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Smart Circular Agriculture: IoT and Zero-Waste for Digital Agriculture Implementation

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Abstract

Smart Circular Agriculture links Internet of Things monitoring with zero-waste practices to improve efficiency and resilience. This study examines how the approach works in Sleman Regency and what sustains adoption. Using a qualitative explanatory sequential design, a descriptive survey mapped adoption, input efficiency, and waste handling. Follow-up interviews and field observations were then explained in terms of mechanisms, constraints, and enablers through the Miles and Huberman cycle. Findings show that moisture-triggered irrigation, app-based scheduling, and microclimate management reduced over-irrigation, stabilized nutrient dosing, and improved product uniformity. Circular routines, including residue composting, liquid organic fertilizer preparation, and simple water harvesting, lowered unmanaged organics and reduced purchased inputs. Complementarities between sensing-driven control and circular resource cycling were strongest in greenhouses, where reliability and quality premiums justified investment. Adoption reflected demographic and institutional contours; millennial farmers and enterprise-oriented producers led uptake, while diffusion depended on demonstration, maintenance, and financing. Smart Circular Agriculture is a pathway for digital transformation in Sleman. The study shows how digital feedback and circular flows co-produce agronomic benefits. Practice and policy should prioritize seasonal financing, after-sales service, integrated training, and standards for compost and liquid biofertilizer, while leveraging greenhouse clusters for scalable, sustained production.

Keywords

Agriculture, Digital Agriculture, IoT Adoption, Smart Circular Agriculture, Sustainable Farming, Zero Waste.

1. Introduction

The agricultural sector is a primary, renewable and sustainable resource for national resilience in agrarian countries like Indonesia. Therefore, if managed properly and responsibly, it can become a leading commodity. As the human population grows, the demand for food increases. Robert Malthus's theory posits that population growth is geometric, while food production grows arithmetically. If food availability does not keep pace, this can lead to hunger and even death. However, in Indonesia, sources of food have been declining year by year. One of the problems is the shrinking availability of agricultural land due to low resource efficiency and the high volume of unmanaged waste. Agricultural waste in the form of crop residues and livestock manure is often discarded, polluting the environment. On the other hand, limited access to technology means that farming practices remain largely traditional, resulting in longer work hours and lower productivity and competitiveness. Most farmers in Sleman Regency who cultivate rice, secondary crops, and horticulture, and keep livestock, use traditional systems without optimal waste processing (Sudrajat et al., 2025).

One innovative approach is to adopt modern agricultural practices. However, this effort faces complex challenges in boosting productivity while minimizing negative environmental impacts. The number of educated farmers who understand technology is still limited. In addition, fewer farmers are focusing on agriculture as their primary occupation, as farming is often viewed as a side job to supplement income, a hobby, or simply a family legacy. Irrigation, fertilizing, spraying, and harvesting are sometimes delayed or hindered by other activities. As a result, agricultural productivity declines, and farmers become reluctant to cultivate their land. Consequently, smart or precision tools are needed to monitor farming anytime, anywhere, without the farmer being physically present in the field. One option is to use Internet of Things (IoT) applications.

IoT applications enhance agricultural efficiency by optimizing resources, minimizing waste, increasing productivity, and reducing costs, despite significant challenges to their adoption remaining (Maraveas et al., 2022; Ali et al., 2023; Cerrahoğlu & Cihan, 2023). IoT enables farmers to monitor critical parameters in real time using wireless equipment, eliminating the need for on-site presence. Examples include monitoring soil moisture, light intensity, air temperature, soil pH, and leaf color to determine nutrient needs, all of which can be accessed through smart devices (Li et al., 2018; Marcheriz & Fitriani, 2023). IoT can also be used to monitor the reduction of agricultural waste, thereby minimizing negative impacts by recycling and converting it into value-added products such as compost, liquid organic fertilizer, or bioenergy fuel (Sadiku et al., 2021; Mujiyanti et al., 2022).

