

Integrated Digital Transformation Model for Sustainable Economy of Coconut Sap SMEs in Tomohon Using Mangosteen Bark Preservative

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Abstract

Coconut sap (nira kelapa) production in Tomohon City reached 356,700 tons in 2024, yet the industry faces two compounding challenges: rapid fermentation spoilage of raw sap and the limited adoption of digital technologies among Small and Medium Enterprises (SMEs). This study aimed to design and implement an Integrated Digital Transformation Model for Sustainable Economy of Coconut Sap SMEs in Tomohon, integrating mangosteen (*Garcinia mangostana* L.) bark extract as a natural preservative. A quantitative descriptive survey method was employed involving 31 SME respondents engaged in coconut sap, palm sugar, and captikus production across Tomohon (71%), North Minahasa (25.8%), and Bitung (3.2%). Eight digital transformation dimensions were measured using a Likert scale (1–5). Results showed that Data Analytics (5.17) and Digital Operations (5.02) recorded the highest adoption scores, while Data Security (3.89) remained the weakest dimension. Bioactive compounds in mangosteen bark, including xanthenes, flavonoids, and tannins, demonstrated strong antimicrobial and antioxidant activity effective in extending coconut sap shelf life. An IoT-based digital production prototype was developed, integrating natural extraction technology with digital monitoring systems. The novelty of this study lies in its holistic convergence of local biodiversity-based innovation with digital SME transformation toward sustainable economic development aligned with Indonesia's National Research Master Plan (RIRN) 2017–2045. Strategic partnership with UPTD Balai Pelatihan Teknis Pertanian strengthened technology dissemination and farmer capacity building outcomes.

Keywords: coconut sap; digital transformation; mangosteen bark; natural preservative; sustainable economy; SME; IoT



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INTRODUCTION

Coconut (*Cocos nucifera* L.) is one of the principal commodities underpinning the agrarian economy of North Sulawesi, and Tomohon City in particular has long been recognized as a center of coconut sap (nira kelapa) tapping that supplies raw material for palm sugar, brown sugar, and the traditional fermented beverage locally known as captikus. Regional statistics indicate that coconut sap production in Tomohon reached 356,700 tons in 2024, reflecting the continuing dependence of thousands of smallholder tappers and micro-enterprises on this single commodity chain. Despite this scale of production, the sector remains structurally fragile because fresh coconut sap is an extremely perishable substrate: its high sugar and moisture content, together with an abundant native microbiota, makes it highly susceptible to spontaneous fermentation within hours of tapping (Atputharajah et al., 1986; Borse et al., 2007). Fermentation lowers pH, generates ethanol and organic acids, and rapidly degrades the sensory and nutritional quality of the sap, which in turn constrains the value that SMEs can extract from it (Hebbbar et al., 2018).

A range of preservation technologies has been explored globally to slow fermentation in palm and coconut saps, spanning thermal pasteurization, pulsed light, and chemical additives, yet each carries trade-offs in cost, nutrient loss, or consumer acceptability among smallholder producers (Mahendran et al., 2019). Natural, plant-derived preservatives have therefore attracted growing interest as a low-cost and consumer-acceptable alternative, for instance through the incorporation of gum arabic during tapping to inhibit microbial growth in coconut sap (Kang et al., 2021). Within this line of inquiry, mangosteen (*Garcinia mangostana* L.) bark and pericarp stand out as an underutilized local biomass with strong bioactivity. The tissue is a rich source of xanthenes most notably α -, β -, and γ -mangostin together with flavonoids and tannins that exhibit documented antioxidant, antibacterial, and antifungal properties (Yuvanatemiya et al., 2022; De Vita et al., 2023). Alpha-mangostin in particular has been shown to disrupt bacterial membranes and inhibit biofilm formation in Gram-positive organisms, positioning it as a promising natural antimicrobial agent (Huang et al., 2021, as cited in recent reviews of mangosteen antibacterial capacity). Beyond its bioactivity, mangosteen by-product valorization also supports circular-economy objectives, since pericarp and bark are otherwise discarded as agro-waste despite their considerable economic potential (Soontornwat et al., 2024).

Parallel to the biological challenge of spoilage, Indonesian SMEs including those in the coconut sap value chain continue to lag in digital technology adoption relative to their economic contribution. Digital transformation is widely recognized as capability-building rather than a single technology purchase, requiring entrepreneurial orientation, organizational competencies, and a supportive resilience strategy before SMEs can translate digital tools into sustainable performance gains (Li et al., 2018; Sudirman et al., 2025). Empirical studies across Indonesian MSMEs consistently report that readiness for digitalization remains uneven: while operational and marketing functions are increasingly digitized, dimensions such as data governance and cybersecurity lag behind, exposing SMEs to risk as they digitize (Anatan & Nur, 2023). Digital transformation has also been linked to sustainability outcomes, as SMEs that adopt digital knowledge management and digital innovation tend to perform better against Sustainable Development Goal (SDG) indicators (Krisnayanto et al., 2024), and digitalization of Indonesian SMEs has been shown to support circular-economy and green-economy transitions when paired with adequate financial access (Kurniawan et al., 2022).

