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Technological Innovation Systems for Agricultural Waste-To-Energy: Driving Circular Bioeconomy Transitions and Scaling Sustainable Pathways in Brazil's and Nigeria's Agribusiness Sectors

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Abstract

This study investigated the effect of Technological Innovation Systems (TIS) on the scaling of Circular Bioeconomy Transitions (CBT) in agricultural waste-to-energy within the agribusiness sectors of Brazil and Nigeria. Specifically, it assessed the influence of knowledge development, market formation, resource mobilization, and entrepreneurial activities on the adoption and expansion of circular bioeconomy practices. A quantitative research design was adopted, employing a cross-sectional survey to collect data from 330 stakeholders, including managers, engineers, entrepreneurs, and researchers across agribusiness and bioenergy projects in both countries. Stratified sampling ensured proportional representation of all stakeholder groups. Data collected through structured questionnaires were analyzed using multiple regression analysis, with a 5% significance level adopted to test the hypotheses. The findings revealed that knowledge development positively and significantly influences CBT scaling ($\beta = 0.312$, $t = 4.56$, $p = 0.000$),

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indicating that research collaboration, technology training, and information sharing enhance adoption of agricultural waste-to-energy innovations. Market formation was also significant ($\beta = 0.271$, $t = 3.89$, $p = 0.001$), suggesting that demand creation and policy support stimulate the uptake of circular bioeconomy practices. Resource mobilization demonstrated a positive effect ($\beta = 0.198$, $t = 2.77$, $p = 0.006$), highlighting the importance of financial, technical, and human resources. Entrepreneurial activities significantly contributed to scaling CBT ($\beta = 0.245$, $t = 3.25$, $p = 0.002$), emphasizing the role of innovation adoption and business model adaptation. The study concludes that TIS components collectively drive sustainable adoption of agricultural waste-to-energy initiatives. It recommends targeted investments in knowledge development, market creation, resource allocation, and entrepreneurial engagement to enhance circular bioeconomy transitions.

Keywords: Technological Innovation Systems, Circular Bioeconomy, Agricultural Waste-to-Energy, Market Formation, Resource Mobilization

Background of the Study

The increasing global demand for sustainable energy and efficient waste management has intensified the search for innovative solutions that integrate environmental sustainability with economic development. Agricultural waste-to-energy systems have emerged as a vital component of the circular bioeconomy, providing pathways for converting biomass residues into renewable energy while reducing environmental degradation. Traditionally, agricultural residues such as crop waste, animal manure, and agro-industrial by-products were either underutilized or poorly managed, contributing to greenhouse gas emissions and pollution. However, advancements in bioenergy technologies have shifted attention toward the productive utilization of these wastes as inputs for energy generation. This transition aligns with global sustainability goals aimed at mitigating climate change and promoting renewable energy adoption (Goldemberg et al., 2021; IEA, 2022). Consequently, agricultural waste-to-energy systems are increasingly recognized as a strategic approach to achieving both environmental sustainability and economic growth.

The concept of the circular bioeconomy has gained prominence since the early 21st century, emphasizing the sustainable use of biological resources within closed-loop systems that minimize waste and maximize resource efficiency. Within this framework, agricultural waste-to-energy plays a central role by transforming waste streams into valuable economic outputs, thereby reducing dependence on fossil fuels. Despite widespread global recognition, the adoption of circular bioeconomy practices varies significantly across countries due to differences in technological capabilities, institutional arrangements, and market structures. Empirical studies suggest that the success of such transitions depends not only on resource availability but also on the strength of innovation systems that facilitate knowledge creation, technology diffusion, and market development (D'Amato et al., 2021; Kircher et al., 2020). This highlights the need to examine the underlying mechanisms that drive or hinder the effective implementation of bioenergy systems.

