Gunung Djati Conference Series, Volume 61 (2025)
International Conference of the 17th OISAA's International Symposium Türkiye
ISSN: 2774-6585
Website: https://conferences.uinsgd.ac.id/

Leveraging ICT to Enhance Bioenergy Production from Agricultural Waste: A Systematic Review

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Abstract

The transition to a circular economy necessitates the valorisation of abundant resources like agricultural waste into bioenergy. However, the development of this sector is frequently hampered by inefficient, fragmented, and economically unviable supply chains. This study aims to systematically review how Information and Communication Technology (ICT) is leveraged to enhance the efficiency, profitability, and scalability of bioenergy production from agricultural waste. Employing a rigorous Systematic Literature Review (SLR) methodology based on the PRISMA guidelines, we synthesized evidence from the major international databases, ScienceDirect and Emerald Insight, focusing on publications from the last five years (2021–2025). The synthesis of results reveals that key ICT applications, such as GIS for route optimisation, IoT sensors for real-time feedstock monitoring, and mobile platforms for coordinating logistics between farmers and biorefineries are critical for overcoming supply chain barriers. These technologies demonstrably reduce logistical costs, improve feedstock quality control, and create transparent, viable business models for farmers. A key finding highlights that ICT creates a powerful synergy where economic efficiency and environmental sustainability are mutually reinforcing. Key challenges identified include the high initial investment for technology adoption and the digital literacy gap in rural communities. In conclusion, strategically leveraging ICT is fundamental to transforming the agricultural waste-to-energy ecosystem from a nascent concept into a robust and sustainable industry. This review's primary contribution is a comprehensive conceptual framework of ICT interventions across the supply chain stages, and the identification of critical socio-institutional research gaps regarding farmer adoption models and supportive policy measures.

Keywords: Agricultural Waste, Bioenergy, ICT (Information and Communication Technology), Supply Chain Management

1. INTRODUCTION

The global imperative to transition towards a sustainable and circular economy has become a central theme in addressing the dual challenges of climate change and achieving the Sustainable Development Goals (SDGs) . This paradigm shift requires a fundamental rethinking of production and consumption systems, moving away from linear models towards closed-loop systems that minimize waste and maximize resource value

(Axon & Darton, 2024). Within this transition, bioenergy has emerged as a critical component of the renewable energy portfolio, with a particular focus on the valorization of abundant and underutilized biomass resources such as agricultural waste (Schlemminger et al., 2024). The utilization of these residues aligns perfectly with the core tenets of the circular bioeconomy, which emphasizes converting waste streams into valuable products like biofuels, thereby contributing to both energy security and environmental sustainability. The development of bioenergy from agricultural waste not only offers a pathway to mitigate greenhouse gas emissions but also supports rural economies and fosters a more resilient and environmentally conscious development model (Sánchez-Lozano et al., 2025).

Despite its immense potential, the widespread development of the bioenergy sector from agricultural waste is consistently hampered by fundamental challenges embedded within its supply chain. This supply chain is inherently complex, geographically dispersed, fragmented, and fraught with inefficiencies and risks, particularly within the context of developing nations (Amoozad Mahdiraji et al., 2022). A systematic evaluation of this sector reveals significant risks, including unstable and often inconsistent government policies, a lack of access to sufficient investment capital for infrastructure, and high volatility in feedstock supply (Mardenli et al., 2023). This volatility is exacerbated by the pressing issue of land competition between food production and energy crops, which further underscores the importance of utilizing non-food agricultural residues (Schlemminger et al., 2024). Furthermore, these systemic challenges are compounded by barriers at the primary producer level. Farmers, who are the source of this biomass, often operate from a weak bargaining position, face significant socio-economic hurdles, and may be hesitant to adopt the new practices required to efficiently collect and supply agricultural waste, a decision process influenced by a complex mix of economic, social, and cultural factors (Harrahill et al., 2023). Consequently, this unreliable and high-risk supply chain remains a major obstacle, preventing the bioenergy sector from realizing its full potential as a cornerstone of the green economy (Evans et al., 2025).

To overcome these deeply entrenched inefficiencies and mitigate the associated risks, the application of Information and Communication Technology (ICT) and the principles of digitalization within the Industry 4.0 framework offer a powerful and transformative solution. The integration of advanced technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), and Blockchain has demonstrated a significant capacity to enhance transparency, efficiency, and sustainability across various complex supply chains, from forestry to large-scale agriculture (Bastos et al., 2024). In the context of the bioenergy supply chain, ICT enables critical functions such as the real-time monitoring of feedstock quality and quantity, the optimization of complex logistics from farm to biorefinery, and the creation of innovative, transparent business models that can more effectively and equitably connect dispersed waste producers with energy facilities (Secinaro et al., 2022). These digital innovations hold the promise of de-risking the supply chain, improving economic viability, and ultimately scaling up bioenergy production.

