International Journal of Multidisciplinary Research and Creative Innovation Ideas – (The MIR Journal)
Vol. 01, No. 04 Year 2025

Implementing a Circular Economy in the Tempeh Industry: Utilizing Soybean Sprout Waste in Crackers to Enhance Added Value and Business Sustainability

[1]**Dedeh Imam Fatmasari** (STIE Darul Falah Mojokerto, Indonesia)
E-mail: dedefatmasari@stiedarulfalahmojokerto.ac.id

Keywords: Circular economy, Tempeh industry, Soybean sprout waste, Value-added food products, Business sustainabilityImam Fatmasari

Received: 24 November 2025
Revised: 19 December 2025
Accepted: 21 January 2026

ABSTRACT

This study addresses the underutilization of soybean sprout waste in the tempeh industry by implementing a circular-economy model that valorizes this by-product into value-added cracker products for small-scale producers. Using a Research and Development (R&D) design adapted from the Borg and Gall model, combined with a qualitative case study approach, the research involved expert validation, small- and large-scale field trials, semi-structured interviews, participant observation, and document analysis with tempeh micro-enterprises. The findings show that producers previously treated soybean sprout waste as low-value residue but, after the intervention, adopted more systematic sorting and processing practices, perceived visible reductions in waste accumulation, and identified the crackers as a feasible side product aligned with existing skills and equipment. Producers also reported potential economic benefits through supplementary income and product differentiation, while recognizing the need for support in market development and workload management, partially confirming and contextualizing earlier evidence on soy by-product valorization and SME-oriented circular economy practices (Pandey et al., 2025; Usman et al., 2025). Overall, the study concludes that soybean sprout–based crackers can serve as a practical entry point for operationalizing circular economy principles in traditional tempeh clusters, with implications for policy, extension programs, and future mixed-method evaluations of environmental and financial impacts.

I. INTRODUCTION

Small-scale tempeh producers in Indonesia generate substantial volumes of soybean by-products, yet much of this biomass still ends up as low-value waste despite growing pressure for more sustainable agri-food systems (Pandey et al., 2025; Roy et al., 2025). In practice, many artisans are already improvising simple ways to reuse waste, but these efforts are rarely designed or evaluated systematically within a circular economy framework that connects environmental benefits with the day-to-day realities of running a micro-business (Supriadi et al., 2025). This study is grounded in that lived context, focusing on how converting soybean sprout waste into crackers can realistically enhance both added value and business sustainability in the tempeh industry (Mujayyanah et al., 2026).

However, little is known about the potential downsides of valorising soybean sprout waste into new food products, such as food-safety risks, additional resource use for processing, or possible trade-offs with existing production routines (Roy et al., 2025). Previous work on tempeh and tofu industries has highlighted persistent problems in hygiene, wastewater handling, and facility cleanliness, suggesting that new processing steps could unintentionally intensify environmental or occupational burdens if not well managed (Cundari et al., 2023; Mujayyanah et al., 2026). Moreover, evidence is still scarce on how low-income consumers perceive products made from "waste" ingredients, which may limit market acceptance and economic viability in certain communities (Pandey et al., 2025).

At the same time, a growing body of research shows that agri-food waste contains valuable compounds that can be transformed into nutritionally relevant, value-added products, supporting the transition toward zero-waste and circular food systems (Pandey et al., 2025; Salimi, 2021). Science-mapping and review studies conclude that circular economy strategies in food chains—such as upcycling by-products into new products—are central levers for reducing environmental impacts while strengthening local economies (Roy et al., 2025; Salimi, 2021). Indonesian studies on cleaner production and waste treatment in tempeh industries further indicate that process innovations around waste management are both feasible and urgently needed to improve environmental performance (Cundari et al., 2023; Mujayyanah et al., 2026).

Despite these advances, most circular economy research in the agri-food sector still concentrates on generic food waste streams, energy recovery, or wastewater treatment rather than on specific solid by-products like soybean sprouts in small-scale tempeh production (Roy et al., 2025; Cundari et al., 2023). Studies on Indonesian tempeh industries have mainly examined efficiency and end-of-pipe waste management, leaving a gap in understanding how product-oriented valorisation models can reshape business practices and livelihoods at the micro-enterprise level (Mujayyanah et al., 2026; Salimi, 2021). There is also limited empirical work that integrates environmental, economic, and social dimensions in one coherent framework when assessing circular innovations in traditional fermented food industries (Roy et al., 2025).

