Journal of Engineering, Management and Information Technology

ASPUR PUBLISHING

Vol. 04, No. 02 (2026) 119-128, doi: doi:10.61552/JEMIT.2026.02.001 - http://jemit.aspur.rs

TECHNOLOGICAL TRANSFORMATION AND CIRCULAR BIOECONOMY IN THE COFFEE INDUSTRY: IMPROVING QUALITY MANAGEMENT

Sandra Cecilia Bautista-Rodríguez [1]
Mariluz Osorio-Quiceno

Received 25.02.2025.
Revised 03.05.2025.
Accepted 01.06.2025.

Keywords:

Circular Economy, Organic Fertilizers, Quality Management, Process Improvement, Bioplant, Technological Surveillance.

Original research

A B S T R A C T

The coffee industry, vital to many national economies, faces challenges in sustainability and efficiency, particularly due to the use of chemical fertilizers that degrade soil and foster dependency on external inputs. Circular bioeconomy provides a strategic framework to promote sustainability by transforming coffee residues and other organic materials into organic fertilizers. This article explores, through a case study, how emerging technologies such as the Mixed Pile, ERP systems, and Lean Manufacturing, combined with continuous quality improvement strategies, enable producers to reduce costs, enhance soil quality, and boost competitiveness in international markets. Key findings emphasize the role of technological surveillance, quality management systems, and advanced tools like the Mixed Pile and ERP systems within a global circular bioeconomy framework. These strategies improve operational efficiency, lower costs, and support sustainability across diverse coffee-producing regions, showcasing their potential to transform the industry and enhance global market competitiveness.

1. INTRODUCTION

Coffee production is one of the leading agricultural activities in many countries worldwide, contributing significantly to local economies and global trade. However, the industry's reliance on chemical fertilizers has raised environmental and economic concerns. In response, there is an urgent need to adopt sustainable approaches that maximize resource utilization and minimize waste. In this context, the circular bioeconomy represents a paradigm shift, enabling the reuse of organic waste to produce eco-friendly fertilizers with direct benefits for soil quality, production efficiency, and environmental sustainability. This article, while based on a specific case in Colombia, has international relevance as its findings are applicable to any coffee-producing country. The analysis focuses on available technologies for transforming waste into organic fertilizers, emphasizing improved quality management and cost reduction. It highlights technological strategies that can be implemented across various global contexts, contributing to a more sustainable and efficient coffee sector.

Coffee production is a cornerstone of agricultural activity worldwide, significantly contributing to local economies and global trade. However, the industry's reliance on chemical fertilizers has led to pressing environmental and economic concerns. These challenges underscore the need for sustainable approaches that maximize resource utilization and minimize waste generation. The circular bioeconomy represents a paradigm shift, offering solutions to transform organic waste into eco-friendly

[1] Corresponding author: Leksir Abdeslem
Email: leksir1@yahoo.fr

fertilizers, directly benefiting soil quality, production efficiency, and environmental sustainability. While this issue is global, the findings in this article, grounded in a specific case from Colombia, demonstrate how such approaches can be applied universally in coffee-producing nations (Martínez & Ramírez, 2020).

Known as "black gold," coffee is not only a globally beloved beverage but also a pillar of Colombia's economy. In the strategic coffee-growing region of Huila (Gómez, 2019a; Gómez, 2019b;), the Riveras del Magdalena Association plays a crucial role in producing and marketing high-quality coffee. This association has begun pioneering the production of organic fertilizers by repurposing waste generated during coffee production. Currently, the process remains largely manual and artisanal, leading to inefficiencies and variable product quality. To address these issues, the association is implementing innovative technologies to transition to a biofactory model. This transformation aims to enhance production efficiency and sustainability while optimizing quality standards.

Despite coffee's economic and cultural importance, the sector faces several challenges threatening its long-term sustainability. Colombian coffee producers are particularly vulnerable to climate change, environmental degradation, and social inequality. Tackling these issues requires collaborative strategies involving businesses, producers, consumers, and governments, all committed to promoting sustainability. Effective waste management, particularly for solid and liquid residues, must be integral to this effort, supported by training and governmental aid (Martínez & Ramírez, 2020). Additionally, global competition and volatile coffee prices have pushed producers to explore innovative ways to add value to their products and boost competitiveness in international markets (Sánchez, 2018a).

In this context, the circular bioeconomy emerges as an innovative approach that offers comprehensive solutions to the current challenges faced by the coffee industry (López et al., 2021). This strategic model addresses issues such as resource scarcity, environmental degradation, climate change, and the need for sustainable economic development. Its practices include the efficient use of renewable biological resources, the promotion of recycling and product reuse, the production of biofuels and bioenergy from organic waste, nutrient recovery for agricultural fertilization, the implementation of sustainable agroforestry systems, and the advancement of technological innovation in biomaterial transformation and waste management.