To overcome these deeply entrenched inefficiencies and mitigate the associated risks, the application of Information and Communication Technology (ICT) and the principles of digitalization within the Industry 4.0 framework offer a powerful and transformative solution. The integration of advanced technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), and Blockchain has demonstrated a significant capacity to enhance transparency, efficiency, and sustainability across various complex supply chains, from forestry to large-scale agriculture (Bastos et al., 2024). In the context of the bioenergy supply chain, ICT enables critical functions such as the real-time monitoring of feedstock quality and quantity, the optimization of complex logistics from farm to biorefinery, and the creation of innovative, transparent business models that can more effectively and equitably connect dispersed waste producers with energy facilities (Secinaro et al., 2022). These digital innovations hold the promise of de-risking the supply chain, improving economic viability, and ultimately scaling up bioenergy production.

However, while a growing body of literature has examined innovation within the broader agri-food sector and the role of technology in supply chain sustainability, a specific and comprehensive synthesis is currently lacking (Bigliardi & Filippelli, 2022). Numerous studies have reviewed digital agriculture or bioenergy as separate fields, but there remains a clear knowledge gap concerning the direct intersection of these domains. Specifically, the state of the art shows that prior reviews tend to focus either on the technical aspects of biomass conversion or the general application of digital agriculture, often failing to integrate both the technological interventions and their specific impacts/barriers within the entire agricultural waste-to-bioenergy supply chain. There has been no systematic review that comprehensively maps the diverse ICT applications being specifically utilized to enhance and accelerate the agricultural waste-to-bioenergy supply chain. Furthermore, a consolidated analysis of the documented impacts of these technologies, the key enablers for their adoption, and the persistent barriers that hinder their implementation is needed. Therefore, this study aims to fill this critical gap by conducting a systematic literature review to synthesize the existing knowledge, structure the current state of research, and identify future research priorities at the nexus of ICT, bioenergy, and agricultural waste management.

2. RESEARCH METHODS

This study employs a Systematic Literature Review (SLR) as its research design (Jetty & Afshan, 2025). The SLR methodology was chosen for its rigorous, transparent, and replicable approach to synthesizing existing research evidence from a wide and often fragmented body of literature (Xu et al., 2023). Given that the primary objective of this research is to comprehensively map the applications of Information and Communication Technology (ICT), analyze their impacts, and identify key challenges within the agricultural waste-to-bioenergy supply chain, the SLR approach is the most suitable method for producing robust, evidence-based conclusions. To ensure methodological rigor and transparency, this study strictly adheres to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. The PRISMA protocol provides an internationally recognized, evidence-based checklist and a flow diagram designed to guide the systematic review process, from the formulation of research questions to the final synthesis of results. This

structured approach enhances the clarity and reliability of the review, allowing for a clear audit trail of the research process (Iqbal et al., 2025).
To provide a clear focus for this review and to ensure that the analysis is targeted and relevant, a set of specific research questions (RQs) were formulated. These questions, detailed in Table 1, are designed to systematically deconstruct the overarching research problem into specific, answerable components that guide the entire data collection and synthesis process.

Table 1. Research Question

RQ Qode	Research Question
RQ1	What are the primary ICT applications (e.g., IoT, AI, Blockchain, GIS) that have been implemented or proposed to enhance the agricultural waste-to-bioenergy supply chain?
RQ2	What are the documented impacts, including both benefits (e.g., increased efficiency, profitability, sustainability) and challenges, of these ICT applications across the different stages of the supply chain?
RQ3	What are the key barriers and enablers influencing the adoption of these technologies by relevant stakeholders (e.g., farmers, biorefineries), and what are the critical research gaps that require further investigation?

The literature search was conducted across several reputable international academic databases to ensure comprehensive and multi-disciplinary coverage of the topic. The primary databases selected were ScienceDirect and Emerald Insight, chosen for their extensive collections of peer-reviewed literature across technology, agriculture, energy, and environmental sciences. To complement these, a search was also performed on ScienceDirect to capture specific publications from Elsevier's extensive journal portfolio. The search strategy was designed to be both sensitive and specific, using a Boolean search string that combines keywords from four core conceptual pillars, "Agricultural Waste", "Bioenergy", "ICT", and "Supply Chain".