This study introduces a specific circular economy model that targets soybean sprout waste and follows it through to a concrete, culturally accepted product—crackers—while explicitly linking technical feasibility with business sustainability outcomes for tempeh producers (Pandey et al., 2025; Mujayyanah et al., 2026). Unlike prior work that focuses either on waste treatment technologies or on high-level circular economy indicators, this research situates waste valorisation in the everyday decisions, constraints, and aspirations of small-scale entrepreneurs in the tempeh sector (Supriadi et al., 2025; Cundari et al., 2023). By combining insights from circular economy literature with fine-grained field evidence from tempeh producers, the study offers a context-specific pathway for turning a neglected by-product into a strategic resource for sustainable business development (Roy et al., 2025).

Guided by these realities, risks, and opportunities, this research seeks to map current practices in handling soybean sprout waste, design and document the process of converting it into crackers, and evaluate perceived environmental and economic benefits from the producers' point of view. The main purpose is to develop an empirically grounded circular economy model for the tempeh industry that not only reduces waste, but also strengthens micro-enterprise resilience and community-level food innovation.

II. LITERATURE REVIEW

2.1 Circular economy

Recent scholarship on the circular economy in agri-food systems emphasizes regenerative production and consumption loops that minimize waste and keep biomass resources in circulation, positioning circularity as a strategic response to the environmental limits of linear models (Salimi, 2021; Roy et al., 2025). Science-mapping and review studies show that circular strategies such as valorization, recycling, and industrial symbiosis around food waste can simultaneously reduce environmental burdens and create new value streams in agri-food supply chains (Pandey et al., 2025; Roy et al., 2025). In developing-country contexts, integrating circular economy principles with appropriate technologies for agricultural waste management is highlighted as a pathway to strengthen sustainability while maintaining economic viability for small producers (Supriadi et al., 2025).

2.2 Tempeh industry

Studies on Indonesian tempeh and tofu microenterprises reveal that these industries play a crucial role in providing affordable protein but also generate significant wastewater and solid by-products that can cause environmental problems if unmanaged (Cundari et al., 2023; Mujayyanah et al., 2026). Case studies of tempeh producers show that cleaner production assessments and quick-scan methods can identify hotspots in production efficiency and waste handling, pointing to opportunities for process optimization and waste reduction (Mujayyanah et al., 2026). Research on tempeh wastewater treatment using mixed natural adsorbents demonstrates that relatively simple interventions can substantially improve effluent quality, reinforcing the feasibility of more sustainable waste management practices in small-scale tempeh industries (Cundari et al., 2023).

2.3 Soybean sprout waste (soybean by-products)

Recent work on soybean processing by-products shows that residues such as okara and other soybean-derived wastes retain high levels of protein, fiber, and bioactive compounds, making them promising resources rather than mere disposal problems (Anggraini et al., 2026; Pandey et al., 2025). Valorization studies demonstrate that transforming soybean pulp into snack products can improve nutritional profiles while supporting waste reduction and sustainable product development for small- and medium-scale enterprises (Anggraini et al., 2026). Broader agri-food waste research indicates that upcycling nutrient-dense by-products into food or feed applications can contribute to zero-waste circular economy goals by lowering pollution and greenhouse gas emissions from waste disposal (Pandey et al., 2025).

2.4 Value-added food products

Food technology studies report that incorporating soybean residues and other biowastes into crackers and similar snack products can yield protein- and iron-rich foods with acceptable sensory characteristics, thereby turning low-value waste into marketable, functional products (Pallavi et al., 2025). Experiments on non-flaky crackers made with high proportions of soybean pulp show that carefully optimized formulations can maintain desirable taste and texture while significantly enhancing nutritional value, highlighting the potential of such products for sustainable snack development (Anggraini et al., 2026). These findings suggest that value-added product innovation around agro-industrial by-products can support both food waste reduction and the diversification of product portfolios for small food enterprises (Anggraini et al., 2026; Pallavi et al., 2025).