In essence, the circular bioeconomy integrates the responsible use of biological resources with the principles of circular economy, projecting a more sustainable, efficient, and environmentally friendly model. This approach benefits not only the natural environment but also communities, enhancing the resilience of production systems against the impacts of climate change (Hodson de Jaramillo et al., 2023).

In response to these challenges, the Riveras del Magdalena Association has initiated the production of organic fertilizers by repurposing waste generated in their production processes. This transition to a circular bioeconomy model enables not only waste reutilization but also improvements in product quality and process efficiency. This article examines the technological transition towards a biofactory within the circular economy framework, analyzing how adopting innovative technologies can enhance production quality standards, increase efficiency, and reduce environmental impacts. The proposal is based on a detailed analysis of the current situation of the Riveras del Magdalena Association and the integration of technological tools to optimize processes and ensure efficient quality control.

2. BACKGROUND

The implementation of circular bioeconomy in the coffee industry has been the focus of various studies, highlighting its potential to address challenges related to sustainability, efficiency, and value creation in the production chain. Multiple investigations have explored innovative alternatives for utilizing solid and liquid waste generated during coffee production, demonstrating their technical feasibility and environmental and economic benefits.

Bairwan et al. (2025) identified the need to repurpose coffee cherry solid and liquid waste, proposing biocomposites for concrete reinforcement as a sustainable alternative. This approach not only mitigates environmental pollution but also aligns with green chemistry principles, contributing to efficient material flow utilization. Similarly, Yong et al. (2022) evaluated the production of furfural from residual coffee biomass, demonstrating its environmental feasibility but highlighting economic constraints, underscoring the importance of process optimization for practical implementation in a circular bioeconomy context.

Sánchez (2018b) proposed an integrated system for transforming coffee husks into products such as biofuels and fertilizers, emphasizing its replicability in other countries. Carmona et al. (2023) highlighted vermicomposting as a solution for converting waste into organic fertilizer, enhancing agricultural productivity and contributing to Sustainable Development Goal 12 on responsible production and consumption.

Murthy and Naidu (2012) discussed the negative environmental impacts of coffee production, such as water pollution and greenhouse gas emissions, while identifying the potential of residues, such as pulp and mucilage, for producing biofuels and fertilizers. These findings underscore the need for sustainable practices that reduce such impacts and generate benefits for coffee-growing communities.

Other studies have explored specific applications for coffee residues. Rybicka et al. (2015) analyzed the use of solid waste for manufacturing composite materials, while Visco et al. (2022) demonstrated the feasibility of using

coffee husks to produce particleboards, a functional solution aligned with circular bioeconomy principles. Garza-García et al. (2023) explored mucilage as a raw material for natural sweeteners, highlighting its antioxidant properties and market-added value.

The production of bioethanol from coffee pulp was investigated by Guerrero-Martin et al. (2024), who identified enzymatic hydrolysis as the most promising technique to increase yields and reduce production costs. These findings, along with those of Arias et al. (2023), who evaluated strategies for utilizing coffee pulp in applications such as fertilizers and biofuels, demonstrate the extensive potential of coffee by-products within a circular economy model.

At the international level, studies such as Rahmah et al. (2023) have emphasized the positive impact of coffee pulp biomass in reducing CO_2 emissions and adding economic value to sustainable agricultural production. Research from Ain (2024) and Glatzel, et al. (2024) highlighted the importance of bio-inputs like fertilizers and biogas, underscoring the need to design technological and administrative systems that optimize the transformation of waste into new products.

These investigations provide a robust foundation for understanding how coffee residues can be fully utilized within the framework of circular bioeconomy. Each of these findings supports the approach of this article, which seeks not only to implement a biofactory for organic fertilizer production at the Riveras del Magdalena Association but also to contribute replicable strategies that enhance quality, efficiency, and sustainability in coffee production processes globally.

3. METHODOLOGY

This study employs a mixed-methods approach, incorporating both quantitative and qualitative methodologies. Field analyses were conducted to identify the main challenges in implementing circular bioeconomy practices in fertilizer production. Additionally, a technological surveillance study was carried out to identify innovative solutions aimed at improving process efficiency and quality (Hernández & Ramírez, 2019; García, 2020).

3.1. Technological Surveillance

Technological surveillance was employed to identify emerging technologies applicable to the transformation of coffee waste into organic fertilizers. This tool enabled the collection, analysis, and synthesis of information on innovations in the field of circular economy, facilitating the identification of technologies such as the Mixed Pile and ERP management systems.

3.2. Process Analysis

Process analysis was conducted using the SIPOC tool to map inputs, processes, and outputs in the production of organic fertilizers. The goal was to optimize production, reduce time, and improve product traceability and quality.

The Material Flow Analysis (MFA) was utilized to identify inputs and outputs within the coffee production chain, mapping the flow of solid and liquid waste. This analysis highlighted critical points where waste generation was highest, leading to the proposal of technologies such as the Mixed Pile to optimize waste management.

