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Circular economy based on bioinnovation: strategies for transforming organic waste into sustainable resources

Economía circular basada en bioinnovación: estrategias para transformar residuos orgánicos en recursos sostenibles

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Abstract

The growing generation of organic waste from agricultural, urban, and industrial activities poses an environmental challenge that requires innovative solutions. This study analyzes the feasibility of implementing circular economy strategies based on bioinnovation in the Peruvian context, with an emphasis on waste recovery to produce sustainable bioproducts such as bioplastics, biochar, and biofuels. Using a mixed approach, data was collected through surveys, interviews, and documentary analysis, complementing the information with national and international regulatory guidelines. The results show that 68% of households already practice organic waste separation and that 85% perceive benefits in its transformation into bioproducts. However, only 42% are familiar with the concept of the circular economy, revealing a gap in environmental awareness. It is concluded that the population has favorable demographic and occupational conditions for the adoption of circular practices, although technological and institutional limitations persist that must be addressed through public policies, education, and strategic alliances.

Keywords: circular economy, bioeconomy, organic waste

Resumen

La creciente generación de residuos orgánicos provenientes de actividades agrícolas, urbanas e industriales plantea un desafío ambiental que exige soluciones innovadoras. En este estudio se analiza la viabilidad de implementar estrategias de economía circular basadas en bioinnovación en el contexto peruano, con énfasis en la valorización de desechos para producir bioproductos sostenibles como bioplásticos, *biochar* y biocombustibles. Mediante un enfoque mixto, se recopilaron datos a través de encuestas, entrevistas y análisis documental, complementando la información con lineamientos normativos nacionales e internacionales. Los resultados

muestran que el 68% de los hogares ya practica la separación de residuos orgánicos y que el 85% percibe beneficios en su transformación en bioproductos. Sin embargo, solo el 42% conoce el concepto de economía circular, lo que revela una brecha de sensibilización ambiental. Se concluye que la población presenta condiciones demográficas y ocupacionales favorables para la adopción de prácticas circulares, aunque persisten limitaciones tecnológicas e institucionales que deben abordarse mediante políticas públicas, educación y alianzas estratégicas.

Palabras clave: economía circular, bioeconomía, residuos orgánicos

Introduction

The increasing generation of organic waste from agricultural, urban, and industrial sources poses a significant environmental challenge today. Patwa et al. (2021) note that these waste streams, if not managed properly, contribute to issues such as greenhouse gas emissions, soil contamination, and the loss of valuable resources. Similarly, Nencheva et al. (2024) argue that the circular economy offers an alternative paradigm to the traditional linear "produce-use-dispose" model, proposing instead a regenerative system in which waste is reintegrated as resources.

Circular bioeconomy, which combines the principles of the circular economy with bioeconomy, emerges as a complementary and innovative strategy. Bruno et al. (2023) assert that this approach is grounded in the utilization of renewable biological resources, including waste, to produce energy, materials, and other value-added goods, a viewpoint also highlighted by Fenoglio (2024). This model promotes resource efficiency, reduces reliance on fossil fuels, and fosters low-carbon economic growth by integrating biotechnological innovation and sustainability (Leong et al., 2021).

In a global context where the transformation of waste into useful inputs has become increasingly relevant, various studies explore multiple valorization pathways. Jõgi and Bhat (2020) emphasize that the production of bioplastics from food waste has shown significant potential as a sustainable alternative, mitigating both the environmental impacts associated with traditional plastics and the negative consequences of organic waste disposal. This perspective is further supported by Synani et al. (2024).

Additionally, Dutta et al. (2025) consider the development of waste biorefineries as a key strategy within the circular bioeconomy. These facilities process residual biomass to produce biofuels, biopolymers, lipids, and other high-value products, while also integrating wastewater treatment solutions and reducing the carbon footprint. Progress has also been made in recovering essential nutrients such as nitrogen and phosphorus from agricultural wastewater. Mehta et al. (2021) highlight that technologies like struvite precipitation contribute to agricultural sustainability and mitigate water-related impacts.

Moreover, recent investigations have focused on designing bioplastics compatible with anaerobic digestion. Studies have examined how variables such as filler concentration and material thickness affect biogas production, providing crucial data for optimizing the integration of these polymers into energy valorization systems (Yadav & Nikalje, 2024; Reyes, 2018).

The literature also explores more innovative and specific solutions. Huilcarema et al. (2024) document the use of agricultural residues, such as banana stems or tuber waste, in the production of bioplastics, merging recyclability with the valorization of exhausted materials by transforming them into biochar, beneficial for soil improvement and wastewater treatment.