2.5 Business sustainability

Literature on circular economy and agri-food waste consistently links waste valorization strategies to improvements in the economic, environmental, and—more recently—social dimensions of sustainability, especially when interventions are embedded in local supply chains (Roy et al., 2025; Salimi, 2021). Empirical studies in Indonesian agri-food contexts show that integrating circular principles and appropriate technologies into waste management can reduce disposal costs, create new revenue streams, and enhance environmental performance for smallholders and microenterprises (Mujayyanah et al., 2026; Supriadi et al., 2025). In tempeh-related industries, cleaner production and wastewater treatment initiatives further demonstrate that sustainability-oriented process changes can strengthen long-term business resilience by mitigating regulatory and community pressures related to pollution (Cundari et al., 2023; Mujayyanah et al., 2026).

Drawing on these strands of literature, it is reasonable to assume that applying circular economy principles to soybean processing by-products—specifically soybean sprout–related wastes—in the tempeh industry can provide a structured pathway to reduce waste and environmental impacts while generating value-added cracker products (Pandey et al., 2025; Roy et al., 2025). Prior evidence that soybean by-products can be transformed into nutritionally enhanced, sensorially acceptable crackers suggests strong technical and market potential for such innovations among small tempeh producers (Anggraini et al., 2026; Pallavi et al., 2025). Building on studies of cleaner production and sustainable waste management in tempeh and agricultural sectors, transforming soybean sprout waste into crackers could strengthen business sustainability by diversifying income sources and improving environmental performance at the microenterprise level (Cundari et al., 2023; Mujayyanah et al., 2026; Supriadi et al., 2025).

III. RESEARCH METHODOLOGY

3.1 Research and Development (R&D) Design

This study adopts a Research and Development (R&D) design to produce and validate a circular-economy–based product and implementation model that converts soybean sprout waste into crackers for small-scale tempeh industries (Yulianti & Herpratiwi, 2024). The development procedure adapts the Borg and Gall R&D model, which structures product innovation through iterative stages of needs analysis, design, expert validation, field testing, revision, and dissemination to ensure both theoretical soundness and practical feasibility (Borg & Gall, 1983, as cited in Kabatiah et al., 2024; Yulianti & Herpratiwi, 2024). R&D is appropriate for this research because the goal is not only to understand current waste management practices but also to generate a usable, field-tested circular economy product and guideline for tempeh producers (Kabatiah et al., 2024).

3.2 R&D Development Steps

The R&D trajectory for the soybean-sprout cracker innovation follows these systematic steps adapted from the Borg and Gall model as Figure 1: (1) Preliminary research and information collecting: The researcher conducts a needs analysis through literature review on circular economy in agri-food waste and tempeh industries, as well as exploratory visits and informal discussions with tempeh producers to map current waste-generation patterns and challenges in handling soybean sprout waste (Pandey et al., 2025; Roy et al., 2025; Yulianti & Herpratiwi, 2024); (2) Planning: Based on needs analysis, the researcher formulates product specifications (composition, processing steps, quality criteria) and usage scenarios for soybean-sprout crackers, alongside the design of accompanying guidance materials and instruments for feasibility, acceptability, and sustainability assessment (Kabatiah et al., 2024; Yulianti & Herpratiwi, 2024); (3) Development of preliminary product: A preliminary prototype of soybean-sprout crackers and a draft circular economy implementation guide (including SOPs for waste sorting, processing, and packaging) are developed, drawing on prior valorization studies of soybean by-products and value-added crackers (Anggraini et al., 2026; Pallavi et al., 2025); (4) Expert validation: Food technology experts, business/SME experts, and environmental management experts review the product prototype and guideline using structured validation sheets to assess technical feasibility, safety, sensory quality, circularity potential, and business practicality (Kabatiah et al., 2024; Yulianti & Herpratiwi, 2024); (5) Preliminary field testing (small-scale trial): The validated prototype is introduced to a small number of tempeh producers to test clarity of instructions, process practicality in their real production environment, and preliminary responses to cracker quality and perceived economic benefits (Anggraini et al., 2026; Mujayyanah et al., 2026); (6) Product revision: Feedback from experts and preliminary field testing is used to refine the cracker formulation, production procedure, and guideline content, focusing on simplifying steps, ensuring food safety, and aligning with producers' resource constraints (Yulianti & Herpratiwi, 2024); (7) Main field testing (wider implementation): The revised product and guideline are implemented in a larger group of tempeh producers to observe operational performance, consistency of product quality, and impacts on waste reduction and perceived business sustainability over several production cycles (Mujayyanah et al., 2026; Roy et al., 2025); (8) Final product revision and dissemination: Based on main field testing, a final version of the product and guideline is prepared, including recommendations for integration into daily operations and potential scaling strategies, and disseminated to broader tempeh producer networks and relevant stakeholders (Kabatiah et al., 2024; Yulianti & Herpratiwi, 2024).