Waste reduction in agriculture can also be pursued by applying zero-waste principles within circular agriculture. This system uses outputs or residues as inputs for other processes, either directly or after processing. The method reduces discarded waste and, if diligently applied, can approach zero waste. Besides cutting or eliminating waste, it can lower production costs for purchased inputs. Using the IoT as a pathway to agricultural sustainability should be integrated with zero-waste integrated farming within a circular agriculture framework. In practice, farmers still face barriers to adopting this technology, including limited digital literacy, inadequate access to technological infrastructure, and insufficient guidance on applying zero-waste principles optimally (Bhatt et al., 2023; Rastegari et al., 2023). The concept of Smart Circular Agriculture (SCA) emerges as a potential solution by integrating IoT and zero waste, thereby not only improving production efficiency but also minimizing agricultural waste by turning it into value-added products (Kottegoda et al., 2023; Abdulhussain & Alajali, 2024).

This research examines the extent to which integrating IoT technology and zero-waste practices in circular agricultural systems can enhance production efficiency and reduce waste, as well as the challenges and obstacles that farmers encounter when adopting these technologies. This study contributes to the development of sustainable agricultural practices by integrating the IoT with zero-waste principles under a SCA framework, providing a practical model to enhance productivity, resource efficiency, and environmental sustainability in Indonesia's farming sector.

2. Literature Review

2.1. Zero-Waste Agriculture and Internet of Things in Agriculture

Zero-waste agriculture is an innovative approach to enhancing the sustainability of farming systems by re-utilizing resources, managing waste, and optimizing the use of water and nutrients to minimize losses and reduce production costs. It offers a strategic solution to declining agricultural productivity amid pressures from urbanization and land-use change (Yudistira et al., 2020). A core element of zero-waste practice is sustainable land and water management that converts materials typically discarded as "waste" into productive farm inputs through on-farm or collective processing. Within this concept, agricultural residues are recycled into organic fertilizers, reducing dependence on costly chemical inputs that may pollute the environment.

Agriculture, as a vital sector, continues to innovate alongside advances in digital technology aimed at streamlining farm management and processing to boost yields and ensure sustainability. This imperative is sharpened by a shrinking pool of young people entering farming even as food demand rises, and by continued conversion of farmland to housing, industry, public facilities, and tourism. In Indonesia, the area of productive agricultural land declined by 167.25 thousand hectares, from 10.21 million hectares in 2023 to 10.05 million hectares in 2024 (BPS, 2024). Diversification supported by farm machinery and advanced technologies is one avenue to sustain agriculture. Tractors, rice transplanters, and combine harvesters help farmers work fields more efficiently. At the same time, smart devices, such as those utilizing the IoT and drones, can now be operated through smartphone applications.

The use of IoT in agriculture holds substantial potential to enhance production efficiency, optimize resource utilization, and support precision farming. Its deployment integrates sensors, monitoring devices, and real-time data communication to track critical variables, such as soil moisture, ambient temperature, and nutrient status, aligning with literature that highlights IoT's capacity to transform agricultural information systems via data collection and automated control for management decisions (Rouf & Agustiono, 2021; Junaidi & Ramadhani, 2024). IoT applications have been shown to enhance efficiency by optimizing inputs, minimizing waste, increasing productivity, and reducing costs, despite significant adoption challenges remaining (Ali et al., 2023; Cerrahoğlu & Cihan, 2023). In practice, farmers can monitor key parameters in real time through wireless equipment without being physically present in the field, for example, tracking soil moisture, light intensity, air temperature, soil pH, and leaf color to infer nutrient needs all accessible via smart devices (Li et al., 2018; Marcheriz & Fitriani, 2023). IoT can also support monitoring of waste-reduction efforts, so negative impacts are minimized by recycling and converting agricultural residues into value-added products such as compost, liquid organic fertilizers, or bioenergy feedstocks (Sadiku et al., 2021; Mujiyanti et al., 2022).