Simultaneously, a systematic literature review confirms that the circular bioeconomy aligns with multiple Sustainable Development Goals (SDGs), particularly those related to affordable energy (SDG 7), decent work and innovation (SDG 8-9), responsible production (SDG 12), and climate action (SDG 13). However, the United Nations (UN, 2015) warns of potential negative impacts, including pressures on land use and social inequality.

The conjunction of these approaches, bioplastics, biorefineries, nutrient recovery, and agricultural valorization, forms an integrative framework for circular bioinnovation, focused on transforming organic waste into sustainable resources that meet environmental, social, and economic needs. Nevertheless, most current studies are oriented towards pilot or laboratory scales, highlighting a gap between innovation and real-world application.

In this regard, there is a need to advance the definition of specific sustainability indicators. Yadav and Nikalje (2024) emphasize that these indicators must encompass environmental dimensions (GHG reduction, resource efficiency), economic aspects (profitability, disposal costs), and social factors (employment, community engagement), as such metrics would allow for the empirical evaluation of large-scale circular bioeconomy projects, facilitating their systematic adoption in sustainable environmental management policies and practices.

Methodology

The study was conducted with an applied and descriptive approach, under a non-experimental and cross-sectional design, aimed at analyzing the possibilities of implementing circular economy strategies based on bioinnovation for the valorization of organic waste in the Peruvian context. The research took place in the provinces of Lambayeque and La Libertad, representative areas of Northern Peru, due to their high agro-industrial production of sugarcane, rice, fruits, and vegetables, which generate large volumes of organic waste with sustainable utilization potential.

For data collection, field techniques and documentary analysis were applied. First, direct observations were conducted in local markets and collection centers, enabling the identification of primary waste flows and the documentation of predominant disposal practices. Simultaneously, structured surveys were administered to 120 households, distributed between urban and rural areas, to understand organic waste management habits, citizens' willingness to separate waste at the source, and interest in participating in community valorization projects. The sample included participants of varying ages, with a notable presence of young adults, middle-aged individuals, and seniors, particularly concentrated among those aged 30 to 44 years, reflecting a profile of young adults crucial for promoting circular economy strategies. Additionally, 20 semi-structured interviews were conducted with key stakeholders, including farmers, municipal authorities, and community managers, who provided insights into institutional barriers, opportunities for bioinnovation, and the acceptance level of technologies such as bioplastics, biochar, and anaerobic digestion.

In the documentary phase, regulatory guidelines from the Peruvian Ministry of the Environment were reviewed, which steer national policy towards sustainability (MINAM, 2021), along with reports from international organizations such as the Food and Agriculture Organization of the United Nations, which emphasize the importance of bioeconomy in food security (FAO, 2022). Contributions from the Economic Commission for Latin America and the Caribbean, identifying circular economy opportunities in the region (CEPAL, 2020), and the United Nations Environment Programme, promoting the transition to climate-focused circular models (PNUMA, 2021), were also considered. This analysis complemented the field findings and allowed for a comparison of local practices with global trends in biorefineries, nutrient recovery, and the production of biodegradable bioplastics.

For data processing, information collected through the surveys was analyzed using descriptive statistics, generating frequencies and behavioral patterns related to waste management among citizens. This analysis was conducted using SPSS v.26. Interviews were subjected to thematic coding using Atlas.ti, enabling the organization of testimonies into four main categories: (1) public perception of sustainability and waste, (2) barriers to the implementation of circular bioeconomy projects, (3) opportunities for technological and community innovation, and (4) alignment of local practices with the Sustainable Development Goals (SDGs).

The triangulation of quantitative, qualitative, and documentary data facilitated a comprehensive view of the phenomenon, providing sufficient evidence to support the findings and propose recommendations applicable within the framework of circular economy and bioinnovation in the Peruvian context.

Results and discussion

The results obtained indicate the potential of a circular economy based on bioinnovation as a viable strategy for transforming organic waste into sustainable resources within the Peruvian context. Demographically, the surveyed population exhibits diverse characteristics in terms of age, educational level, and occupation, allowing for the identification of key stakeholders in the adoption of circular practices, particularly among farmers and employees involved in waste management.

Regarding environmental practices and public perceptions, a significant majority of households already separate their organic waste, and there is a strong appreciation for the benefits of converting it into bioproducts such as biogas, biochar, or bioplastics. However, a limited understanding of the circular economy concept persists, highlighting the need to strengthen environmental education and awareness processes.

These findings, detailed in the accompanying tables and graphs, demonstrate that, despite gaps in conceptual knowledge, there is a favorable disposition among citizens that provides a solid foundation for promoting bioinnovation projects aimed at sustainability. Each table and graph is analyzed specifically, enabling a deeper exploration of demographic aspects, waste management practices, and perceptions that underpin the viability of transforming waste into useful resources.