3.3. Case Study

A case study was conducted with the Riveras del Magdalena Association in Colombia. This association's challenges and opportunities are globally relevant, representing the issues faced by coffee producers worldwide.

To collect qualitative data, semi-structured interviews were held with the manager of the Riveras Coffee Association and other key members of the organization (Martínez, 2021). These interviews provided detailed insights into the perceptions, experiences, and specific challenges faced by coffee producers in adopting circular practices. Additionally, farm visits were conducted to directly observe production practices and gather additional information on the processes and technologies in use.

For qualitative data analysis, techniques such as content analysis and thematic coding were employed (Sánchez, 2018a). Content analysis identified patterns and emerging themes from the interviews and field observations, while thematic coding helped systematically organize and categorize the data. These qualitative techniques provided a deep understanding of the producers' perceptions and experiences regarding circular bioeconomy practices.

In addition to the qualitative approach, statistical techniques were employed to analyze the quantitative data collected during the field study (Gómez, 2019a). This included the use of descriptive analyses to examine the distribution of respondents' answers and hypothesis testing to explore relationships between key variables, such as the adoption of circular practices and the economic performance of coffee farms.

4. RESULTS

4.1 Characterization of the Current Process

The initial phase of this study involved an exploratory field investigation in the municipality of Pitalito, located in the Department of Huila, Colombia, with a specific focus on the coffee production practices of the Riveras Coffee Association. Fifteen representative farms were selected from the fifty that comprise the association.

The association has been recognized for its quality, achieving 5th place in the 2020 National Roasted Coffee Brands Competition** in the "Exotic" category, competing against over 200 participants. This achievement highlights the association's commitment to quality and customer satisfaction. Additionally, the group

has implemented good agricultural and manufacturing practices, using both organic and chemical inputs to enrich the soils according to the nutrient requirements of their coffee plants.

During the farm visits, diverse agricultural practices were observed, showcasing the adaptability and innovative approaches adopted by coffee producers in the Huila region. For instance, some producers have implemented water conservation measures, such as constructing reservoirs to capture and store rainwater, and using efficient irrigation systems to maximize available water resources. Integrated crop management practices were also noted, aimed at preserving soil moisture and reducing irrigation needs. These strategies demonstrate the Huila coffee producers' commitment to sustainability and responsible natural resource management.

On one of the farms, a noteworthy process was observed: the production of biofertilizers using organic waste from coffee production, such as pulp and husks, alongside plantain residues. An innovative aspect of this process involved incorporating specific types of rocks [specify type if known] into the composting process to further enrich the resulting natural fertilizer.

This approach not only reduces reliance on chemical fertilizers but also naturally enhances soil properties. The addition of rocks to the compost provides essential minerals that support the growth and development of coffee crops, promoting soil health and long-term fertility. Furthermore, this practice contributes to agroecosystem biodiversity and supports a healthy environment for producing high-quality coffee in the Huila region.

Another farm showcased agroecological practices, including planting native shade trees and fostering biodiversity within the agroecosystem. These measures not only help conserve the environment and natural resources but also improve coffee quality and enhance the resilience of farms to climate change effects.

Interviews with coffee producers revealed a series of perceived challenges affecting farm production and sustainability in the region. These included climate variabilities, a shortage of skilled labor, high production costs, and global competition in the coffee market.

In summary, the exploratory field study of the association's farms provided a comprehensive overview of coffee production practices among the members of the Riveras Coffee Association, as well as the challenges perceived by producers in their agricultural context. These findings are crucial for understanding the specific context in which the investigation on challenges and opportunities in adopting circular practices in the Colombian coffee sector takes place.

The research findings indicate that Riveras Coffee Association producers face several challenges in transitioning to a circular bioeconomy. These include a lack of access to appropriate technologies, limited financial resources, and inadequate recycling infrastructure. However, significant opportunities were also identified, such as product diversification and improved energy efficiency. Additionally, a high level of environmental awareness was observed among producers, suggesting considerable potential for adopting sustainable practices.

The current production process at the Riveras del Magdalena Association relies on manual techniques, including draining, composting, maturation, grinding, sieving, and storage. A closer analysis reveals that draining takes 8 days, while composting, the most time-consuming stage, lasts up to 60 days and is entirely manual. Maturation adds another 10 to 15 days, also handled manually. On the other hand, grinding and sieving are more efficient, requiring just 1 day each to process 5 to 6 tons, using grinders and sieves (100 and 150 micrometers).

The production of organic fertilizers from coffee residues presents several operational challenges:

- Extended composting times (up to 60 days), which significantly limits production capacity.
- Lack of appropriate technologies for controlling leachates and reducing odors, which hinders process optimization.
- Low levels of mechanization, resulting in reduced efficiency and higher labor demands.