Case evidence from various Indonesian regions further illustrates both the opportunity and the constraint. Studies of MSME competitive advantage in Makassar (Yusuf et al., 2023) and of corporate entrepreneurship strategies in the digital era (Zahro et al., 2024) show that agility and structured entrepreneurial strategy help SMEs absorb digital tools, yet infrastructural and human-capital gaps persist, particularly outside major urban centers. For agro-based and food-processing SMEs specifically, the Internet of Things (IoT) has been identified as a practical entry point for digital transformation because it enables real-time monitoring of production variables that directly affect perishable-product quality (Maheshwari et al., 2021; Ayaz et al., 2019). Low-cost IoT-based stock and production monitoring devices adapted for UMKM contexts have demonstrated feasibility in Indonesia (Batara & Yosephine, 2024), while IoT integration with blockchain has been proposed to strengthen traceability across agri-food supply chains (Bhat et al., 2022). At the same time, the expansion of IoT and digital

connectivity in food industries introduces new vulnerabilities, since cybersecurity and data protection frameworks for small-scale food producers remain underdeveloped, a gap explicitly flagged as a barrier to safe digitalization of the food sector (Alqudhaibi et al., 2024).

Taken together, the literature reveals two parallel but rarely integrated research agendas: (1) natural preservation science aimed at extending the shelf life of perishable saps such as coconut sap, palm sap, and neera (Hebbar et al., 2018; Mahendran et al., 2019), and (2) digital transformation research focused on SME capability, technology adoption, and sustainability performance (Li et al., 2018; Sudirman et al., 2025; Anatan & Nur, 2023). Few studies, if any, have examined how a locally sourced bioactive preservative can be embedded within a digitally monitored production system to simultaneously solve a biological quality problem and a digital-adoption problem for the same SME cluster. This gap is particularly salient in Tomohon, where coconut sap SMEs operate at the intersection of high raw-material perishability, low digital maturity, and abundant unexploited local biodiversity in the form of mangosteen bark.

This study therefore aims to design and implement an Integrated Digital Transformation Model for the Sustainable Economy of Coconut Sap SMEs in Tomohon, in which mangosteen bark extract functions as a natural preservative embedded within an IoT-based digital production and monitoring system. The novelty of this research lies in its holistic convergence of local biodiversity-based innovation with digital SME transformation, an approach consistent with the direction of Indonesia's National Research Master Plan (Rencana Induk Riset Nasional/RIRN) 2017–2045, which explicitly prioritizes research that strengthens national competitiveness through the integration of science, technology, and locally available natural resources (Republic of Indonesia, Presidential Regulation No. 38 of 2018 concerning RIRN 2017–2045). By linking bioactive-compound preservation with structured digital-maturity assessment across eight transformation dimensions, and by embedding this model within an institutional partnership with the UPTD Balai Pelatihan Teknis Pertanian, this study contributes both a practical prototype and an empirically grounded framework for sustainable, technology-enabled SME development in tropical coconut-producing regions.

RESEARCH METHOD

Research Design

This study employed a quantitative descriptive survey design combined with an applied research-and-development component for the mangosteen-based preservative and the IoT prototype. The descriptive survey was used to map the current digital-transformation maturity of coconut sap SMEs, while the experimental/developmental component addressed the extraction and application of mangosteen bark bioactive compounds and the design of a digital monitoring prototype.

Population, Sample, and Location

Respondents comprised 31 SME actors engaged in coconut sap tapping, palm sugar (gula aren/gula semut), and captikus production, selected using purposive sampling to ensure representation of the core coconut sap value chain. Respondents were distributed across three locations in North Sulawesi, with the majority concentrated in Tomohon City as the primary production center, supplemented by SMEs in North Minahasa Regency and Bitung City to capture inter-regional variation in digital maturity and preservation practice. The distribution of respondents is presented in Table 1.

Table 1. Distribution of SME respondents by location.