Technological Innovation Systems (TIS) provide a comprehensive framework for analyzing how emerging technologies evolve, develop, and scale within specific socio-economic contexts. The TIS approach focuses on key functional elements, including knowledge development, market formation, resource mobilization, entrepreneurial activities, and legitimation, which collectively influence the success of technological transitions. Previous studies have demonstrated that strong institutional support, active stakeholder engagement, and continuous innovation are critical for scaling renewable energy technologies (Hekkert et al., 2020; Markard et al., 2020). Brazil represents a leading example of a well-established bioenergy system, particularly in bioethanol production from sugarcane, supported by long-standing government initiatives such as the Proálcool program. The country's success is attributed to effective knowledge development,

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robust market structures, and strong policy support, making it a global benchmark in integrating agricultural waste-to-energy into its circular bioeconomy (Goldemberg et al., 2021; Bergek et al., 2021).

In contrast, Nigeria possesses abundant agricultural resources and generates significant biomass waste from crops such as cassava, rice, and maize, yet struggles to develop a sustainable waste-to-energy sector due to systemic challenges. These include limited technological expertise, inadequate infrastructure, weak policy implementation, low investment levels, and underdeveloped entrepreneurial activities. Additionally, low public awareness and acceptance hinder the legitimation of bioenergy technologies, further constraining their adoption (Akinwale & Ogundari, 2021; Ebhota & Tabakov, 2023). A comparative analysis of Brazil and Nigeria therefore provides valuable insights into the factors influencing the scaling of circular bioeconomy transitions. By examining key TIS functions such as knowledge development, market formation, resource mobilization, and entrepreneurship, this study seeks to identify context-specific strategies for enhancing innovation systems. Ultimately, the research contributes to the broader discourse on sustainable development by highlighting the critical role of innovation systems in advancing agricultural waste-to-energy initiatives (Bergek et al., 2021; Markard et al., 2020; D'Amato et al., 2021; Ebhota & Tabakov, 2023).

Statement of the Problem

Agricultural waste-to-energy systems are widely recognized as a transformative pathway for advancing circular bioeconomy transitions by converting abundant agricultural residues into sustainable energy. This approach not only reduces environmental pollution but also enhances energy security and stimulates economic development. Within an effective Technological Innovation System (TIS), key functions such as knowledge development, market formation, resource mobilization, and entrepreneurial activities are expected to operate cohesively to support the large-scale adoption of bioenergy technologies. Countries like Brazil exemplify this ideal, where strong institutional frameworks, sustained investment in research and development, and supportive policy environments have enabled the successful integration of agricultural waste-to-energy into the national energy mix. This has, in turn, promoted sustainable agribusiness growth and efficient resource utilization within a circular economy framework.

However, this ideal scenario contrasts sharply with the reality in many developing economies, particularly Nigeria, where the scaling of agricultural waste-to-energy initiatives remains limited despite the country's vast biomass potential. Challenges such as weak knowledge development systems, underdeveloped market structures, inadequate resource mobilization, and low entrepreneurial participation continue to hinder progress in the bioenergy sector. Additionally, inconsistent policy implementation, infrastructural deficits, and low stakeholder awareness further constrain the development and diffusion of these technologies. Without this study, critical gaps in understanding how TIS functions influence the scaling of waste-to-energy systems—especially through a comparative lens between Brazil and Nigeria—will persist. This lack of insight may impede the formulation of effective strategies needed to strengthen innovation systems, thereby limiting opportunities for sustainable energy generation, environmental sustainability, and agribusiness development, while prolonging dependence on non-renewable energy sources.

Objectives of the Study

The broad objective of the study was to examine the effect of Technological Innovation Systems (TIS) on the scaling of Circular Bioeconomy Transitions (CBT) in agricultural waste-to-energy within the agribusiness sectors of Brazil and Nigeria. Specifically, the study seeks to:

i. Assess the effect of knowledge development on the scaling of circular bioeconomy transitions in agricultural waste-to-energy in the agribusiness sectors of Brazil and Nigeria.

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ii. Examine the effect of market formation on the scaling of circular bioeconomy transitions in agricultural waste-to-energy in the agribusiness sectors of Brazil and Nigeria.
iii. Investigate the effect of resource mobilization on the scaling of circular bioeconomy transitions in agricultural waste-to-energy in the agribusiness sectors of Brazil and Nigeria.
v. Analyze the effect of entrepreneurial activities on the scaling of circular bioeconomy transitions in agricultural waste-to-energy in the agribusiness sectors of Brazil and Nigeria.