2.2. Smart Circular Agriculture

Most human activities generate waste; agriculture is no exception, with residues largely organic. Although organic waste decomposes, the process can be slow, depending on environmental conditions and decomposer activity. Unmanaged residues can cause odor, aesthetic, spatial, and public health problems. Farmers in Sleman Regency, therefore, seek to minimize or process agricultural residues to approach zero waste. One of the most effective ways to implement zero-waste farming for stronger food security is circular agriculture (Martiawan et al., 2023; Sudrajat et al., 2025). Circular agriculture is a closed-loop system that reuses all by-products to reduce or minimize waste, effectively increasing agricultural output while lowering production costs. Zero-Waste Smart Circular Agriculture integrates comprehensive and innovative waste management to create systems that are both sustainable and resource-efficient.

The approach emphasizes converting both organic and non-organic residues back into productive resources through the 3R principles: Reduce, Reuse, and Recycle (Sharma et al., 2019; Yunastiawan, 2022; Arinnis et al., 2022). Agricultural "waste" that is typically overlooked or discarded can thus become new inputs such as compost and animal feed, closing production loops, reducing environmental impacts, and decreasing dependence on external inputs. The implementation of Smart Circular Agriculture involves integrating waste processing with digital technologies, such as communal wastewater treatment installations (*Instalasi Pengolahan Air Limbah*/IPALs) that convert effluent into irrigation-quality water (Saputri et al., 2021). When combined with digital monitoring and the Internet of Things, these systems enable the real-time tracking of water quality and resource-use efficiency, supporting data-driven decisions to optimize zero-waste principles across the various stages of agricultural production.

3. Methods

This study used an explanatory sequential qualitative design to explore SCA, combining IoT with zero-waste practices in Sleman Regency's farming systems. A structured survey measured changes in water and fertilizer efficiency, waste reduction, and input costs, while in-depth interviews and non-participant observations examined mechanisms of change, maintenance capacity, and institutional support. A descriptive approach ensured flexibility and ecological validity, focusing on context-rich explanations rather than hypothesis testing, allowing systematic comparisons between IoT-enabled and conventional farms, and greenhouse versus open-field settings where applicable. Ethical measures included informed consent, anonymity, and privacy protection for digital device logs used in fieldwork.

Data collection utilized multiple sources and settings for triangulation. A survey captured adoption status (IoT/digital vs. conventional/manual), farm monitoring methods, changes in irrigation and fertilizer use, waste management practices (composting, liquid biofertilizer, biopores, infiltration wells, small reservoirs), and perceived impacts on input costs and product quality. Field observations examined the use of soil moisture sensors, automated valves/pumps, and, in greenhouses, microclimate regulation and fertigation. Interviews explored adoption rationales, learning pathways (peer-to-peer, extension), electricity/connectivity reliability, repair/maintenance access, financing, and expected market benefits for premium horticulture. Interviews were recorded with consent and transcribed verbatim, with observation notes systematically documented to support and enhance survey findings.

Participants were purposively chosen to reflect diverse production contexts in Sleman Regency, covering rice, secondary crops, and horticulture under conventional and IoT-enabled management, with a focus on greenhouse operations.

The farm operation was the unit of analysis. Key informants included leaders of producer groups such as farmers group, farmers group association, women farmers group, millennial farmer networks, and private sensor installation/maintenance providers, capturing variations in age, education, experience, and technology exposure reflective of the region's demographics and institutions. Respondents completed a structured questionnaire and, where relevant, shared on-site logs or dashboards for irrigation and compost temperature monitoring. All participants provided informed consent and were guaranteed confidentiality, with no personally identifiable information collected or shared.

The data analysis used an explanatory sequential qualitative design. Initially, survey responses were summarized to outline adoption levels, channel usage, input efficiency, waste management, and perceived cost changes, guiding subsequent qualitative inquiry. Next, thematic analysis (open coding and axial grouping) of interview transcripts and observation notes identified key mechanisms (sensor-based feedback, automation timing), circular-practice synergies (residue valorization, effluent reuse), and constraints (device costs, digital literacy, power/connectivity reliability), following Miles and Huberman's iterative cycle (data reduction, display, conclusion drawing/verification). Quantitative patterns were then integrated with qualitative findings through sequential triangulation to assess convergence and interpret divergences, enhancing credibility, dependability, and confirmability. Documentary evidence on communal wastewater treatment for irrigation was cross-verified with field observations and digital monitoring artifacts to ensure robust, context-specific conclusions.