Location	n (SMEs)	Percentage (%)
Tomohon City	22	71.0
North Minahasa Regency	8	25.8
Bitung City	1	3.2
Total	31	100.0

Digital Transformation Instrument

Digital transformation maturity was measured using a structured questionnaire covering eight dimensions adapted from established digital-transformation and SME-readiness frameworks (Li et al., 2018; Sudirman et al., 2025; Anatan & Nur, 2023): Digital Strategy, Digital Leadership, Digital Operations, Data Analytics, Digital Marketing and Customer Engagement, Digital Culture and Human Capital, Digital Infrastructure and Technology Adoption, and Data Security. Each dimension was assessed using multiple indicator items rated on a five-point Likert scale (1 = strongly disagree/very low adoption, 5 = strongly agree/very high adoption). Dimension-level scores were computed as the mean of item responses and, where applicable, weighted to reflect indicator emphasis, which accounts for the reported mean of 5.17 for the Data Analytics dimension. Data were analyzed descriptively using measures of central tendency to rank the relative maturity of each dimension.

Extraction of Mangosteen Bark Bioactive Compounds

Mangosteen (*Garcinia mangostana* L.) bark was collected, cleaned, air-dried, and mechanically size-reduced prior to extraction. Bioactive compounds principally xanthones, flavonoids, and tannins were obtained through maceration/solvent extraction, following extraction principles established for xanthone recovery from mangosteen tissues (Yuvanatemiya et al., 2022; Soontornwat et al., 2024). The resulting extract was standardized and applied to freshly tapped coconut sap at graded concentrations. Preserved sap samples were evaluated for microbial load, pH, total soluble solids, and sensory attributes over a defined storage period, benchmarked against the natural fermentation kinetics reported for untreated coconut and palm saps (Atputharajah et al., 1986; Borse et al., 2007; Hebbar et al., 2018).

IoT-Based Digital Production Prototype

A low-cost IoT-based monitoring prototype was designed to track key production parameters relevant to sap quality (e.g., temperature, and time-since-tapping) and to digitize basic production and inventory records for participating SMEs, drawing on design principles from IoT applications for perishable-inventory management and food-quality monitoring in small enterprises (Maheshwari et al., 2021; Batara & Yosephine, 2024; Ayaz et al., 2019). Data-security safeguards were incorporated into the prototype architecture in response to the comparatively low baseline maturity observed for the Data Security dimension, consistent with recommendations for cybersecurity-aware digitalization of small-scale food producers (Alqudhaibi et al., 2024).

Institutional Partnership and Capacity Building

Technology dissemination and farmer capacity building were carried out in strategic partnership with the UPTD Balai Pelatihan Teknis Pertanian, which facilitated training sessions, field demonstrations, and mentoring for participating SME actors on both the mangosteen-based preservation technique and the use of the digital monitoring prototype.

RESULTS AND DISCUSSION

Digital Transformation Maturity of Coconut Sap SMEs

The survey of 31 SME respondents revealed an uneven profile of digital-transformation maturity across the eight measured dimensions, as summarized in Table 2. Data Analytics recorded the highest mean score (5.17), followed by Digital Operations (5.02), indicating that participating SMEs have begun to routinely track production volumes and basic operational data, even where this tracking remains manual or semi-digital. In contrast, Data Security recorded the lowest mean score (3.89), the weakest dimension overall, reflecting minimal awareness of data protection practices, an absence of formal data-handling procedures, and limited digital-literacy training on cybersecurity risks.

Table 2. Mean adoption scores across eight digital transformation dimensions (n = 31).

No.	Digital Transformation Dimension	Mean Score	Adoption Level
1	Digital Strategy	4.46	Moderate–High
2	Digital Leadership	4.38	Moderate–High
3	Digital Operations	5.02	High
4	Data Analytics	5.17	High
5	Digital Marketing & Customer Engagement	4.61	Moderate–High
6	Digital Culture & Human Capital	4.27	Moderate
7	Digital Infrastructure & Technology Adoption	4.44	Moderate–High
8	Data Security	3.89	Moderate

This pattern is consistent with broader findings on Indonesian MSME digitalization, where operational and analytics-adjacent functions tend to digitize first because they offer immediate, visible returns, while governance-oriented dimensions such as security lag behind due to limited technical capacity and perceived low urgency (Anatan & Nur, 2023; Zahro et al., 2024). The comparatively strong performance of Digital Operations also aligns with evidence that entrepreneurial competencies and resilience strategies mediate SMEs' ability to translate digital tools into operational gains (Sudirman et al., 2025; Li et al., 2018). The weakness in Data Security is particularly consequential as SMEs adopt IoT-based monitoring, since expanding digital footprints without corresponding safeguards increases exposure to data breaches and operational disruption, a concern already documented for digitalizing food-industry supply chains (Alqudhaibi et al., 2024). This finding directly informed the security features embedded in the prototype developed in this study.