Hypotheses

The following null hypotheses were formulated in line with the specific objectives of the study:
Ho_1: Knowledge development has no significant effect on the scaling of circular bioeconomy transitions in agricultural waste-to-energy in the agribusiness sectors of Brazil and Nigeria.
Ho_2: Market formation has no significant effect on the scaling of circular bioeconomy transitions in agricultural waste-to-energy in the agribusiness sectors of Brazil and Nigeria.
Ho_3: Resource mobilization has no significant effect on the scaling of circular bioeconomy transitions in agricultural waste-to-energy in the agribusiness sectors of Brazil and Nigeria.
Ho_4: Entrepreneurial activities have no significant effect on the scaling of circular bioeconomy transitions in agricultural waste-to-energy in the agribusiness sectors of Brazil and Nigeria.

REVIEW OF RELATED LITERATURE

Conceptual Review

Technological Innovation Systems (TIS)

Technological Innovation Systems (TIS) refer to the network of actors, institutions, and interactions that influence the development, diffusion, and utilization of new technologies within a specific domain. Bergek, Hekkert, and Jacobsson (2021), TIS provides a systemic framework for analyzing how technological innovations emerge and evolve through coordinated activities among stakeholders such as firms, governments, and research institutions. The concept emphasizes that innovation is not a linear process but a complex system shaped by institutional structures and socio-economic dynamics. In the context of agricultural waste-to-energy, TIS helps explain how bioenergy technologies are developed and scaled within agribusiness sectors.
From another perspective, Markard, Raven, and Truffer (2020) describe TIS as a tool for understanding sustainability transitions by focusing on the processes that enable or hinder the diffusion of environmentally friendly technologies. They argue that TIS highlights the importance of system functions such as knowledge creation, market development, and resource mobilization in driving innovation. This approach is particularly relevant for circular bioeconomy transitions, where the successful integration of waste-to-energy technologies depends on the coordination of multiple actors and institutional support mechanisms.

Knowledge Development

Knowledge development refers to the generation, diffusion, and application of scientific and technical knowledge necessary for innovation. It is a fundamental component of Technological Innovation Systems, as it drives the creation and improvement of technologies. Hekkert et al. (2020), knowledge development encompasses research and development (R&D), learning processes, and information exchange among stakeholders. In the context of agricultural waste-to-energy, knowledge development involves advancements in bioenergy technologies, such as anaerobic digestion and biomass conversion. Similarly, Bergek et al. (2021) define knowledge development as the accumulation of expertise and technological capabilities that enable innovation. They argue that effective knowledge development requires collaboration between universities, research institutions, and industry players. Such collaboration fosters innovation by

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facilitating the transfer of knowledge and the development of new technologies. In countries with strong research systems, knowledge development plays a crucial role in enhancing the efficiency and scalability of waste-to-energy systems.

Market Formation

Market formation refers to the creation and development of markets that support the adoption and commercialization of new technologies. It is a critical function of Technological Innovation Systems, as it provides the economic incentives necessary for innovation. According to Bergek et al. (2021), market formation involves the establishment of demand, pricing mechanisms, and regulatory frameworks that encourage the use of new technologies. In agricultural waste-to-energy, market formation includes the development of markets for bioenergy products such as biogas, bioethanol, and electricity.

Resource Mobilization

Resource mobilization refers to the allocation and utilization of financial, human, and physical resources necessary for innovation. It is a key function of Technological Innovation Systems, as it determines the capacity of a system to support technological development and diffusion. Hekkert et al. (2020), resource mobilization includes access to funding, infrastructure, and skilled labor. In agricultural waste-to-energy, resource mobilization involves securing investments, developing infrastructure, and building technical expertise. Bergek et al. (2021) define resource mobilization as the process of attracting and deploying resources to support innovation activities. They argue that adequate resource mobilization is essential for the successful implementation of new technologies. In the context of bioenergy, this includes investments in research, production facilities, and distribution networks.