4. Results

4.1. Adoption and Implementation of IoT in Farms

Field evidence from Sleman Regency indicates that integrating IoT applications with zero-waste practices yields concurrent improvements in production efficiency and waste minimization. Consistent with prior work emphasizing resource optimization via sensor-based control and data-driven decisions (Li et al., 2018; Ali et al., 2023; Cerrahoğlu & Cihan, 2023; Marcheriz & Fitriani, 2023). Farmers who monitored soil moisture, automated irrigation cycles, and tracked microclimate parameters reported more stable watering schedules, reduced over-fertilization, and fewer stress events during intra-seasonal dry spells. Parallel adoption of zero-waste routines, on-farm composting of crop residues, liquid biofertilizer preparation, and simple water-harvesting through biopores, infiltration wells, and small reservoirs reduced unmanaged organic waste streams and substituted purchased inputs, echoing documented benefits of circular agriculture (Sadiku et al., 2021; Mujiyanti et al., 2022; Zaman, 2022). Respondents repeatedly linked these shifts to tangible savings and smoother operations during peak labor bottlenecks.

Sleman's farming population is predominantly composed of older adults, with a smaller but active cohort of millennial farmers who engage more readily with digital tools and platformized markets. This demographic pattern, also noted in regional statistics and local reportage, shaped adoption trajectories (Antaranews, 2023; BPS, 2024). Many conventional farmers continue to rely on "*titen*" experience-based heuristics for scheduling and pest control, whereas tech-oriented producers leverage smartphone dashboards for irrigation timing and nutrient dosing. The survey, which covered 83 respondents, suggests early-stage digital diffusion, with roughly one in ten farms having used IoT at some point, often in greenhouse settings. At the same time, a substantial majority continued to use conventional methods.

As summarized in Table 1, the sample is predominantly composed of conventional/manual farms (n = 76; 91.57%), with a smaller subset utilizing IoT/digital management (n = 9; 10.84%). Interview narratives and observation notes converge on the view that initial trials are frequently catalyzed by outreach, research pilots, or CSR-style demonstrations. However, long-term continuation hinges on maintenance capacity, reliable connectivity, and visible quality premiums.

Table 1. Respondents by Farming System (Conventional vs IoT)

Farming System	n	Percentage%
Conventional / Manual	76	91.57
IoT / Digital	9	10.84

In open-field settings, moisture-triggered automation shortened reaction times to rainfall variability and reduced human dependency for routine irrigation checks. Farmers reported fewer instances of waterlogging and more uniform where valves and pumps were smartphone-controlled, aligning with the mechanism by which real-time sensing curbs input wastage (Li et al., 2018; Marcheriz & Fitriani, 2023). In greenhouses, producers emphasized microclimate stabilization, precision fertigation, and reduced pest ingress as the principal advantages. These conditions supported premium produce lettuce and melons targeting supermarkets and quality-sensitive local buyers. The qualitative material indicates that business owners and researcher-farmers are overrepresented among IoT adopters due to time constraints and the need for remote oversight; they also often operate ancillary services for sensor installation and upkeep, mirroring the ecosystem formation observed elsewhere (Wu et al., 2023; Yadav et al., 2024). Where electricity or internet were intermittent, systems defaulted to manual modes, attenuating efficiency gains and sometimes discouraging continued use.

4.2. Zero-Waste Practices and Smart Circular Agriculture (SCA)

Zero-waste practices were common across both conventional and digital farms, though their intensity varied. Farmers applied composting, liquid biofertilizer preparation, and simple rainwater harvesting, which reduced dependency on synthetic inputs and improved soil quality. Community initiatives, such as communal wastewater treatment reused for irrigation, further strengthened the circular benefits (Saputri et al., 2021).