To ensure that the articles selected for this review were of high relevance and quality, a strict set of eligibility criteria was established. Table 2 outlines the inclusion criteria that each potential study had to meet to be considered for the final analysis.

Table 2. Inclusion Criteria

Criterion	Description
Topical Relevance	Articles must explicitly discuss the application, impact, or potential of ICT within the context of the bioenergy supply chain derived from agricultural waste.
Publication Type	Only peer-reviewed journal articles and full-text conference proceedings were included to maintain academic rigor.

Timeframe	Publications were limited to the last 5 years (January 2021 – September 2025) to ensure the analysis reflects current and emerging technological advancements.
Language	Only studies published in English were included to ensure consistency and facilitate a comparable analysis.

Conversely, studies were systematically removed if they met any of the conditions outlined in Table 3, which specifies the exclusion criteria for this review.

Table 3. Exclusion Criteria

Criterion	Description
Irrelevant Focus	Studies focusing solely on agricultural production without a link to bioenergy, or on bioenergy without a clear supply chain or ICT component, were excluded.
Publication Type	Editorials, book reviews, commentaries, opinion pieces, and other non-scientific publications were excluded.
Accessibility	Studies that were not available in full-text format were excluded due to the inability to perform a detailed data extraction.

The entire selection process followed the four-stage PRISMA framework, which is visually summarized in the flow diagram presented in Figure 1.

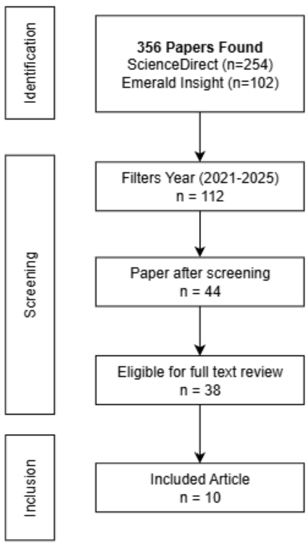

Figure 1 PRISMA Flow Diagram

As illustrated in the diagram, the Identification stage began with an initial search across the selected electronic databases, yielding a total of 356 articles. During the Screening phase,

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after removing duplicates and screening titles and abstracts based on the predefined eligibility criteria, 44 records were assessed for relevance. Following this, 38 articles were advanced to the full-text review stage. Finally, in the Inclusion stage, a final set of 10 studies was deemed fully eligible and was included in the qualitative synthesis for this review.

The entire selection process, from initial identification to the final inclusion of studies, was meticulously documented using a PRISMA flow diagram, which will be presented in the results section to ensure methodological transparency. For data analysis, a qualitative Thematic Synthesis approach was employed. This method is well-suited for an SLR as it moves beyond simple summarization to generate new, integrative insights from the literature. The process involved three systematic stages: first, Data Familiarization and Extraction, where all included articles were systematically reviewed to identify and extract key information pertaining to the research questions. Relevant data such as specific technologies, reported impacts, and identified barriers were extracted and assigned conceptual codes, facilitated by qualitative data analysis software. Second, Developing Descriptive Themes, where the extracted codes were organized into a hierarchical structure to form themes that closely mirrored the primary findings reported in the literature, such as "IoT Applications for Feedstock Monitoring" or "Barriers to Farmer Adoption." Finally, Generating Analytical Themes, where the descriptive themes were interpreted further to identify patterns, relationships, and contradictions across the studies, leading to the construction of a new conceptual framework. This synthesis forms the core of the "Results and Discussion" chapter.

3. RESULTS AND DISCUSSIONS

This chapter presents the synthesized findings from the Systematic Literature Review (SLR), structured to systematically answer the three research questions (RQs) established in the methodology. The analysis integrates and interprets evidence from the selected literature to identify the primary Information and Communication Technology (ICT) applications, their documented impacts, and the key factors influencing their adoption in the agricultural waste-to-bioenergy supply chain. Each section compares the synthesized findings with prior studies to highlight their contribution to the broader research context.

The synthesis of the reviewed literature indicates that the optimization of the agricultural waste-to-bioenergy supply chain is increasingly reliant on an integrated ecosystem of digital technologies, often framed within the Industry 4.0 paradigm. These technologies, summarized in Table 4, function by transforming a previously opaque and fragmented supply chain into a data-rich, interconnected system capable of managing the inherent complexity and variability of agricultural waste.