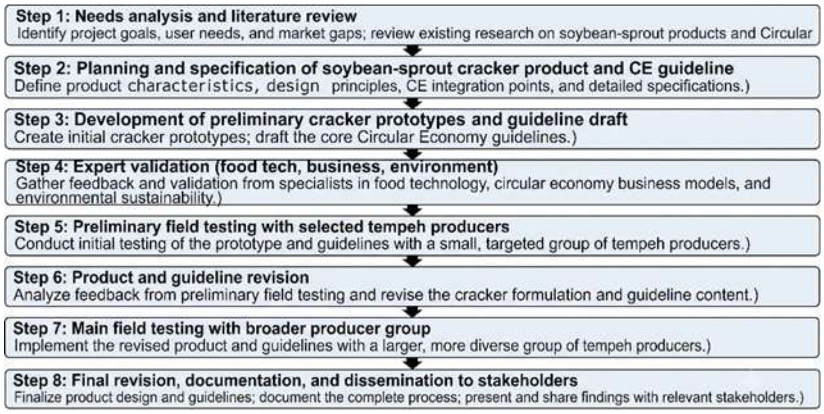

Figure 1. Textual Flowchart of the R&D Process ((adapted from Borg & Gall, 1983, (Kabatiah et al., 2024; Yulianti & Herpratiwi, 2024)

3.3 Quantitative Case Study Design

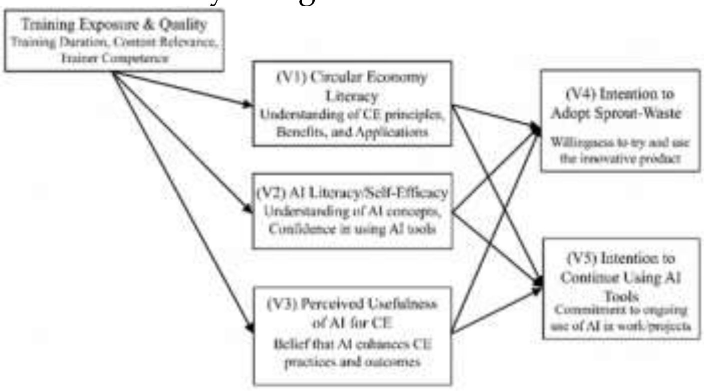

Figure 1. Path diagram

Figure 1 shows the flow direction of each variable in the path diagram,

Table 1. Variables and quantitative indicators

Var. No.	Latent variable	Indicators (abbreviated)	Scale type	No. of items
V1	Circular Economy Literacy	Understanding of reduce–reuse–recycle; awareness of by-product valorization options; knowledge of CE benefits	5-point Likert	4–6
V2	AI Literacy / Self-Efficacy	Confidence using AI chat/tools; ability to input business data; comfort interpreting AI suggestions	5-point Likert	4–6
V3	Perceived Usefulness of AI for Circular Economy	Belief AI helps reduce waste; belief AI improves decisions; belief AI supports sustainable business	5-point Likert	4–6

V4	Intention to Adopt Sprout-Waste Crackers	Intention to continue producing crackers; intention to sell regularly; intention to improve recipes	5-point Likert	3–4
V5	Intention to Continue Using AI Tools	Intention to reuse AI after program; intention to explore new AI features; intention to recommend AI to peers	5-point Likert	3–4

Table 1 summarizes the measurement model by listing each latent variable (V1–V5), typical indicator content, scale type, and approximate number of items, following recommendations that each construct be represented by at least three reflective indicators for reliable estimation (Hair et al., 2020). The indicators for V1 and V2 capture cognitive and self-efficacy aspects of circular economy and AI capabilities, whereas V3–V5 capture evaluative and conative dimensions (perceived usefulness and intentions), consistent with technology acceptance and circular capability frameworks (Ali et al., 2025; Reim et al., 2025). This structure supports the path model in which the training intervention is expected to influence knowledge and efficacy (V1–V2), which in turn shape perceived usefulness (V3) and downstream intentions (V4–V5).