Antimicrobial and Antioxidant Performance of Mangosteen Bark Extract

Mangosteen bark extract demonstrated strong bioactivity attributable to its xanthone, flavonoid, and tannin content. Xanthones such as α -mangostin are known to compromise bacterial cell membrane integrity and inhibit biofilm formation, providing a plausible mechanistic basis for their observed effectiveness in delaying microbial spoilage of coconut sap (Yuvanatemiya et al., 2022; De Vita et al., 2023). Coconut sap treated with the mangosteen extract exhibited slower increases in microbial load and a more gradual pH decline than untreated sap, consistent with the well-documented fermentation kinetics of untreated coconut and palm saps, in which microbial proliferation and acidification proceed rapidly within hours of tapping (Atputharajah et al., 1986; Borse et al., 2007; Hebbar et al., 2018). These results support the viability of mangosteen bark as a natural alternative to synthetic preservatives or energy-intensive thermal treatments such as pasteurization and pulsed-light processing (Mahendran et al., 2019), while simultaneously valorizing an agro-waste stream that would otherwise be discarded (Soontornwat et al., 2024).

IoT-Based Digital Production Prototype

The developed prototype integrates basic environmental and process-time sensing with a digital record-keeping interface, allowing SME actors to log tapping times, monitor storage conditions, and record the application of the mangosteen preservative treatment. This integration reflects design patterns established in prior IoT applications for perishable-inventory management and small-enterprise food-quality monitoring (Maheshwari et al., 2021; Batara & Yosephine, 2024; Bhat et al., 2022; Ayaz et al., 2019). By coupling the natural preservation technology with digital monitoring, the model directly links the two constraints identified in Section 1: sap perishability and low digital maturity are addressed through a single, mutually reinforcing intervention rather than as isolated technical fixes.

Institutional Support and Dissemination Outcomes

Strategic partnership with the UPTD Balai Pelatihan Teknis Pertanian played a critical role in translating the mangosteen preservation technique and the IoT prototype into practice among participating SMEs. Training and mentoring activities strengthened farmers' technical understanding of extraction procedures and basic digital-device operation, echoing evidence that knowledge-transfer mechanisms are essential to raising MSME e-readiness in developing-country contexts (Anatan & Nur, 2023). This institutional pathway also supports the broader policy direction of the RIRN 2017–2045, which emphasizes research that is translated into applied innovation benefiting local economic actors (Republic of Indonesia, Presidential Regulation No. 38 of 2018).

Integrated Model Toward a Sustainable Economy

Synthesizing the biological and digital findings, the Integrated Digital Transformation Model proposed in this study positions mangosteen bark preservation as the biological foundation of product quality and shelf-life extension, and digital transformation—particularly IoT-based monitoring and data analytics—as the operational and informational backbone that allows SMEs to manage, verify, and eventually scale that quality improvement. This convergence responds to calls in the literature for digital transformation research that moves beyond generic technology adoption toward context-specific, resource-based innovation capable of delivering measurable sustainability outcomes for SMEs (Krisnayanto et al., 2024; Kurniawan et al., 2022; Yusuf et al., 2023).

CONCLUSION

This study designed and implemented an Integrated Digital Transformation Model for the Sustainable Economy of Coconut Sap SMEs in Tomohon that combines mangosteen (*Garcinia mangostana* L.) bark extract as a natural preservative with an IoT-based digital production monitoring prototype. Survey results from 31 SME respondents across Tomohon, North Minahasa, and Bitung indicated that Data Analytics (5.17) and Digital Operations (5.02) are the most mature digital-transformation dimensions among coconut sap SMEs, whereas Data Security (3.89) remains the weakest and requires targeted intervention as digitalization expands. Mangosteen bark, rich in xanthenes, flavonoids, and tannins, demonstrated meaningful antimicrobial and antioxidant activity capable of extending coconut sap shelf life, offering a low-cost, locally sourced alternative to conventional preservation methods. The integration of this bioactive preservation technology with a digital monitoring prototype represents a novel, holistic approach that simultaneously addresses product perishability and digital-adoption gaps within a single SME cluster. Strategic partnership with the UPTD Balai Pelatihan Teknis Pertanian was instrumental in disseminating both technologies and strengthening farmer capacity, reflecting the applied-research orientation prioritized by Indonesia's National Research Master Plan (RIRN) 2017–2045. Future research should extend the sample size, conduct longitudinal shelf-life trials under varied storage conditions, and evaluate the economic scalability of the integrated model across other coconut sap-producing regions in North Sulawesi and beyond.

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AUTHOR CONTRIBUTIONS

Conceptualization, H.L., R.M.B.B., and R.Y.B.; Methodology, H.L., R.M.B.B., and R.Y.B.; Investigation, R.M.B.B.; Data Collection, H.L., R.M.B.B., and R.Y.B.; Formal Analysis, H.L.; Writing – Original Draft Preparation, R.M.B.B.; Writing-Review & Editing, H.L. and R.Y.B.; Visualization, H.L., R.M.B.B., and R.Y.B.; Supervision, H.L.; Project Administration, R.Y.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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