Entrepreneurial Activities

Entrepreneurial activities refer to the actions of individuals and organizations in exploring and exploiting new business opportunities. In Technological Innovation Systems, entrepreneurial activities play a crucial role in driving innovation and market development. According to Hekkert et al. (2020), entrepreneurial experimentation is essential for testing new technologies and business models. In agricultural waste-to-energy, entrepreneurs are key actors in developing and commercializing bioenergy solutions.

Bergek et al. (2021) define entrepreneurial activities as the process of identifying opportunities and mobilizing resources to create value. They argue that entrepreneurs play a critical role in bridging the gap between technological innovation and market adoption. In the context of circular bioeconomy transitions, entrepreneurial activities facilitate the commercialization of sustainable technologies. Markard et al. (2020) emphasize that entrepreneurial activities are influenced by the broader innovation system. They note that supportive policies, access to funding, and strong networks can enhance entrepreneurial performance. In agricultural waste-to-energy systems, a conducive environment is essential for encouraging entrepreneurship and innovation.

Scaling of Circular Bioeconomy Transitions (CBT)

The concept of **scaling of Circular Bioeconomy Transitions (CBT)** refers to the expansion and diffusion of systems that utilize biological resources in a sustainable, circular manner across sectors and regions. According to Leong et al. (2021), the circular bioeconomy integrates the principles of circular economy and bioeconomy to promote the efficient use, reuse, and recycling of biomass for economic and environmental sustainability. Scaling in this context involves increasing the adoption, geographical spread, and impact of circular bio-based innovations. It goes beyond pilot initiatives to full industrial and policy integration, ensuring that biological resources are continuously cycled within production systems.

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From another perspective, D'Amato et al. (2021) define circular bioeconomy transitions as systemic shifts from linear "take–make–dispose" models toward regenerative systems that prioritize resource efficiency and waste valorization. Scaling such transitions implies not only technological diffusion but also institutional alignment, policy support, and behavioral change among stakeholders. This highlights that scaling is a multidimensional process involving technological, economic, and social transformations that reinforce sustainable development pathways.

Agricultural Waste-to-Energy within the Agribusiness

Agricultural waste-to-energy refers to the process of converting agricultural residues and by-products into usable forms of energy such as biogas, bioethanol, and electricity. According to Atelge et al. (2020), waste-to-energy technologies enable the transformation of organic waste into renewable energy, thereby addressing both waste management and energy generation challenges. In the agribusiness context, this process involves utilizing crop residues, animal manure, and agro-industrial waste to produce energy that can support agricultural production and rural development. From another viewpoint, Ogbu and Okey (2023) describe agricultural waste-to-energy as a key component of sustainable agricultural systems, where waste materials are recycled and converted into valuable resources. They emphasize that traditional agricultural systems were inherently circular, with minimal waste generation, but modern industrial agriculture has led to increased waste accumulation. Waste-to-energy technologies restore this circularity by converting waste into energy, thereby reducing environmental impacts and enhancing resource efficiency.

Comparative Study on Scaling of Circular Bioeconomy Transitions in Agricultural Waste-to-Energy in the Agribusiness Sectors of Brazil and Nigeria

Agricultural waste-to-energy systems provide a critical pathway for advancing circular bioeconomy transitions by converting biomass residues into renewable energy while promoting environmental sustainability and economic growth. In Brazil, widely regarded as a global leader in bioenergy, the utilization of agricultural waste has evolved into a large-scale industrial sector. The country generated approximately 784 million tons of agricultural residues in 2023, with sugarcane bagasse alone accounting for over 600 million tons, making it one of the largest biomass waste streams globally. This resource base has been effectively harnessed, with Brazil producing about 3,250 megawatts of electricity from biomass in 2024, contributing roughly 5% to the national electricity mix. With over 780 bioenergy production facilities, including biogas, bioethanol, and biomass power plants, Brazil demonstrates a high level of integration of waste-to-energy systems within its agribusiness sector, supported by decades of policy development and sustained investment.