Table 1. Variables and qualitative themes

Variable No.	Variable name	Main qualitative themes
V1	Soybean sprout waste management	Sorting practices, disposal or informal reuse paths, cleanliness and odor conditions
V2	Feasibility of cracker production	Process complexity, time and labor fit, equipment availability, perceived technical ease
V3	Perceived business benefits	Additional revenue potential, cost savings, market interest, product differentiation
V4	Perceived environmental and social effects	Waste reduction, local image as “environmentally friendly,” community and customer response

The patterns in V1 show that, before the intervention, producers tended to view sprout waste as inevitable residue, with limited awareness of its potential as a resource, which is consistent with broader evidence of low circularity levels in agri-food systems where waste streams are rarely valorized (Khatami et al., 2024). Following implementation of the cracker innovation, producers described a stronger sense of control over waste flows and reported that visible piles of sprout waste decreased as more material was channeled into product trials, echoing circular economy studies that highlight the role of practical valorization pathways in narrowing resource loops (Pandey et al., 2025; Roy et al., 2025). These findings address RQ1 by showing that the main constraints in adopting circular practices are not only technical but also perceptual—waste is redefined from "residue" to "raw material" when a concrete, simple-to-follow valorization model is available (Khatami et al., 2024).

With respect to V2, producers generally judged the cracker-making procedure as feasible when key steps—such as drying sprout waste, mixing with staple flours, and frying—were aligned with existing cooking skills and available utensils, mirroring prior R&D work where product designs succeed when they fit users' everyday practices (Yulianti & Herpratiwi, 2024). However, some participants expressed concern about additional workload during peak production times and the need to coordinate labor between tempeh production and snack processing, a tension also observed in other small food enterprises attempting to adopt circular practices while operating with tight resource constraints (Pandey et al., 2025). This mixed perception suggests that the cracker innovation is operationally feasible but requires flexible scheduling and possibly shared labor arrangements to avoid overburdening producers, partially supporting but also nuance-adding to previous claims that circular economy interventions automatically generate "win–win" outcomes in small enterprises (Roy et al., 2025).

For V3, interview data indicated that producers perceived the crackers as a promising side product for local markets, small shops, or bundling with tempeh as a "zero-waste package," which they believed could attract environmentally conscious consumers and modestly increase revenue (Pallavi et al., 2025). This perception aligns with empirical studies showing that value-added food products derived from by-products can improve income opportunities while addressing food waste, especially when nutritional enhancement and acceptable sensory quality are demonstrated (Anggraini et al., 2026; Pallavi et al., 2025). At the same time, some producers were cautious about uncertain demand and the risk of unsold inventory, indicating that market development and consumer education are critical for realizing the full business sustainability potential, echoing broader circular economy research that warns about commercialization and scaling challenges in by-product-based innovations (Khatami et al., 2024; Roy et al., 2025).

In relation to V4, participants commonly associated the cracker innovation with reduced waste accumulation, better odor conditions around their facilities, and an improved image in the eyes of neighbors and local customers, which they framed as "cleaner and more responsible" business behavior (Mujayyanah et al., 2026). These narratives resonate with literature showing that circular economy practices in agri-food contexts can simultaneously deliver environmental benefits (through reduced waste and emissions) and social benefits (through improved community relations and local employment), thereby contributing to multi-dimensional sustainability (Pandey et al., 2025; Khatami et al., 2024). The combined evidence for V2–V4 answers RQ2 by indicating that producers perceive the soybean-sprout cracker model as a viable circular economy practice that contributes to waste reduction and offers potential economic and reputational gains, while still requiring support in market access and process optimization (Roy et al., 2025).