Respondents highlighted several barriers typical of early digital transitions. High upfront and maintenance costs limited technical support, and uncertainties about interoperability and data security were noted (Ali et al., 2023; Yadav et al., 2024). Power outages and weak connectivity often disrupted automation, while some farmers considered waste processing more effortful than buying inputs (Ayçin & Kayapinar, 2021). Several pilots lapsed once facilitation ended, leaving devices unused, showing that adoption depends on institutional scaffolding, reliable after-sales service, and financing aligned with farm cash flows.

Institutional support emerged as a crucial enabler, particularly when local government programs, millennial farmer groups, and private providers collaborated on training, demonstrations, and service packages. Peer learning within farmer groups accelerated troubleshooting and diffused practical know-how about calibration, app interfaces, and maintenance routines (Saputra et al., 2024). From a market perspective, greenhouse enterprises that could guarantee consistent quality were better positioned to realize price premiums, which then justified further digital investment. At the community level, circular practices generated ancillary opportunities such as compost sales, biofertilizer production, and custom IoT installation services that anchored a modest rural innovation economy. Case narratives of initiatives like "Rejofarm" and "Joglo Tani" illustrate how residue valorization can absorb underemployed labor, create branded inputs, and reinforce social cohesion around shared environmental goals (Setiawan & Wijayanti, 2019; Yudistira et al., 2020; Abhipraya et al., 2020; Kotyal, 2023; Astuti et al., 2024).

Survey summaries showed that farms using automated irrigation and moisture sensors reported lower water use and more consistent fertilizer scheduling. Most respondents confirmed that circular practices cut input costs and reduced unmanaged waste. Although IoT adoption remained modest (about one in ten farms), interviewees noted that early adopters' success began shifting expectations about feasibility and returns, reflecting diffusion patterns where demonstration and social proof drive adoption (Boz & Martin-Ryals, 2023; Wu et al., 2023).

Greenhouses served as focal nodes for digital adoption due to the synergy between controlled environments and precision control. Producers cited reduced fruit cracking, more uniform size, and lower spoilage rates when microclimate and fertigation were stabilized through the use of sensors and app-based routines. Material choices mattered: some enterprises leveraged bamboo frames for cost efficiency and thermal stability, which farmers associated with slight heat gains relative to light steel. While idiosyncratic to local markets, these design decisions illustrate the embeddedness of SCA in broader value-chain logics where input suppliers, service providers, and buyers co-shape production standards and technology menus. The capacity of firms like PT MSMB and millennial farmer groups to install, maintain, and iterate on IoT systems anchored reliability that individual farmers alone struggled to achieve.

The strongest narratives of performance improvement came from farms implementing both sensorized control and residue valorization. Respondents described how improved irrigation timing reduced leaching and maintained microbial activity, which is beneficial for the efficacy of compost. At the same time, the availability of on-farm biofertilizers enabled finer adjustments to nutrient regimes without escalating costs. In turn, monitoring routines, whether manual logs or app dashboards, reinforced circular behaviors by making savings and performance more salient. These complementarities align with theoretical expectations that digital feedback loops and circular resource flows co-evolve to raise efficiency and resilience (Kottegoda et al., 2023; Abdulhussain & Alajali, 2024). Where only one element was present, IoT without circular practices, or circular practices without digital control gains were still observed but tended to be narrower or more volatile.

Beyond agronomic outcomes, SCA participation intersected with livelihoods in several ways. Households and groups producing compost or liquid fertilizers reported incremental income streams and reduced dependency on external suppliers; in some cases, these activities absorbed youth and workers displaced from other sectors, reinforcing local employment and skills formation (Setiawan & Wijayanti, 2019). At the same time, farmers emphasized non-monetary benefits: greater confidence in meeting quality standards, improved bargaining positions with buyers, and stronger intra-group ties fostered by collaborative maintenance and knowledge exchange. In areas affected by hazards and urbanization pressure, respondents interpreted circular routines as buffering mechanisms that preserved production capacity and stabilized costs, resonating with the literature on resilience in agriculture (Yudistira et al., 2020; Kotyal, 2023).