Table 1
Educational level of respondents

Category	Educational level	Percentage
Education	Primary	15%
Education	Secondary	32%
Education	Technical/Higher	28%
Education	University	25%

Note. Secondary education predominates, followed by technical/higher and university levels, indicating a diverse human capital that is amenable to training in bioinnovation.

The analysis of educational levels reveals that the majority of respondents achieved secondary education (32%), followed by those with technical (28%) and university (25%) qualifications. This distribution shows that while specialized knowledge of bioeconomy may be limited, there exists a segment with sufficient academic preparation to understand and apply circular economy strategies, provided that awareness and training processes are reinforced.

Table 2
Primary occupation of respondents

Category	Occupation	Percentage
Occupation	Farmer	22%
Occupation	Employee	30%
Occupation	Student	18%
Occupation	Housewife	20%
Occupation	Other	10%

Note. Employees and farmers emerge as strategic actors, while students and housewives complete the occupational distribution of the sample.

The predominant occupations are employees (30%) and farmers (22%), reflecting the importance of engaging both the urban formal sector and the rural sector in waste transformation. Farmers are key players in the valorization of agro-industrial waste (biochar, composting), while urban employees can contribute to processes of separation and responsible consumption, fostering complementarity between urban and rural contexts in circular management.

Table 3
Separation of organic waste at home

Category	Response	Percentage
Waste separation	Yes	68%
Waste separation	No	32%

Note. The majority of respondents already separate their organic waste, although a percentage still does not, which poses a challenge for circular management.

Sixty-eight percent of respondents indicated that they separate their organic waste, while 32% do not. This finding suggests that there is already a favorable initial practice for implementing circular economy projects, although there remain barriers related to habits and access to differentiated disposal systems that require institutional attention.

Table 4
Awareness of the circular economy

Category	Response	Percentage
Stated knowledge	Yes	42%
Stated knowledge	No	58%

Note. More than half of the respondents are unaware of the concept, underscoring the need for education and environmental awareness programs.

Only 42% reported familiarity with the concept of the circular economy, while 58% do not. This result indicates a significant gap in information and civic education, representing a challenge for public policies and educational outreach. Nevertheless, it also represents an opportunity to introduce awareness programs linking the circular economy to tangible benefits in daily life.

Table 5

Perception of benefits from transforming waste into bioproducts

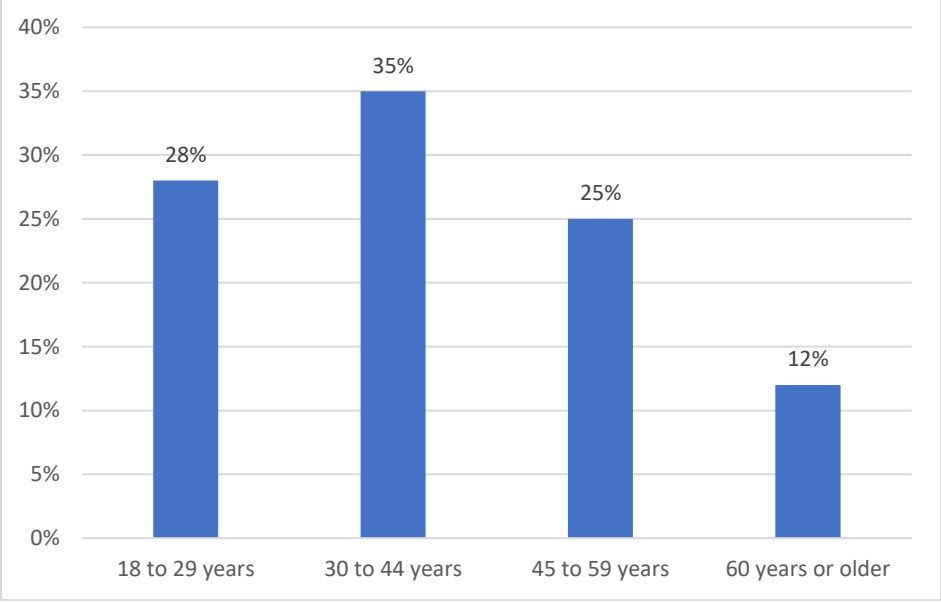
Category	Response	Percentage
Opinion on benefits	Considers beneficial	85%
Opinion on benefits	Does not consider beneficial	15%

Note. A significant majority regards the utilization of waste to generate biogas, biochar, or bioplastics as beneficial, indicating openness towards the circular bioeconomy.