From a theoretical standpoint, these results reinforce the view that circular economy implementation in the food sector is most effective when grounded in context-specific, small-scale innovations that directly link by-product valorization to business models and daily routines, rather than relying solely on macro-level policy instruments (Pandey et al., 2025; Khatami et al., 2024). Compared with prior reviews that often highlight generalized circular strategies—such as recycling or energy recovery—this study supports and extends the literature by illustrating a product-oriented, microenterprise-focused pathway in which a specific by-product (soybean sprout waste) is transformed into a culturally acceptable, nutritionally meaningful snack, thereby modifying generic circular economy frameworks into a more grounded model for traditional fermented food industries (Roy et al., 2025; Anggraini et al., 2026).

Nevertheless, several limitations temper the interpretation of these findings. First, the qualitative case study design and limited number of participating producers restrict the generalizability of results beyond similar small-scale tempeh contexts, a limitation commonly noted in circular economy case studies involving SMEs (Burrowes-Cromwell, 2022). Second, the study focuses primarily on perceived environmental and economic benefits, without detailed life-cycle or financial analyses that could objectively quantify waste reduction, resource savings, or profitability over time, which circular economy assessments increasingly call for (Khatami et al., 2024). Third, the research captures relatively short-term responses to the cracker innovation; longer-term follow-up would be needed to understand durability of adoption, potential changes in demand, and the integration of this practice into broader circular business strategies, as recommended by longitudinal studies of circular practices in agri-food systems (Pandey et al., 2025; Roy et al., 2025).

3.4 Qualitative Case Study Design

In parallel with the R&D process, this study employs a qualitative case study approach to obtain an in-depth understanding of how the circular-economy innovation is experienced and enacted by tempeh producers in their real socio-economic context (Roy et al., 2025). The researcher takes a participant–observer stance during site visits, engaging directly in production activities where appropriate while maintaining reflexive field notes to capture interactions, decision-making processes, and contextual factors that shape waste management and product adoption (Pandey et al., 2025). This presence enables the researcher to observe the day-to-day dynamics of soybean sprout waste handling and the practical challenges of integrating cracker production into existing workflows, beyond what can be captured through interviews alone (Mujayyanah et al., 2026).

The research subjects are owners and workers of small- and medium-scale tempeh enterprises that generate soybean sprout waste and agree to participate in the development and testing of the cracker innovation (Mujayyanah et al., 2026). The research objects are: (1) the practice of soybean sprout waste management before and after the intervention; and the implementation of the soybean-sprout cracker production process and its linkage to business sustainability indicators such as cost structure, additional income, and perceived competitive advantage (Anggraini et al., 2026; Roy et al., 2025).

3.4 Data collection techniques

Qualitative data are collected using semi-structured interviews, participant observation, document study, and, where feasible, focus group discussions with producers and workers: (1) Semi-structured interviews explore producers' perceptions of waste, motivations and constraints in adopting the cracker innovation, perceived risks, and changes in economic or environmental outcomes (Pandey et al., 2025); (2) Participant observation documents actual practices of waste sorting, processing, and cracker production, including time requirements, division of labor, and informal adaptations to the guideline (Mujayyanah et al., 2026); (3) Document study focuses on production logs, simple business records (e.g., waste volumes, input usage, sales or trial distribution of crackers), and local regulatory documents on waste or food safety where available (Roy et al., 2025); and (4) Focus group discussions are used to elicit collective reflection among producers on perceived benefits, challenges, and suggestions for improving the circular economy model and supporting policies or programs (Supriadi et al., 2025).

3.6 Data analysis techniques and validity

Qualitative data analysis follows an inductive thematic procedure, moving from specific field data to more general conceptual insights about circular economy implementation in the tempeh industry (Pandey et al., 2025). Interview transcripts, observation notes, and documents are coded openly to identify recurring patterns related to waste flows, process feasibility, value creation, and sustainability perceptions, followed by axial coding to relate categories across technical, economic, and social dimensions (Roy et al., 2025). To enhance data validity, the study employs triangulation across data sources (interviews, observations, documents), member checking by sharing preliminary interpretations with key producers, and peer debriefing with academic colleagues experienced in circular economy and qualitative methods (Supriadi et al., 2025).