Brazil's success in scaling circular bioeconomy transitions is largely attributed to consistent policy frameworks and strong institutional support dating back to initiatives such as the Proálcool program. These policies have fostered market development, technological innovation, and infrastructure expansion in the bioenergy sector. The country's National Bioenergy Plan projects further growth, with biomass electricity expected to reach nearly 4,200 megawatts by 2030, driven by investments exceeding US$28 billion. Additionally, Brazil's bioethanol industry produced over 36 billion liters in 2024, much of it derived from agricultural residues, reinforcing its position in both domestic and international energy markets. In contrast, Nigeria remains at an early stage of scaling agricultural waste-to-energy systems despite generating about 85 million tons of agricultural residues annually and possessing significant untapped energy potential. Although these resources could supply up to 20% of national electricity demand, current utilization remains minimal, with biomass contributing less than 1% to grid electricity and fewer than 15 operational commercial biogas plants as of 2025.

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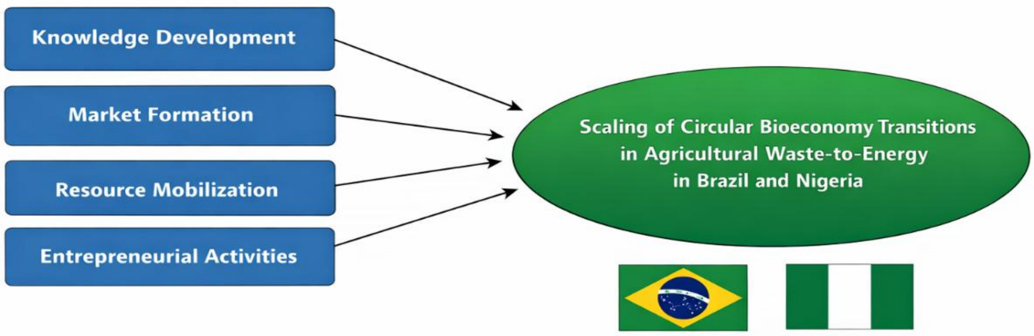
The disparity between Brazil and Nigeria highlights the importance of strong innovation systems, policy consistency, and investment frameworks in scaling bioenergy solutions. While Brazil has successfully aligned policy, market incentives, and technological development to drive large-scale adoption, Nigeria continues to face challenges such as limited financing, inadequate infrastructure, low stakeholder awareness, and weak institutional capacity. However, recent efforts including renewable energy incentives, draft bioenergy policies, and donor-funded initiatives exceeding US$120 million indicate growing momentum toward improving the sector. Pilot projects in rural areas also demonstrate emerging grassroots adoption. Ultimately, the comparison underscores that beyond resource availability, effective scaling of circular bioeconomy transitions requires coordinated efforts in policy implementation, market formation, and technological innovation. Strengthening these areas in Nigeria, while fostering international collaboration and knowledge exchange, could unlock its vast biomass potential and support a more sustainable and resilient agribusiness sector.

Conceptual Model



Theoretical Framework

The study is anchored on the Technological Innovation Systems (TIS) Theory, first conceptualized by Carlsson and Stankiewicz (1991), which provides a comprehensive framework for analyzing the structural and functional elements that influence the development, diffusion, and utilization of new technologies. TIS posits that technological advancement is driven by the interaction of key components actors, networks, and institutions that collectively generate, disseminate, and apply innovation within a specific context. In this study, the TIS framework is applied to examine how agricultural waste-to-energy technologies are developed and scaled within the agribusiness sectors of Brazil and Nigeria, with particular focus on knowledge development, market formation, resource mobilization, and entrepreneurial activities. Subsequent contributions by Bergek et al. (2008) expanded the framework by identifying seven critical system functions, including knowledge development and diffusion, entrepreneurial experimentation, market formation, resource mobilization, legitimation, and guidance of search, which serve as analytical tools for evaluating both enabling and constraining factors in innovation systems. Hekkert et al. (2007) further emphasized that weaknesses in these system functions such as inadequate knowledge flows, poor market incentives, or insufficient funding can significantly