Eighty-five percent of respondents perceive the conversion of waste into biogas, biochar, or bioplastics as beneficial, compared to 15% who do not. The high social acceptance indicates fertile ground for promoting circular bioinnovation projects, where citizens would be willing to adopt sustainable solutions as long as their viability and community benefit are demonstrated.

Figure 1

Distribution of respondents by age

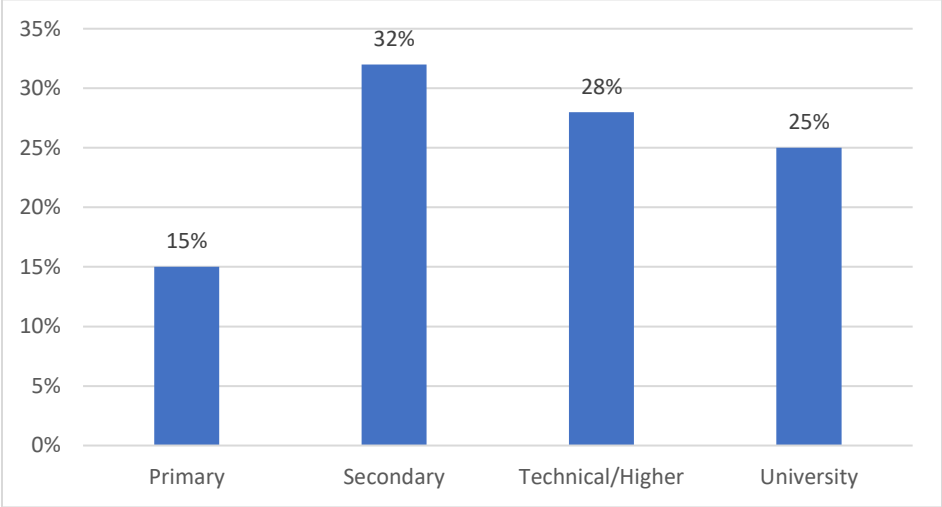


Note. The figure illustrates the proportion of participants by age group, highlighting the predominance of the 30 to 44 age range.

This confirms the concentration of participants in productive age groups, reinforcing the idea that the transformation of organic waste can find in this demographic a key ally for practical implementation and sustainability over time.

Figure 2

Educational level of respondents

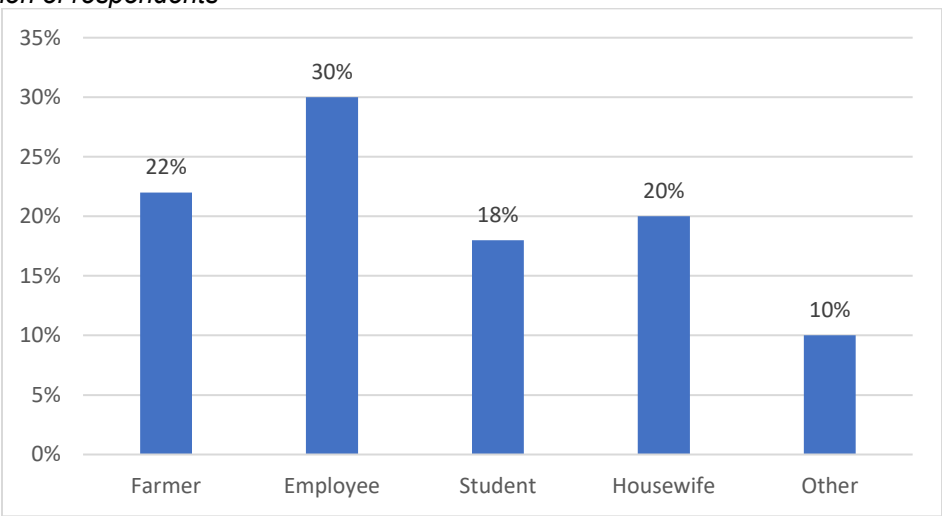


Note. The graph reflects the distribution of the sample according to educational level, evidencing secondary education as the most represented, followed by technical and university training.

The visual representation shows that secondary education predominates, although there remains a considerable percentage with technical and university qualifications. This indicates that the population possesses sufficient foundations to assimilate training programs focused on bioinnovation, though additional pedagogical effort is required.

Figure 3

Primary occupation of respondents



Note. The figure illustrates the occupational diversity among participants, where employees and farmers hold the highest percentages, complemented by students and housewives.

This reflects the diverse occupations within the sample, highlighting employees and farmers as the majority groups. This labor composition indicates the potential to articulate circular economy projects both in rural community settings (agricultural waste utilization) and in urban contexts (waste separation and responsible consumption).

