resource recycling, and renewable energy-based circular systems [19]. A study by [21] highlights several examples, such as optimizing grazing practices in livestock farming, which enhances animal health and productivity while reducing greenhouse gas emissions. Similarly, the adoption of water-efficient practices in rice farming not only improves yields but also significantly reduces methane emissions. Another strategy discussed is the use of biochar in soils, which effectively enhances carbon storage, resulting in an annual reduction of approximately 1,102 million tons of CO_2. Additionally, [20] emphasize that adopting efficient crop and nutrient management practices can substantially decrease fertilizer overuse, reducing nitrogen losses by 44 million tons annually. These examples illustrate the potential of NbS to align with circular agricultural principles, delivering extensive environmental, social, and economic benefits. Although nature-based solutions (NbS) and circular agriculture provide substantial environmental and economic benefits, their widespread adoption faces challenges. Key issues include a lack of comprehensive data on their effectiveness, particularly in agricultural production, and limited integration into existing urban and rural systems [19,21]. Overcoming these obstacles will be essential to fully unlock the potential of NbS and circular agriculture in advancing sustainability goals.

7.0 Relevant Circular Agriculture Case Studies

7.1 Case Study 1: Circular Palm Project in Ghana

An example of circular agricultural practices is the Serendipalm project, an initiative by Dr. Bronner's, a U.S.-based personal care company, which has revolutionized palm oil production in Ghana through the integration of regenerative farming and circular economy principles [9]. As a key ingredient in their soaps and skincare products, palm oil is sourced sustainably by collaborating with local farmers who grow organic palm fruits on existing community land using agroforestry techniques. Unlike conventional practices that often lead to deforestation, this approach preserves natural forests, enhances biodiversity, and improves soil health. Consistent with the principles of circular agriculture, the project ensures that all materials from local palm fruit production are fully utilized. For instance, waste generated during production is sold to other soap manufacturers, while crop by-products are converted into organic fertilizers. These fertilizers not only enhance soil quality for subsequent planting seasons but also help to reduce carbon emissions. The Serendipalm project has generated significant environmental benefits while providing local farmers with improved incomes and the opportunity to retain their land. This initiative exemplifies how circular agricultural practices can reduce waste, lower emissions, and create mutually beneficial outcomes for businesses and the environment [9].

7.2 Case Study 2: Nairobi Water Fund

The Nairobi Water Fund discussed in a study by [20] is another interesting circular agriculture practice that is focused on supporting agricultural conservation projects in watershed areas in Kenya. This project also integrates a nature-based solutions approach, thus making it a very significant case study for other countries to learn from. This program emphasizes riparian management, the creation of buffer zones, agroforestry, terracing of hill slopes, forest restoration, and the adoption of sustainable farming practices, enhanced by soil conservation and water harvesting strategies. The Nairobi Water Fund has successfully managed one million hectares of watershed, ensuring 95% of Nairobi's drinking water supply while improving hydropower generation. Its potential for replication offers significant environmental, social, and economic benefits, all while enhancing agricultural systems to address increasing food demand in Kenya. The implementation of sustainable agricultural practices within this project, which delivered widespread benefits across multiple sectors while promoting environmental and social gains, underscores the vital role of circular agriculture in driving sustainable development.

7.3 Case study 3: Bustan Aquaponic farm

The Bustan Aquaponics, an inspiring aquaponic farm in Egypt also reflects key principles of circular agriculture. In their study, [2] described the Bustan aquaponic farm established in 2011 on 1000 m^2 of land in Egypt's Giza governorate that integrates recirculating aquaculture with hydroponic vegetable and herb production. The farm ensures maximum nutrient cycling significantly useful for crop growth while reducing environmental pollution.

In the Bustan Aquaponics, nutrient waste from Nile tilapia cultivation, including fish manure and decomposing feed, is filtered and used as liquid fertilizer for plants like lettuce, basil, and chili peppers, which in turn act as bio-filters, enabling water recirculation. This space-efficient, circular system reduces water consumption, generates no toxic waste, and biologically controls pests through methods like companion planting and natural predators. Economically, the farm produces pesticide-free, high-value vegetables and herbs sold to markets, with potential for direct consumer sales, and it can yield production equivalent to 500-600 m^2 of traditional land use. Socially, the farm envisions an educational role, offering open houses for adults and schoolchildren to learn about food production through interactive planting and harvesting experiences. Currently operating as a pilot module, the farm plans to expand to six modules, producing 30-40 kg of fish and significant quantities of vegetables and herbs annually, while exploring solar heating systems and optimizing greenhouse insulation for year-round production. The farm clearly adheres to the core principles of circular agriculture, delivering significant environmental, social, and economic advantages while promoting food security.