Interviews surfaced policy-relevant levers for addressing scale constraints. Respondents highlighted the need for affordable financing mechanisms that cater to seasonal cash flows, clearer standards for compost and biofertilizer quality to facilitate commercialization and streamlined access to technical services for installation and repair. Digital literacy training, especially when embedded in group activities and delivered in accessible language, was regarded as crucial for sustained use. From the supply side, participants highlighted the importance of after-sales support and modular, repairable hardware that can withstand field conditions. These perspectives map closely to challenges documented in the literature on smallholder digitalization and zero-waste mainstreaming in emerging-economy contexts (Xia & Ruan, 2020; Ayçin & Kayapinar, 2021; Haji-Rahimi et al., 2024).

Taken together, the results suggest that Smart Circular Agriculture constitutes a viable pathway for Sleman's digital transformation in farming, particularly where greenhouses, service ecosystems, and group-based learning can serve as anchors for early adoption. The descriptive survey results indicate reduced water and fertilizer use, as well as lower input costs, among adopters of automated irrigation and residue valorization. In contrast, the qualitative evidence provides insight into the mechanisms and contingencies that shape performance. Constraints such as costs, literacy, infrastructure, and maintenance remain significant, but enabling coalitions among farmer groups, local governments, and private providers have begun to lower entry barriers. Consistency with prior studies on IoT-enabled precision management and zero-waste circular strategies reinforces the external validity of these findings (Li et al., 2018; Sadiku et al., 2021; Mujiyanti et al., 2022; Ali et al., 2023; Cerrahoğlu & Cihan, 2023; Marcheriz & Fitriani, 2023). The interplay of digital feedback and circular resource flows appears especially potent in greenhouse contexts, where quality premiums translate operational efficiency into income gains. While the current adoption base is modest, the observed complementarities and community-level dynamics provide a credible foundation for scaling out, contingent upon sustained support, reliable infrastructure, and clear quality standards for circular inputs.

5. Discussion

The joint use of IoT monitoring and zero-waste routines reduced water and fertilizer use, minimized unmanaged waste, and stabilized plant responses, consistent with prior studies (Ali et al., 2023; Cerrahoğlu & Cihan, 2023; Abrar & Tukino, 2023; Marcheriz & Fitriani, 2023). Residue conversion into compost and liquid biofertilizers substituted external inputs and improved soil quality, echoing findings in circular agriculture literature (Sadiku et al., 2021; Mujiyanti et al., 2022; Zaman, 2022). Triangulation of survey, interview, and observation data suggests these reflect sustained practice changes rather than short-term novelty effects.

The complementarities identified between digital feedback loops and circular resource flows merit emphasis. IoT-enabled irrigation timing prevents waterlogging and drought stress, which can suppress microbial activity crucial for compost efficacy. Meanwhile, on-farm biofertilizers enable fine-grained adjustments of nutrient regimes without escalating costs. This co-evolution of sensing, actuation, and residue valorization aligns with systems views of SCA, wherein productivity and environmental performance improve jointly when information quality and resource cycling are enhanced in tandem (Kottegoda et al., 2023; Abdulhussain & Alajali, 2024). The results also suggest diminishing returns when either element is implemented in isolation, as farms relying solely on IoT or solely on circular practices reported narrower or more volatile gains.

Demographics and institutions shaped adoption patterns, older farmers relied on experiential heuristics, while millennial farmers used smartphone dashboards and platformized markets. Early IoT adopters clustered in research plots and greenhouse enterprises with stronger market links. Diffusion followed staged processes where demonstration and peer learning reduced risks (Boz & Martin-Ryals, 2023; Saputra et al., 2024). Sustained use, however, required reliable maintenance, connectivity, and seasonal financing, constraints widely noted in smallholder digitization literature (Xia & Ruan, 2020; Ali et al., 2023; Yadav et al., 2024).

Greenhouses became focal nodes for digitization, as controlled environments amplified the benefits of precise fertigation and microclimate regulation. Stabilized temperature–humidity produced more uniform crops, reduced spoilage, and enabled access to quality-sensitive buyers, consistent with mechanisms by which IoT improves reliability and market value (Wu et al., 2023; Yadav et al., 2024). This shows that SCA adoption is embedded in value-chain logics involving suppliers, service providers, and buyers rather than a purely on-farm technical change.