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hinder technological scaling, a situation evident in Nigeria's underdeveloped waste-to-energy sector. Additionally, Markard and Truffer (2008) introduced a dynamic perspective, highlighting how innovation systems evolve through continuous interactions and feedback loops shaped by institutional and socio-economic contexts. By anchoring this study on TIS theory, a structured and comparative analysis is enabled, allowing for the identification of systemic gaps and the formulation of practical strategies to enhance policy effectiveness, strengthen innovation capacity, and promote the successful scaling of circular bioeconomy transitions in both Brazil and Nigeria.

Theoretical Exposition

Innovation Dynamics of Agricultural Waste-to-Energy in Brazil and Nigeria

Knowledge development is a critical driver of technological advancement in agricultural waste-to-energy systems, particularly when supported by strong institutional frameworks and collaborative research networks. In Brazil, close integration among universities, research institutes, and private sector actors has accelerated innovation in bioenergy technologies, especially in the conversion of sugarcane residues into energy. This reflects high absorptive capacity, where sustained investment in research and development enables the adoption of advanced technologies such as digesters and bioconversion systems. In contrast, Nigeria faces challenges including fragmented research structures, limited funding, and weak knowledge transfer mechanisms, all of which constrain technological progress. Similarly, market formation plays a vital role in transforming innovations into viable economic activities. Brazil has successfully developed its bioenergy market through supportive policies, fiscal incentives, and regulatory frameworks, resulting in a thriving industry. Nigeria, however, continues to struggle with weak regulatory systems, low demand, and lack of incentives, limiting the commercialization of waste-to-energy solutions. Resource mobilization and entrepreneurial activities further influence the scalability of agricultural waste-to-energy systems. Brazil has benefited from strong financial support from government and private investors, enabling large-scale deployment of bioenergy infrastructure. In contrast, Nigeria faces high financing costs, limited access to credit, and weak investment structures, which restrict participation and slow growth. Entrepreneurial activity also plays a key role in linking knowledge, markets, and resources into practical innovations. Brazil's dynamic ecosystem of clean energy startups, supported by incubators and networks, has enhanced commercialization and innovation. Nigeria's entrepreneurial environment, however, remains underdeveloped, with limited access to mentorship and market linkages. Overall, the interaction between knowledge development, market formation, resource mobilization, and entrepreneurship highlights the importance of a well-coordinated innovation system. While Brazil demonstrates strong integration and growth, Nigeria must strengthen these interconnected elements particularly financing and market incentives to effectively scale circular bioeconomy transitions.

Empirical Review

López, Fernández & Rojas (2021) investigated the role of public–private technological innovation actors in advancing circular bioeconomy transitions within Argentina's soybean and maize agribusiness sectors. The population consisted of R&D unit staff from four major agribusiness corporations and representatives from the national agricultural research institute. Utilizing Structural Equation Modelling (SEM), the results showed that formalized coordination mechanisms between public institutions and private firms strengthened TIS performance, resulting in faster deployment of biogas and biomass-to-energy technologies. Findings indicated that institutional integration positively affects technological learning, reducing barriers to scalability in regional bioeconomy initiatives.

Chukwu & Adeniran (2023) carried out an empirical study on how technological innovation systems affect the performance and sustainability of cassava waste-to-energy projects in

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southeastern Nigeria's agribusiness sector. The population involved project developers, technology providers, and policymakers in Rivers and Anambra states. Applying Partial Least Squares Structural Equation Modelling (PLS-SEM), the study identified that innovation resource availability, knowledge transfer networks, and regulatory support significantly predicted the successful scaling of circular bioeconomy systems. The results highlighted that policy incentives and localized technological support contributed to improved waste conversion efficiency and economic viability.