Table 4. Synthesis of Primary ICT Applications in the Bioenergy Supply Chain

ICT Application	Description and Role in the Supply Chain	References
Internet of Things (IoT) & Sensors	Deployment of sensors on farms, in storage facilities, and on transport	(Bastos et al., 2024; Xu et al., 2023)

	vehicles to monitor real-time data on feedstock quantity, quality (e.g., moisture content), location, and processing conditions.	
Artificial Intelligence (AI) & Machine Learning (ML)	Use of algorithms to analyze data for predictive modeling (e.g., forecasting feedstock availability), process optimization (e.g., optimizing biorefinery operations), and decision support for farmers and supply chain managers.	(Cipollina et al., 2025; González-Sánchez et al., 2025; Sánchez-Lozano et al., 2025)
Geographic Information Systems (GIS)	Spatial analysis tools for optimizing feedstock collection routes, identifying suitable locations for storage hubs or biorefineries, and mapping biomass availability across regions.	(Axon & Darton, 2024; Mardenli et al., 2023)
Blockchain Technology	A distributed ledger technology to create a transparent, immutable, and traceable record of transactions and product flow, from the farm to the end-user. This enhances trust and facilitates certification for sustainability.	(Spada et al., 2025)
Digital Platforms & Mobile Apps	Centralized platforms or mobile applications that connect farmers with biorefineries, logistics providers, and markets, facilitating coordination, price discovery, and efficient transactions.	(Csedő et al., 2025; Evans et al., 2025)

The significance of the technologies identified in Table 4 lies not in their individual capabilities, but in their successful convergence into a cohesive digital toolkit for biomass supply chain management. This finding suggests a maturing field where a best-practice model is beginning to emerge, moving beyond piecemeal solutions. This aligns with the digital transformation in adjacent sectors, such as forestry, which demonstrates how "Forest 4.0" principles create transparent and sustainable value chains (Bastos et al., 2024). The scientific interpretation is that managing heterogeneous, geographically dispersed feedstocks necessitates a fundamental technological shift from manual coordination to automated, data-driven logistics and decision-making. This represents a move from a reactive management style, which is vulnerable to the risks, towards a proactive and predictive approach that enhances system-wide resilience (Axon & Darton, 2024).

The implementation of these ICT solutions generates a spectrum of impacts that directly address the core challenges of profitability, reliability, and sustainability that have historically hampered the bioenergy sector. These documented impacts, both positive and negative, are synthesized in Table 5.

Table 5. Benefits and Challenges of ICT in the Bioenergy Supply Chain

ICT Application	Benefits	Challenges	References
Economic	- Increased profitability through cost reduction (logistics, fuel, waste). - Creation of new, viable business models for farmers.	- High initial investment costs for technology. - Uncertainty in return on investment (ROI).	(Axon & Darton, 2024; Csedő et al., 2025; Sánchez-Lozano et al., 2025)
Operational	- Improved logistical efficiency and optimized routes. - Enhanced real-time monitoring and quality control of feedstock. - Increased supply chain resilience and reduced risk of disruptions.	- Requirement for robust digital infrastructure (e.g., internet connectivity) in rural areas. - Data management and cybersecurity risks.	(Bastos et al., 2024; Mardenli et al., 2023; Xu et al., 2023)
Environmental & Social	- Facilitates the transition to a circular economy. - Reduces carbon emissions by optimizing logistics and preventing waste. - Enhances transparency and traceability for sustainability certification.	- Potential for a digital divide, excluding smallholder farmers who lack access or skills. - Energy consumption of data centers and digital infrastructure (e-waste).	(Cipollina et al., 2025; Evans et al., 2025; Spada et al., 2025)

The findings presented in Table 5 underscore a significant dual benefit: ICT enables the pursuit of environmental goals, not as a separate corporate social responsibility initiative, but as a direct driver of economic and operational performance. This counters the traditional view of a trade-off between sustainability and profitability. For instance, the operational efficiencies gained from real-time monitoring directly reduce feedstock waste, which in turn lowers costs and supports the circular economy principles outlined (González-Sánchez et al., 2025). This synergy provides a powerful scientific interpretation: in a digitized supply chain, economic optimization and environmental stewardship become mutually reinforcing (Mardenli et al., 2023). This directly addresses the real-world disruptions reported by transforming the supply chain from a reactive to a resilient system, thereby strengthening the business case for investment as explored in the techno-economic assessments (González-Sánchez et al., 2025).

Beyond the technology itself, the literature strongly indicates that the human and institutional dimensions are the most critical determinants of successful implementation. The key barriers, enablers, and resulting research gaps that shape the adoption landscape are summarized in Table 6.