8.0 Tech-Driven Solutions for Circular Agriculture

The effectiveness of circular agriculture depends on several key factors including technology. [29] innovative technologies like sensors can significantly maximize resource use efficiency in farms through water regulation and optimum nutrient delivery to plants. Similarly, [18] analyzed data from Henan Province between 2000 and 2018 to establish an evaluation framework for circular agriculture performance and developed a regression model to identify critical factors influencing performance. Their findings indicate that circular agriculture in Henan exhibited an overall upward trend during this period, with significant advancements noted after 2013. Their study also highlights that urbanization, technological progress, and natural resources per capita are pivotal in shaping circular agriculture outcomes. Specifically, agricultural technology and water resources per capita showed a positive correlation with improved circular agricultural performance. Based on this study in consensus with other authors' assertions, there is a strong emphasis on the role technology in facilitating the advancement of circular agriculture.

The utilization of technology is gaining traction and more pilot projects are emerging. For instance, Twiga Foods, a Kenyan-based farm, has implemented Liquid Intelligent Technologies to advance precision agriculture system that offers real-time monitoring of critical farm parameters, such as soil moisture, produce conditions, and irrigation needs. This technology employs Internet of Things (IoT) solutions to optimize farm productivity, enabling comprehensive monitoring of weather conditions, soil moisture and temperature, water acidity, and salinity [26]. The system provides data on temperature, humidity, rainfall, and wind speed, helping farmers make informed decisions about irrigation, pesticide application, and resource management [26]. By using this precision technology, farmers can avoid uniform application of water, fertilizers, and pesticides, instead applying the minimum required amounts and targeting specific areas or individual plants. This approach significantly reduces resource waste while improving efficiency.

9.0 Challenges of Circular Agriculture

The adoption of circular agricultural practices faces numerous challenges, including technological, economic, policy-related, and socio-cultural barriers, which significantly hinder their implementation and scalability. Educational and cultural factors, such as low literacy rates among farmers and the reliance on traditional subsistence farming methods, restrict the understanding and willingness to transition to circular agriculture, particularly in regions like Kurdistan Province, Iran [13]. This argument was contested by [24] who also assert that lack of adequate information and knowledge on circular agriculture poses great limitation to its scalability. The second challenge is technological and environmental obstacles, including the high costs and contamination risks associated with technologies like anaerobic digestion and nutrient recycling, further impede progress [5,14]. Additionally, the lack of appropriate feedstock properties and inadequate infrastructure often limit the efficiency of waste conversion systems [14]. Economic and policy challenges, such as the substantial initial investment required for circular agricultural technologies, create financial barriers for small-scale farmers [23]. Furthermore, insufficient policy support and market incentives discourage widespread adoption, underscoring the need for effective regulatory frameworks and active stakeholder engagement 5,12]. Lastly, social and structural issues, including the fragmentation of agricultural lands and the complexity of coordinating collaboration among governments, farmers, and consumers, also pose significant limitations to circular agriculture [13,14]. Addressing these barriers is crucial for advancing circular agriculture, as doing so enhances environmental sustainability while fostering economic resilience within the agricultural sector.

10.0 Recommendations for Achieving a Circular Agriculture Practices in Nigeria

Despite the growing recognition of circular agriculture as a sustainable model for food production, its adoption in Nigeria remains limited. Addressing this gap requires learning and drawing lessons from existing global best practices on circular economy and their adoption them to Nigeria's contexts. The following recommendations outline key strategies to establish circular agriculture in Nigeria.

10.1 Education and Awareness Programs

Robust education and awareness programs should be organized for farmers, research institutions, and community organizations to promote the adoption of circular agriculture principles. These programs should emphasize the environmental, social, and economic benefits of circular practices, empowering farmers to integrate circular solutions into their farming systems. Community-targeted workshops, training sessions, and informational campaigns can enhance understanding and encourage the widespread adoption of sustainable practices. This knowledge dissemination is essential for driving long-term sustainability and transforming Nigeria's agricultural landscape.

10.2 National Framework for Circular Agriculture

The development of a national framework that aims to minimize natural resource consumption, maximize waste reuse, and promote regenerative practices in Nigeria's agriculture sector is important. Key lessons from established frameworks, such as those outlined by [32,9,1], can guide the design of Nigeria's framework. However, ensuring long-term sustainability and swift policy integration, Nigeria's circular economy framework development must align with National agricultural development strategies [16].