Kumar, Singh & Das (2022) studied technological innovation systems' influence on rice husk bioenergy adoption within the agribusiness clusters of Uttar Pradesh and West Bengal, India. The population included 300 agribusiness SMEs, technology incubators, and agricultural extension agents. Employing factor analysis and path modelling, findings revealed that strong linkages among universities, industry actors, and government agencies were positively associated with the commercialization of rice husk digesters. The study also showed that localized innovation brokerage and finance mechanisms effectively bridged gaps between inventors and end users, facilitating CBT scaling.

Müller, Schwarz & Weber (2021) examined the trajectory of innovation systems in Germany's dairy and biogas industries to determine how TIS elements contribute to scaling agricultural waste-to-energy transitions. The population encompassed executives of dairy cooperatives, biogas plant operators, and innovation policy analysts. Using a comparative case study design and social network analysis, results indicated that dense collaboration networks and highly coordinated research consortia significantly enhanced knowledge flows. The study concluded that regions with integrated TIS configurations experienced faster diffusion of circular bioeconomy practices and larger shares of renewable energy from manure-based biogas.

Zhang & Li (2023) explored the role of technological innovation systems in facilitating the scaling of circular bioeconomy initiatives within China's intensive vegetable cultivation zones, focusing on vegetable waste-to-energy conversion. The population comprised agribusiness firms, technology suppliers, and provincial agricultural research bodies in Guangdong and Shandong provinces. Using multi-level modelling and innovation system mapping, the study found that policy-driven R&D funding, combined with strong industry–university collaborations, significantly improved both technology performance and stakeholder uptake. It was shown that TIS effectiveness was mediated by entrepreneurial orientation and absorptive capacity of firms.

Torres, Jiménez & Castillo (2022) investigated the impact of TIS on circular bioeconomy transitions in Mexico's maize and sorghum agribusiness supply chains, with special focus on waste anaerobic digestion schemes. The population included 250 agribusiness enterprises, technology consultants, and public innovation fund representatives. Structural modelling techniques demonstrated that innovation intermediaries and dedicated bioeconomy policy frameworks were key drivers of technology adoption and upscaling. Results indicated that strong institutional support and coordinated innovation infrastructures positively influenced operational performance and environmental outcomes.

Bwalya, Tembo & Mwansa (2024) conducted a study in Zambia's emerging bioenergy sector to understand how TIS affects the scaling of agricultural waste-to-energy solutions in cassava and groundnut processing zones. The population consisted of agribusiness firms, technology accelerators, and rural energy cooperatives. Through survey research and SEM analysis, the study revealed that access to innovation resources, interactive learning platforms, and effective governance structures were statistically significant predictors of successful CBT adoption and expansion. Findings suggested that strengthening TIS pillars enhanced investment flows, improved technology adaptation, and supported sustainable rural development outcomes.

Methodology

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The study employs a quantitative research design to examine the effect of Technological Innovation Systems (TIS) on the scaling of Circular Bioeconomy Transitions (CBT) in agricultural waste-to-energy within the agribusiness sectors of Brazil and Nigeria. A cross-sectional survey was used to collect data from key stakeholders, including agribusiness managers, engineers, entrepreneurs, researchers, and policy actors involved in bioenergy projects. The structured questionnaire facilitated standardized data collection across both countries, enabling the measurement of relationships between TIS components knowledge development, market formation, resource mobilization, and entrepreneurial activities and the scaling of CBT initiatives. The study population comprised approximately 2,300 stakeholders, with Brazil contributing 1,200 and Nigeria 1,100. Using Krejcie and Morgan's (1970) formula, a sample of 330 respondents was selected through stratified sampling to ensure proportional representation across stakeholder groups and countries. Data were analyzed using multiple regression to assess the effect of each TIS component on the scaling of CBT. The regression model specified the scaling of CBT as the dependent variable and knowledge development, market formation, resource mobilization, and entrepreneurial activities as independent predictors. Assumptions of linearity, normality, multicollinearity, and homoscedasticity were tested to validate the analysis. Hypotheses were evaluated at a 5% significance level, where p-values ≤ 0.05 indicated a significant effect of a predictor on CBT scaling, leading to rejection of the null hypothesis, while p-values > 0.05 indicated no significant effect. This approach allowed for determining the relative contribution of each TIS component to the adoption and scaling of circular bioeconomy practices in agribusiness waste-to-energy projects across Brazil and Nigeria.