While the association has successfully produced high-quality fertilizers, these challenges underscore the need for modernization. The heavy reliance on manual processes contributes to production delays and complicates traceability and quality control. Composting, the longest and most resource-intensive phase, exemplifies the system's inefficiencies.

Addressing these challenges through the introduction of innovative technologies—such as systems to accelerate composting, improve leachate management, and reduce odors—could significantly enhance efficiency. Furthermore, automating key stages like draining and composting would not only optimize production times but also improve product consistency and sustainability, positioning the association as a leader in sustainable fertilizer production within the coffee sector.

4.2 Material Flow Analysis: Discussion and Process Improvement Potential

The material flow analysis (MFA) of the Riveras del Magdalena Association provides a detailed view of the coffee production process, highlighting significant inefficiencies and opportunities for quality-driven optimization. The evaluation reveals that 97.7% of material inputs become waste, illustrating a pressing need for strategies to enhance resource utilization and reduce environmental impacts.

The production process comprises seven stages: harvesting, pulping, fermentation, washing, drying, hulling, and packing. Each stage contributes to material losses, with notable inefficiencies in pulping, fermentation, and washing (show Figure 1):

- Harvesting: Of the 1,837,500 kg of coffee cherries collected, 7.5% (137,813 kg) is discarded due to quality issues, reflecting the need for improved pre-harvest quality controls.

- Pulping: The largest contributor to waste, this stage generates 968,822 kg of mucilage, equivalent to 60% of the input weight, which is currently underutilized.
- Washing: Although essential for ensuring quality, this stage consumes 2,583,525 liters of water, of which 89% becomes liquid waste, emphasizing the need for water recycling systems.
- Drying: This stage loses 150,852 kg as husks and 284,188 kg as water vapor, which could be recovered or repurposed for added value.

Despite these inefficiencies, the association produces 422,729 kg of export-quality coffee, reflecting the commitment to quality despite the challenges posed by traditional, manual methods.

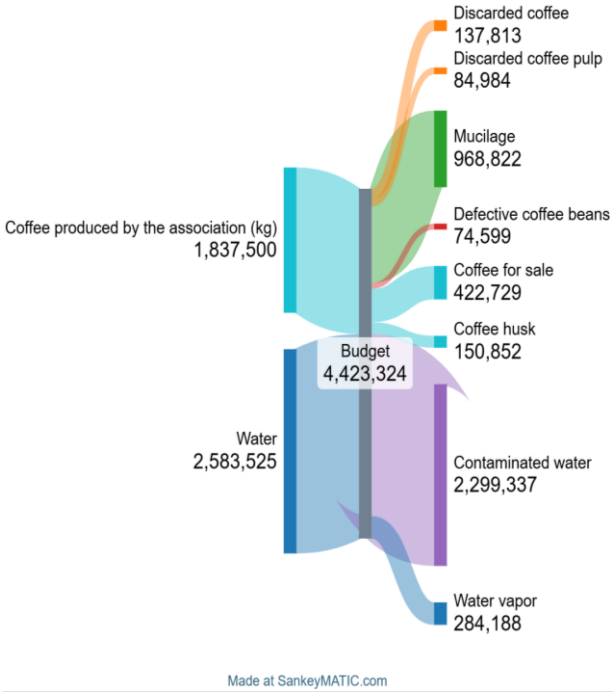

Figure 1. Sankey diagram

However, the lack of mechanization and reliance on resource-intensive practices impede scalability and consistency.

4.3 Potential Quality Improvements Through Circular Practices

- Valorization of Residues: The 60% mucilage waste generated during pulping presents an opportunity for circular practices. By leveraging technologies to convert mucilage into biofertilizers or biofuels, the association can reduce waste while adding economic value. Similarly, husks discarded during drying could be repurposed for energy generation or soil amendments.
- Process Efficiency Through Mechanization: The reliance on manual processes, particularly in composting and pulping, extends processing times and introduces variability in quality. Integrating mechanized solutions, such as automated pulping and drying systems, would streamline operations and ensure consistency in final outputs.
- Water Management: Washing contributes significantly to liquid waste, with 2,299,337 liters of water discharged per cycle. Installing water recycling and treatment systems could drastically reduce consumption, aligning with sustainability goals while maintaining quality standards.
- Digital Tools for Traceability: Implementing ERP systems and digital tools could enhance traceability across the production chain, enabling real-time monitoring of quality parameters and compliance with international export standards.

Aligning Efficiency with Quality Objectives: The findings from the MFA highlight a dual challenge: maintaining the association's recognized quality standards while addressing significant resource inefficiencies. The association's existing manual methods reflect a deep commitment to traditional practices but limit the scalability of their operations and create bottlenecks in production. Addressing these inefficiencies through quality-focused research and technological adoption would support the transition toward a circular bioeconomy, reducing waste and enhancing sustainability.