10.3 Development of National Circular Agriculture Indicators

A comprehensive set of national indicators should be developed to measure and monitor circularity within agricultural systems. These indicators must capture environmental dimensions while integrating social and economic aspects [7]. Measuring factors such as resource losses, material recycling rates, nutrient balance, food waste reduction, and carbon emissions will provide actionable steps for optimizing circular practices across the Nigerian food system. These metrics can inform policy decisions, guide investments, and drive continuous improvements in agricultural sustainability.

10.4 Enhanced Research on Nature-Based Solutions

Improved research is necessary to enhance circular agriculture principles, particularly in advancing existing nature-based solutions among local farmers. This research is critical for optimizing both urban and rural agricultural systems in Nigeria, addressing the limited integration of circular agriculture noted by [9,21]. Collaborative efforts with universities and research institutes can lead to innovative approaches that enhance resource efficiency and resilience in agricultural systems.

10.5 Regulations for Sustainable Industrial Feedstock Extraction

Drawing lessons from the Serendipalm project in Ghana, Nigeria's government should establish regulations that ensure the industrial extraction of agricultural feedstocks complies with circular agriculture principles. Such regulations will promote sustainability within supply chains from production to consumption. Compliance with these principles will not only enhance natural resource management but also improve product credibility, thereby attracting more patronage and fostering trust in Nigerian agricultural products on a global scale.

10.6 National Programs for Conservation and Restoration

The government should fund national programs that establish buffer zones, scale up agroforestry practices, terrace hill slopes, improve forest restoration, and enhance soil conservation. Inspired by the Nairobi Water Fund in Kenya, these initiatives can yield significant environmental, social, and economic benefits. Through the replication of such models, Nigeria can strengthen its commitment to sustainable resource management and improve the resilience of its agricultural ecosystems.

10.7 Strengthening Technology Adoption in Agriculture

Partnerships with technological agencies and agro-tech start-ups should be prioritized to enhance circular agricultural practices. As noted by [1,26], technology can play a pivotal role in monitoring weather conditions, soil moisture, temperature, water acidity, and salinity. Precision farming techniques enabled by technology can optimize the use of water, fertilizers, and pesticides, leading to improved efficiency and reduced waste. The success of Twiga Foods in Kenya serves as a compelling case study for Nigeria to emulate, demonstrating the transformative impact of technology in agriculture.

11.0 Conclusion

Circular agriculture presents a significant potential for addressing Nigeria's agricultural shortcomings and unlocking its future food production capacity in an environmentally sustainable way. The integration of principles such as resource efficiency, waste minimization, and ecosystem regeneration, will not only mitigate low productivity poised by environmental degradation due to unsustainable agricultural practices, but will also minimize inefficient resource use and increase income for Nigerian farmers. Furthermore, the adoption of practices like organic farming, agroforestry, and mixed farming can build resilience, enhance biodiversity, and meet the food demands of Nigeria's rapidly growing population.

However, for circular agriculture to thrive, increased research is essential to contextualize these practices to Nigeria's unique socio-economic and environmental landscape. Developing robust indicators, tailored frameworks, and implementation strategies is crucial for scaling adoption nationwide. Policymakers must play a pivotal role by enacting supportive legislation, creating financial incentives for sustainable practices, and integrating circular principles into national agricultural development plans. A strong policy framework, paired with research-driven solutions and community-level education, can position Nigeria as a global leader in sustainable food production, harnessing its vast agricultural potential to achieve long-term food security, climate resilience, and inclusive rural development.

12. Methodology

This study adopted a literature review to critically examine the potential of circular agriculture in Nigeria. The review was conducted using a structured search and synthesis of relevant secondary sources drawn from journal articles, institutional reports, and other relevant literature. Key academic databases and platforms used during this research include Scopus, ScienceDirect, Web of Science, SpringerLink, and Google Scholar. Additionally, relevant data were sourced from credible institutions including the Food and Agriculture Organization (FAO), World Bank, United Nations Industrial Development Organization (UNIDO), and national policy documents. Furthermore, the search focused on specific keywords and Boolean combinations such as “circular agriculture,” “sustainable agriculture,” “circular economy,” “resource efficiency in farming,” “agriculture in Nigeria,” and “agroecology,”. Studies were selected based on their relevance to the core themes of sustainable and circular agricultural practices.

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