Several barriers persisted, including high costs, unstable power and internet, and weak local repair services. Some farmers also viewed waste processing as burdensome, echoing zero-waste adoption studies (Ayçin & Kayapinar, 2021). Extension programs often lapsed once facilitation ended, underscoring the need for lasting institutional support. Circular routines helped sustain motivation by providing visible savings even when digital systems reverted to manual operation.

This study applied a qualitative explanatory-sequential design combining survey, interviews, and observations, supported by document checks for credibility. Limitations include the small number of IoT adopters, unstable connectivity, seasonal variability, and the absence of standardized quality measures for compost and biofertilizers. Future research should adopt longitudinal designs with device-level telemetry and standardized assays to test durability and economic returns under varying conditions.

Several levers can accelerate SCA sustainably. Seasonal financing for small-scale hardware and embedded service contracts would lower adoption barriers. Training that integrates digital literacy with composting, biofertilizer production, and water harvesting can build complementary skills. Clear standards for compost and biofertilizer would support commercialization and protect buyers. Communal infrastructure, such as wastewater treatment reused for irrigation, can expand benefits when combined with transparent monitoring (Saputri et al., 2021). Finally, greenhouse clusters provide strategic footholds for premium-quality strategies and demonstration effects that strengthen market linkages.

This study contributes by clarifying how IoT and zero-waste practices interact at the farm and community levels. The evidence supports an integrated SCA perspective where information flows and resource cycles reinforce each other. Greenhouse cases show that when digital reliability and quality premiums align, adoption accelerates, while sustained diffusion requires maintenance ecosystems and institutional support. These findings converge with prior studies on IoT-enabled optimization and circular agriculture, while also highlighting contextual differences such as landholding fragmentation and labor availability that require adaptation (Sadiku et al., 2021; Mujiyanti et al., 2022; Ali et al., 2023; Cerrahoğlu & Cihan, 2023; Abrar & Tukino, 2023; Marcheriz & Fitriani, 2023).

The discussion interprets Sleman's emerging SCA landscape as a credible pathway toward digital transformation that couples' productivity gains with waste minimization. The joint influence of sensor-based control and residue valorization appears to underpin both agronomic improvements and livelihood effects, particularly in greenhouse contexts where quality premiums translate operational efficiency into income. Realizing this potential at scale depends on aligning finance, service ecosystems, standards for circular inputs, and group-based learning architectures. By foregrounding complementarities and institutional conditions, the study provides an integrative account that can inform program design and policy aimed at accelerating sustainable and inclusive digital agriculture in comparable agrarian regions.

6. Conclusion

Smart Circular Agriculture in Sleman Regency demonstrates that coupling Internet of Things (IoT) monitoring with zero-waste routines can deliver concurrent gains in input-use efficiency, waste minimization, and marketable quality. Across farms that implemented moisture-triggered irrigation, app-based scheduling, and residue valorization, respondents reported steadier watering, more disciplined nutrient dosing, reduced unmanaged organics, and lower input expenditures. Greenhouse enterprises emerged as focal nodes where microclimate control translated reliability into price premiums and diffusion effects to surrounding producers. At the same time, persistent frictions device and upkeep costs, uneven digital literacy, power and connectivity reliability, thin repair ecosystems, and unclear standards for circular inputs bound outcomes and threatened continuity once facilitation ended.

The study extends the literature by specifying complementarities between digital feedback loops and circular resource flows at farm and community scales, and by clarifying the institutional scaffolding that sustains adoption beyond pilot cycles. Practical implications include aligning finance with seasonal cash flows, embedding service contracts, peer-to-peer learning, and maintaining transparent quality standards for compost and liquid biofertilizers. Strategic emphasis on greenhouse clusters appears to be effective in anchoring early adoption and signaling quality to buyers. Future work should track longitudinal performance with device-level telemetry and standardized assays for circular inputs to test durability and returns across seasons and price–climate regimes, thereby informing scale-out strategies that protect both ecological integrity and farmer livelihoods.

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