Integrating circular practices not only aligns with environmental objectives but also positions the association to meet the increasing market demand for sustainable, high-quality coffee. By focusing on innovations in residue valorization, process automation, and water management, the Riveras del Magdalena Association can set a precedent for other coffee producers globally, showcasing how quality and sustainability can coalesce to drive competitive advantage in the coffee industry.

This discussion underscores the need for further research into tailored solutions that optimize both production processes and quality outcomes, offering a roadmap for a sustainable future in coffee production.

4.4 Qualitative Insights: Producer Perceptions and Practices

A qualitative analysis conducted with 30% of the association's coffee producers revealed key themes reflecting their perceptions and experiences regarding circular practices:

- Environmental Awareness: 85% of participants expressed concern for the environmental impact of their agricultural practices, indicating a shift toward sustainability in their mindset. Producers highlighted the importance of adopting eco-friendly methods to align with global sustainability goals.
- Adoption of Circular Practices: 70% of participants reported implementing at least one circular practice, such as composting organic residues or planting native shade trees. These practices contribute to soil health and agroecosystem resilience, reflecting a gradual shift toward sustainable production models.
- Need for Support: 95% of producers identified technical and financial support as critical for

effectively transitioning to circular practices. This underscores systemic barriers, such as limited access to funding and technology, that hinder widespread adoption.

4.4.1 Socioeconomic and Environmental Impacts:
The Riveras Coffee Association has demonstrated significant economic and social contributions within the Huila region, strengthening small-scale farmers through collective action. This has resulted in:

- Enhanced productivity and financial resilience among farmers, enabling intergenerational continuity in coffee farming.
- Integration of former guerrilla members into productive activities, contributing to post-conflict reconciliation.
- Empowerment of women in rural communities through targeted initiatives.

Environmentally, the association has prioritized biodiversity conservation and circular economy practices, such as producing organic fertilizers and reducing contaminant waste. These efforts align with the association's goal to achieve zero contamination in the medium term, advancing a sustainable and efficient production model.

4.4.2 Quality-Driven Innovation for Circular Systems:
The findings reveal a critical interplay between resource inefficiencies, producer perceptions, and systemic challenges that shape the association's production processes. While producers demonstrate environmental awareness and a willingness to adopt circular practices, significant barriers—such as extended composting times, high material losses, and limited access to technology—impede progress.
From a quality research perspective, opportunities to integrate innovative solutions are evident:

- Waste Valorization: Technologies for repurposing mucilage and husks into biofertilizers or biofuels can reduce waste while enhancing product value.
- Water Management: Recycling systems for washing processes would mitigate liquid waste and improve resource efficiency.
- Mechanization and Digitalization: Introducing mechanized systems for pulping and hulling, combined with digital tools for quality control and traceability, would streamline operations and ensure product consistency.

The association's socioeconomic initiatives further illustrate the importance of integrating quality improvement with community development. By fostering environmental stewardship and empowering local stakeholders, the Riveras del Magdalena Association provides a model for how circular bioeconomy principles can drive both sustainability and economic growth in the global coffee sector.
This synthesis underscores the necessity of quality-focused interventions to optimize production, elevate sustainability standards, and enhance the association's competitive position in international markets.

4.5 Technological Gaps and Quality Improvement: A Path Toward Circular Bioeconomy
The Riveras del Magdalena Association exemplifies the potential for transitioning to a circular bioeconomy model while highlighting critical technological gaps that hinder efficiency and product quality. An analysis of these gaps has identified several areas where targeted innovations can significantly enhance the sustainability and productivity of the coffee production process.

4.5.1 Technological Gaps in Coffee Residue Management
The absence of integrated systems for tracking and controlling production processes impacts both operational efficiency and quality management. Key challenges include:

- Extended Composting Times: Manual composting requires up to 60 days, causing delays and variability in the final product.
- Limited Use of By-products: The association lacks systems to valorize significant volumes of waste, including mucilage, husks, and washing water.
- Low Mechanization Levels: The manual handling of materials between production stages reduces efficiency and scalability.

To address these challenges, various technological solutions aligned with circular bioeconomy principles have been proposed:

- Mixed Pile with Forced Aeration: This technology reduces composting times by 50% to approximately 30 days while controlling leachates, odors, and pests. It has the capacity to transform 80 tons of organic waste monthly into 32 tons of compost, significantly enhancing operational efficiency (Michel et al., 2022).
- Mucilage Valorization: Mucilage from fermentation has shown high potential for producing biofuels, such as bioethanol. Studies in Brazil demonstrate a 94% conversion efficiency for bioethanol from mucilage, highlighting its role in reducing reliance on fossil fuels (Orrego et al., 2018; Martínez, 2021).
- Husk Utilization: Coffee husks can be repurposed into compost (Trujillo-González et al., 2024), biofuels (Dias et al., 2020), or construction materials. These applications reduce waste while contributing to economic diversification (Tamilselvan et al., 2024; Thomas et al. 2024).
- Water Treatment and Reuse: Contaminated water from the washing stage can be treated using reverse osmosis (Macias-Bu et al. 2023) or demulsifiers, enabling its reuse for irrigation or domestic operations, thus minimizing environmental impact.