DATA PRESENTATION, ANALYSIS AND INTERPRETATION

Test Test of Hypotheses

The regression model was specified as follows:

Scaling of CBT = $\beta_0 + \beta_1$(Knowledge Development) + β_2(Market Formation) + β_3(Resource Mobilization) + β_4(Entrepreneurial Activities) + ε

Where β_0 is the intercept, β_1–β_4 are regression coefficients of the independent variables, and ε represents the error term. The sample size for the analysis was 330 respondents. The decision criterion was based on the significance level ($\alpha = 0.05$). Any variable with a **p-value ≤ 0.05** would be considered to have a significant effect on scaling CBT, and the null hypothesis would be rejected. Conversely, p-values greater than 0.05 would indicate no significant effect, and the null hypothesis would not be rejected.

Independent Variable	Beta (β)	t-value	p-value	Decision
Knowledge Development	0.312	4.56	0.000	Significant (Reject Ho_1)
Market Formation	0.271	3.89	0.001	Significant (Reject Ho_2)
Resource Mobilization	0.198	2.77	0.006	Significant (Reject Ho_3)
Entrepreneurial Activities	0.245	3.25	0.002	Significant (Reject Ho_4)
$R^2 = 0.62$, $F(4, 325) = 135.4$, $p < 0.001$				Overall model significant

Source: SPSS version 23, (2026)

From the table, all the independent variables have **p-values less than 0.05**, indicating that each of the TIS components has a statistically significant positive effect on the scaling of circular bioeconomy transitions. The R^2 value of 0.62 suggests that **62% of the variation in scaling CBT is explained by knowledge development, market formation, resource mobilization, and entrepreneurial activities,** while the remaining 38% is due to other factors not included in the model. The F-statistic ($F = 135.4$, $p < 0.001$) shows that the regression model is overall statistically significant.

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Summary of Findings

The findings from the multiple regression analysis are summarized as follows:
Knowledge development has a **positive and significant effect** on the scaling of circular bioeconomy transitions. The regression coefficient (β = 0.312), **t-value of 4.56** and a **p-value of 0.000.**
Market formation was also found to **positively influence the scaling of CBT,** with a regression coefficient of **β = 0.271,** a **t-value of 3.89,** and a **p-value of 0.001.**
Resource mobilization has a **significant positive effect** on CBT scaling, as evidenced by **β = 0.198, t = 2.77**, and **p = 0.006.**
Entrepreneurial activities were found to **significantly contribute** to the scaling of circular bioeconomy transitions. The regression coefficient of **β = 0.245,** with a **t-value of 3.25** and a **p-value of 0.002**.

Conclusion

Based on the findings, it can be concluded that **Technological Innovation Systems (TIS)** play a significant role in scaling circular bioeconomy transitions in agricultural waste-to-energy within the agribusiness sectors of Brazil and Nigeria. All components of TIS examined in the study knowledge development, market formation, resource mobilization, and entrepreneurial activities exert a **positive and significant influence** on the successful adoption and expansion of agricultural waste-to-energy projects. This highlights the importance of coordinated innovation efforts, policy support, resource allocation, and entrepreneurial engagement for achieving sustainable circular bioeconomy outcomes.
Recommendations

i. Policymakers and agribusiness stakeholders should invest in research, training, and technology dissemination programs to strengthen knowledge development, as this significantly boosts the adoption of waste-to-energy innovations.
ii. Governments and industry associations should create incentives and supportive policies to stimulate market demand for bioenergy products. Effective market formation will encourage agribusinesses to scale circular bioeconomy practices.
iii. Financial institutions, innovation funds, and technology incubators should provide targeted resources, including funding, technical support, and skilled manpower, to reduce barriers to implementing agricultural waste-to-energy projects.
iv. Programs that foster entrepreneurial engagement such as business development support, venture capital access, and innovation competitions should be promoted to ensure that bioenergy solutions are effectively commercialized and scaled.

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