The study results show that, within the Peruvian context, there exists a favorable social foundation for implementing circular economy strategies based on bioinnovation, although knowledge gaps remain. This finding aligns with the observations of Tsegaye et al. (2021), who assert that citizen participation is a critical factor for the sustainable functioning of waste valorization systems. In our case, the 68% of households that already separate organic waste represents an incipient practice that can be bolstered, whereas in other studies conducted in Europe

and Asia, the separation rate exceeds 80% (Merino et al., 2022), presenting a challenge for education and management in Peru.

Regarding knowledge of the circular economy, only 42% of respondents reported familiarity with the concept. This result contrasts with international studies, such as that by Cruz et al. (2022) in the bioplastics sector, where citizen understanding is deemed a key axis for the acceptance of alternative materials. The low familiarity detected in this study reinforces the necessity for environmental awareness programs, in line with Ahmed et al. (2023), who warn that without education and active participation, large-scale circular bioeconomy projects cannot be consolidated.

On the other hand, the high positive perception regarding the benefits of transforming waste into bioproducts (85%) is an encouraging result. This level of social acceptance coincides with findings by Yang et al. (2012), who identify that populations tend to view the conversion of waste into resources favorably when tangible benefits such as energy, fertilizers, or biodegradable materials are perceived. However, unlike laboratory and pilot plant studies in Europe and Asia (Leong et al., 2021; Merino et al., 2022), large-scale experiences have yet to be established in Peru, reflecting a gap between social predisposition and installed technological capacity.

Finally, the demographic and occupational composition of the respondents shows significant potential. The concentration in productive ages and the participation of both farmers and urban employees constitute a meeting point between rural and urban sectors to promote waste valorization projects. This result aligns with the proposals of McCormick and Kautto (2013) concerning the need to integrate diverse actors to build robust circular bioeconomy models. Nevertheless, it is also necessary to consider the risks highlighted by Rodríguez et al. (2019) regarding potential social inequalities and pressures on land use if initiatives are not managed with principles of equity and sustainability.

Overall, the results confirm that there is a positive citizen disposition and initial socioeconomic conditions to promote the circular economy in Peru, but that public policies, environmental education, and technological support are required to bridge the gap with international experiences. The discussion evidences that, although the country shares similar challenges to those described in the global literature, it possesses unique characteristics, such as a strong agro-industrial presence, which can become a competitive advantage for the development of a sustainable circular bioeconomy.

Conclusions

The study demonstrates that the circular economy, rooted in bioinnovation, represents a viable alternative for transforming organic waste into sustainable resources within the Peruvian context. The results indicate that a significant portion of the surveyed population is of productive age and possesses a favorable disposition towards waste separation and valorization. This human capital, combined with the high acceptance of bioproducts, creates a conducive environment for advancing initiatives that integrate environmental sustainability with local socioeconomic development, even as challenges remain in knowledge and civic education.

The findings reflect that, although the majority of households separate organic waste, ignorance of the circular economy concept continues to be a significant barrier. This aligns with international research that emphasizes the importance of environmental education as a pillar of sustainable project success. In this context, it is recommended that educational institutions, local governments, and social organizations develop community awareness programs that allow citizens to understand the tangible benefits of the circular bioeconomy and encourage their active participation in environmental innovation processes.

The high valuation of bioproducts such as biogas, biochar, and bioplastics confirms that there is social acceptance for implementing waste valorization technologies. However, this readiness contrasts with the limited technological infrastructure available in Peru, indicating a gap between social intention and actual capacity for application. Therefore, it is crucial to generate alliances between universities, regional governments, and the private sector, aimed at strengthening technical capabilities and promoting pilot projects that can serve as benchmarks for future large-scale applications in urban and rural communities.

The occupational and educational profile of respondents shows that farmers and urban employees can play a central role in waste management and the adoption of the circular economy. The synergy between these two sectors opens opportunities for developing integrated projects that combine agricultural valorization with source separation in urban areas. This complementarity between rural and urban settings becomes a competitive advantage for Peru compared to other international contexts, provided intersectoral cooperation mechanisms are promoted and local capacities in biotechnological innovation are strengthened.

Ultimately, the research confirms that the country has encouraging initial conditions for promoting the circular bioeconomy, though it also faces significant challenges that require clear public policies, financing, and effective regulatory frameworks. Aligning these initiatives with the Sustainable Development Goals can establish

Peru as a regional reference in organic waste valorization. For this to happen, it will be necessary to advance the definition of sustainability indicators that integrate environmental, social, and economic dimensions, facilitating project assessment and promoting a genuine transition toward regenerative, low-carbon production models.

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