4.5.2 Key Technologies for Implementation

- Mixed Pile with Forced Aeration: Reduces composting time by half, improves biodegradation processes, and produces high-quality organic fertilizer. Air circulation ensures uniform aerobic decomposition, eliminating leachates and odors.

- Stainless Steel Channels: Streamlines the transportation of materials between production stages, enhancing efficiency and reducing labor intensity.
- ERP System for Process Management: Facilitates inventory control, production planning, and traceability, ensuring quality standards at every stage.
- Biofuel Production from Mucilage: Converts fermentation residues into sustainable energy sources, reducing dependence on chemical inputs and fossil fuels. In Brazil, this strategy has decreased reliance on fossil fuels by up to 20% in certain coffee-producing regions.

4.5.3 Improving Product Quality Through Organic Fertilizers

The production of organic fertilizers from coffee residues not only addresses waste management but also significantly enhances soil quality. Analyses have shown that organic fertilizers increase soil nutrient content and water retention capacity. These improvements reduce dependency on chemical fertilizers, resulting in a more competitive and sustainable product. Such benefits are replicable in other coffee-growing regions, offering a pathway to global adoption of circular practices.

5. DISCUSSIONS

The implementation of advanced technologies like the Earth-Green Mixed Pile and ERP systems presents a strategic opportunity to modernize production processes at the Riveras del Magdalena Association. These innovations directly address inefficiencies identified through material flow analysis and producer feedback, improving processing times, enhancing traceability, and transforming waste into valuable by-products.

By closing technological gaps, the association can achieve a dual objective: improving operational efficiency and aligning with international standards for sustainable, high-quality coffee production. These interventions not only support environmental goals but also enhance the association's competitiveness in global markets, positioning it as a leader in adopting circular bioeconomy principles within the coffee sector.

The adoption of technologies such as the Earth-Green Mixed Pile and ERP systems will not only improve fertilizer production efficiency but also enable the Riveras del Magdalena Association to meet international quality standards. This is especially important given the growing interest in organic fertilizers that comply with environmental and sustainability regulations.

Focusing on continuous process improvement will allow the association to better position itself in the market and reduce dependence on chemical fertilizers. Furthermore, adopting a circular bioeconomy model creates opportunities for local farmers to diversify their income while contributing to environmental sustainability and soil quality improvement.

The study shows that the circular bioeconomy is a viable strategy for the sustainable production of fertilizers in the global coffee industry. The implementation of technologies like the Mixed Pile and ERP systems not only enhances operational efficiency but also creates a positive feedback loop that maximizes the use of organic waste and minimizes environmental impact.

This approach can be adopted by coffee producers in countries like Brazil, Vietnam, and Ethiopia, where the industry faces similar challenges regarding sustainability and dependence on chemical fertilizers. Circular bioeconomy offers an integrated solution that not only improves the quality of coffee produced but also increases the resilience of agricultural systems to the effects of climate change.

5.1 Challenges in Maintaining Sustainable Practices

Coffee associations in Colombia, including the Riveras Coffee Association, face several challenges in maintaining sustainable practices:

- Price Volatility: The fluctuation of coffee prices on the international market can affect producers' ability to invest in sustainable practices.
- Climate Change: Climate change poses a significant risk to coffee production, affecting growing conditions and product quality.
- Market Access: Finding markets that value and pay a fair price for sustainable coffee remains an ongoing challenge.
- Certification Costs: Obtaining and maintaining sustainability certifications can be expensive and complex for small producers.
- Education and Training: Educating and training producers in sustainable practices is essential but also represents a challenge in terms of resources and reach.
- Infrastructure and Technology: The lack of adequate infrastructure and access to advanced technology can limit the implementation of sustainable practices.

These challenges require a coordinated response involving producers, associations, governments, and other sector stakeholders to ensure that sustainable practices remain viable in the long term and continue to contribute to the economic and social development of coffee-growing communities. The importance of close collaboration and strategic planning is emphasized to maximize the benefits of the circular bioeconomy at the Riveras Coffee Association and promote sustainable development in the region.

5.2 Challenges in Adapting to Climate Change

The Riveras Coffee Association, like other coffee organizations in Colombia and the region, is adopting several measures to cope with the challenges posed by the effects of climate change. These measures include:

- Crop Diversification: Introducing more resilient coffee varieties and diversifying with other crops to reduce vulnerability to extreme weather events.
- Agroecological Practices: Implementing agroecological practices that improve soil resilience and biodiversity, such as using organic fertilizers and integrated pest management.
- Water Conservation: Improving water management through rainwater collection and storage systems, and implementing efficient irrigation systems.
- Reforestation and Soil Management: Engaging in reforestation activities and sustainable soil management to conserve ecosystems and prevent erosion.
- Training and Education: Providing ongoing training and education to producers on climate change adaptation and sustainable resource management.