Table 6. Key Barriers, Enablers, and Identified Research Gaps for ICT Adoption

Key Factors	Specific Examples	References
Barriers	- Socio-Cultural & Behavioral: Farmer resistance to change, lack of digital literacy, and mistrust in new technologies. - Economic: High upfront investment costs and perceived financial risks for smallholders. - Institutional: Lack of stable and supportive policy frameworks; inconsistent government support.	(Axon & Darton, 2024; Evans et al., 2025; Mardenli et al., 2023)
Enablers	- Policy & Governance: Clear, long-term green policies that support the circular bioeconomy and provide financial incentives. - Technological: Development of user-friendly, affordable, and scalable ICT solutions tailored for the agricultural sector. - Market Drivers: Increased demand for sustainable energy and transparent supply chains.	(Bastos et al., 2024; Cipollina et al., 2025; Csedő et al., 2025; Spada et al., 2025)
Identified Research Gaps	- Farmer Adoption Models: Lack of in-depth research on the socio-economic factors driving ICT adoption specifically among farmers in the bioenergy context. - Integrated Policy Analysis: Need for studies on how to design coherent policies that support the entire bio-based ecosystem without creating internal competition. - Scalability & Business Models: Further research is needed on scalable and inclusive business models that ensure equitable benefit-sharing across the supply chain.	(González-Sánchez et al., 2025; Sánchez-Lozano et al., 2025)

The factors detailed in Table 6 contribute significantly to the broader research context by highlighting a critical misalignment between bottom-up technological advancement and top-down institutional support. The scientific interpretation of this finding is that the primary challenge is shifting from being merely a technical problem to a socio-institutional one. This aligns with the findings regarding the risk of policy frameworks creating unintended competition between complementary technologies (Csedő et al., 2025). Therefore, the identification of specific research gaps particularly the need for farmer-centric adoption models, integrated policy analysis, and scalable business models is the key contribution of this study. It provides a clear and actionable agenda for future research, aiming to bridge the gap between technological potential and its practical, widespread implementation.

4. CONSLUSION

This systematic review sought to elucidate how Information and Communication Technology (ICT) can transform the agricultural waste-to-bioenergy supply chain from a fragmented, economically challenging system into an efficient and sustainable industry. The findings confirm that a cohesive ecosystem of digital technologies primarily comprising the Internet of Things (IoT), Artificial Intelligence (AI), Geographic Information Systems (GIS), and Blockchain is pivotal for overcoming long-standing operational barriers. These technologies collectively enable a paradigm shift from reactive to proactive management by providing real-time data, optimizing logistics, and ensuring feedstock quality, which directly answers the fundamental need for greater efficiency and resilience in the supply chain. The significance of this research lies in its demonstration that ICT implementation fosters a powerful synergy where economic and environmental objectives are not mutually exclusive but are, in fact, mutually reinforcing; improved logistical efficiency simultaneously reduces operational costs and carbon emissions, while enhanced transparency through Blockchain strengthens both market trust and sustainability certification. Ultimately, this study's primary contribution to scientific knowledge is the identification that the most critical impediments to progress are not technological limitations but are socio-institutional in nature. It highlights a critical misalignment between rapid bottom-up technological innovation and the lack of consistent top-down policy support, revealing crucial research gaps in farmer adoption models, integrated policy design, and the development of scalable, inclusive business models. Therefore, strategically leveraging ICT is fundamental to realizing the full potential of the circular bioeconomy, contingent upon creating an enabling ecosystem that supports all stakeholders, from the individual farmer to the industrial investor.

Derived from the findings of this systematic review, a coordinated, multi-stakeholder approach is essential to accelerate the effective integration of Information and Communication Technology (ICT) into the agricultural waste-to-bioenergy supply chain. It is recommended that industry stakeholders, including agribusinesses and technology providers, pioneer the development of user-friendly digital platforms that integrate IoT for real-time monitoring and AI for logistical optimization, while also leading targeted digital literacy programs to bridge the farmer adoption gap. However, these industry-led initiatives must be complemented by a stable and technology-neutral policy framework from governments, which should provide consistent financial incentives and prioritize investment in robust rural digital infrastructure to prevent a digital divide. To inform these practical and policy actions, future academic research should urgently address critical knowledge gaps by developing robust farmer adoption models that consider socio-economic drivers and perceived risks, conducting integrated policy analysis to ensure coherent governance, and designing scalable and inclusive business models that guarantee equitable value distribution. Collectively, these actions will create a supportive ecosystem necessary to transform the circular bioeconomy from a nascent concept into a robust and sustainable industry.

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