These adaptation strategies are essential to ensure the long-term sustainability of coffee production and the economic viability of coffee-growing communities in the context of climate change. The Riveras Coffee Association is committed to implementing these practices to address current and future challenges in the sector.

6. CONCLUSIONS

The adoption of circular bioeconomy models can have a significant global impact, not only on the coffee industry but also on any agricultural sector seeking a transition to more sustainable practices. The reduction in the use of chemical fertilizers and the reuse of organic waste allows coffee-producing countries to improve their international competitiveness while also meeting the Sustainable Development Goals (SDGs).

The study also demonstrates that the technologies applied in Colombia are replicable in any coffee-growing context worldwide. In countries like Brazil, one of the largest coffee producers in the world, the implementation of circular bioeconomy systems could significantly reduce operational costs and improve soil quality in regions where erosion and nutrient loss are recurring issues.

Implementing a circular bioeconomy model in the global coffee industry is a key strategy for improving sustainability, product quality, and operational efficiency. Although this study is based on a case in Colombia, it holds international relevance, as the challenges and proposed solutions can be applied to any coffee-producing country. The adoption of technologies like the Mixed Pile and ERP systems enhances traceability, waste reduction, and energy efficiency, contributing to a more resilient and sustainable coffee sector on a global scale.

Acknowledgement:
The authors would like to express their sincere gratitude to the Riveras del Magdalena Association for their invaluable support and collaboration throughout the development of this research. Their commitment to promoting circular bioeconomy and sustainable agricultural practices was essential to the successful completion of this study.

References:

Ain, N. U. (2024). Advancing sustainable agriculture: Bioinputs and solid-state fermentation innovations for eco-friendly farming. *International Journal of Agriculture and Sustainable Development*, *6*(2), 90-101.

Arias, A., Ioannidou, S. M., Giannakis, N., Feijoo, G., Moreira, M. T., & Koutinas, A. (2023). Review of potential and prospective strategies for the valorization of coffee grounds within the framework of a sustainable and circular bioeconomy. *Industrial Crops and Products*, *205*, 117504.

Bairwan, R. D., Khalil HPS, A., Nuryawan, A., Ahmad, M. I., Kassim, M. H. M., & Ahmad, A. (2025). Enhancing biopolymer materials with coffee waste-derived reinforcements. *Polymer Engineering & Science*, *65*(2), 455-477.

Carmona, I., Aguirre, I., Griffith, D. M., & García-Borrego, A. (2023). Towards a circular economy in virgin olive oil production: Valorization of the olive mill waste (OMW)“alpeorujo” through polyphenol recovery with natural deep eutectic solvents (NADESs) and vermicomposting. *Science of the Total Environment*, *872*, 162198.

Dias, C. D. A., Andrade, E. T. D., Lemos, I. A., Borém, F. M., & Barros, E. A. (2020). Sorption isotherms and isosteric heat of pericarp and endosperm tissues of arabica coffee fruit. *Engenharia Agrícola*, *40*(1), 78-89.

García, A. (2020). Estudio de campo sobre la producción de café en la región del Huila. *Revista de Agricultura Sostenible*, 7(1), 30-45.

Garza-García, J. J., Hernández-Díaz, J. A., León-Morales, J. M., Velázquez-Juárez, G., Zamudio-Ojeda, A., Arratia-Quijada, J., ... & García-Morales, S. (2023). Selenium nanoparticles based on Amphipterygium glaucum extract with antibacterial, antioxidant, and plant biostimulant properties. *Journal of nanobiotechnology*, *21*(1), 252.

Glatzel, K., Virchow, D., Nakitto, A. M. S., Niyonsenga, S., Babu, S. C., Srivastava, N., ... & Osano, P. (2024). Bioeconomy pathways: Experience from Africa, Asia, and Latin America. *IFPRI book chapters*, 116-149.

Gómez, A. (2019a). El impacto económico del café en Colombia. *Revista de Economía del Café*, 12(2), 45-58.

Gómez, R. (2019b). Análisis estadístico de datos en estudios de campo. *Revista de Estadística Aplicada*, 15(3), 102-115.

Guerrero-Martin, C. A., Prieto-Moreno, L. A., Arturo-Calvache, J. E., Camacho-Galindo, S., Guerrero-Martin, L. E., Guerrero, W. A., ... & Lucas, E. F. (2024). Conceptual Design Study of a Coffee Stem Gasification Scheme in the Context of a Biorefinery. *Energies*, *17*(19), 4972.

Hernández, J., & Ramírez, M. (2019). Revisión bibliográfica sobre bioeconomía circular y café en Colombia. *Revista de Economía Circular,* 4(2), 60-75.

Hodson de Jaramillo, E., Niggli, U., Kitajima, K., Lal, R., & Sadoff, C. (2023). Boost nature-positive production. *Science and innovations for Food systems Transformation*, 319-340.

López, R., et al. (2021). La bioeconomía circular como estrategia de desarrollo sostenible en la industria cafetera. *Investigación en Desarrollo Sostenible*, 8(2), 35-50.

Macias-Bu, L., Guerra-Valle, M., Petzold, G., & Orellana-Palma, P. (2023). Technical and environmental opportunities for freeze desalination. *Separation & Purification Reviews*, *52*(4), 326-335.

Martinez, C., Saari, J., Melo, Y., Cardoso, M., Almeida, G., & Vakkilainen, E. (2021). Evaluation of thermochemical routes for the valorization of solid coffee residues to produce biofuels: A Brazilian case. *Renewable & Sustainable Energy Reviews*, 137, 110585. DOI: 10.1016/j.rser.2020.110585.

Martínez, J., & Ramírez, M. (2020). Cambio climático y producción de café en Colombia: una revisión de la literatura. *Revista Latinoamericana de Cambio Climático*, 5(1), 78-92.

Martínez, L. (2021). Entrevistas semiestructuradas como herramienta de investigación cualitativa. *Métodos de Investigación Cualitativa*, 12(3), 105-120.

Michel, F., O'Neill, T., Rynk, R., Gilbert, J., Smith, M., Aber, J., & Keener, H. (2022). Forced aeration composting, aerated static pile, and similar methods. In The composting handbook (pp. 197-269). Academic Press.

Murthy, P. S., & Naidu, M. M. (2012). Sustainable management of coffee industry by-products and value addition—A review. *Resources, Conservation and recycling*, *66*, 45-58.

Orrego, D., Zapata-Zapata, A., & Kim, D. (2018). Optimization and Scale-Up of Coffee Mucilage Fermentation for Ethanol Production. *Energie*s, 11, 786. DOI:10.3390/EN11040786.

Rahmah, D. M., Mardawati, E., Kastaman, R., Pujianto, T., & Pramulya, R. (2023). Coffee pulp biomass utilization on coffee production and its impact on energy saving, CO2 emission reduction, and economic value added to promote green lean practice in agriculture production. *Agronomy*, *13*(3), 904.

Rybicka, J., Tiwari, A., Del Campo, P. A., & Howarth, J. (2015). Capturing composites manufacturing waste flows through process mapping. *Journal of cleaner production*, *91*, 251-261.

Sánchez, F. (2018a). Análisis de contenido en investigación cualitativa. *Revista de Investigación Educativa*, 25(4), 78-92.

Sánchez, L. (2018b). Competitividad del café colombiano en el mercado internacional. *Revista de Comercio Exterior*, 25(3), 102-115.

Tamilselvan, K., Sundarajan, S., Ramakrishna, S., Amirul, A. A. A., & Vigneswari, S. (2024). Sustainable valorisation of coffee husk into value added product in the context of circular bioeconomy: Exploring potential biomass-based value webs. *Food and Bioproducts Processing*.

Thomas, L., Neelima, T. K., & Archana, T. M. (2024). Renewable functional materials derived from animal wastes and organic garbage waste to wealth–a green innovation in biomass circular bioeconomy. *Handbook of Advanced Biomass Materials for Environmental Remediation*, 43-73.

Trujillo-González, J. M., Jiménez-Ballesta, R., Silva-Parra, A., Torres-Mora, M. A., & Navarro, F. J. G. (2024). A comprehensive review of composting from coffee waste: Revalori-sation of coffee residue in Colombia. *International Journal of Recycling of Organic Waste in Agriculture*, *13*(3), 1-12.

Visco, A., Scolaro, C., Facchin, M., Brahimi, S., Belhamdi, H., Gatto, V., & Beghetto, V. (2022). Agri-food wastes for bioplastics: European prospective on possible applications in their second life for a circular economy. *Polymers*, *14*(13), 2752.

Yong, K. J., Wu, T. Y., Lee, C. B. T. L., Lee, Z. J., Liu, Q., Jahim, J. M., ... & Zhang, L. (2022). Furfural production from biomass residues: Current technologies, challenges and future prospects. *Biomass and Bioenergy*, *161*, 106458.

Sandra Cecilia Bautista-Rodríguez
Universidad El Bosque; Faculty of Engineering, Research Group GINTECPRO, Department of Industrial Engineering.
Colombia.
sbautistar@unbosque.edu.co
ORCID: 0000-0002-9856-4706

Mariluz Osorio-Quiceno
Universidad El Bosque; Faculty of Engineering, Research Group GINTECPRO, Department of Industrial Engineering.
Colombia
mosorioq@unbosque.edu.co
ORCID: 0000-0002-2926-9789