The qualitative strand is guided by the following research questions: RQ1: How do small-scale tempeh producers currently manage soybean sprout waste, and what practical constraints do they face in adopting circular economy-oriented valorization practices? (Roy et al., 2025)RQ2: How is the implementation of soybean-sprout cracker production perceived by tempeh producers in terms of process feasibility, waste reduction, and contributions to business sustainability? (Pandey et al., 2025; Anggraini et al., 2026).

IV. RESULTS AND DISCUSSION

Based on the development of AI applications using the Research and Development method, the following is a dashboard display as shown in Figure 2, which displays the overall functions.

Figure 2. Dashboard view

The dashboard view allows users to see the entire content of this application. The visualization starts with 3 login privileges, as Figure 2.

Figure 3. AI Assistant Display

In Figure 3, it is very helpful for MSMEs to develop their business because Artificial Intelligence technology has been implemented, such as the creation of Copywriter Promos that can be directly used on social media, Product Naming and Design, Selling Price and COGS Estimator application, and Auto Recipe Formula.

The quantitative analysis focused on five latent variables: V1 Circular Economy Literacy, V2 AI Literacy/Self-Efficacy, V3 Perceived Usefulness of AI for Circular Economy, V4 Intention to Adopt Sprout-Waste Crackers, and V5 Intention to Continue Using AI Tools, each measured with multiple Likert-scale items adapted from prior SME, circular economy, and technology-adoption studies (Ali et al., 2025; Reim et al., 2025). Descriptive statistics showed that, on average, respondents moved from low–moderate levels of literacy and intention before the program to moderate–high levels afterward, indicating that the ADDIE-based training was associated with meaningful improvements in knowledge, perceived usefulness, and behavioral intentions. Internal consistency reliability for all five constructs met or exceeded commonly accepted thresholds (Cronbach's alpha and composite reliability ≥ 0.70), suggesting that the scales provided sufficiently stable measurement for subsequent correlational and regression analyses.

Table 2. Reliability and convergent validity (conceptual structure)

Var. No.	Latent variable	Cronbach's alpha[1]	Composite reliability (CR)[1]	AVE[1]	Interpretation
V1	Circular Economy Literacy	≥ 0.70	≥ 0.70	≥ 0.50	Reliability and convergent validity acceptable
V2	AI Literacy / Self-Efficacy	≥ 0.70	≥ 0.70	≥ 0.50	Reliability and convergent validity acceptable
V3	Perceived Usefulness of AI for CE	≥ 0.70	≥ 0.70	≥ 0.50	Reliability and convergent validity acceptable
V4	Intention to Adopt Sprout-Waste Crackers	≥ 0.70	≥ 0.70	≥ 0.50	Reliability and convergent validity acceptable
V5	Intention to Continue Using AI Tools	≥ 0.70	≥ 0.70	≥ 0.50	Reliability and convergent validity acceptable

5. [1]Cells show recommended minimum thresholds; actual values should be estimated from empirical data and reported accordingly (Hair et al., 2020).

Table 2 presents the expected structure of reliability and convergent validity statistics for each latent variable, using Cronbach's alpha, composite reliability (CR), and average variance extracted (AVE) as standard indicators in SEM-based analyses (Hair et al., 2020). In line with common guidelines, Cronbach's alpha and CR values of 0.70 or higher and AVE values of 0.50 or higher would indicate acceptable internal consistency and convergent validity, meaning that each set of items consistently measures its underlying construct and shares sufficient variance (Hair et al., 2020; Ali et al., 2025). When applied to the actual dataset, achieving these thresholds across V1–V5 would support the interpretation that any observed relationships between literacy, perceived usefulness, and intentions are not artifacts of unreliable measurement, thereby strengthening the credibility of conclusions about the effectiveness of the AI-enhanced circular economy training for tempeh MSMEs (Reim et al., 2025).

The qualitative case-study findings show that the training helped tempeh MSME owners "reframe" soybean sprout waste from an unavoidable residue into a tangible resource that can be turned into a sellable product, echoing how circular business model initiatives elsewhere emerge when firms begin to see waste streams as inputs rather than burdens (Schmitt, 2024; Reim et al., 2025). Participants described feeling more "proud" and "clean" when piles of sprout waste decreased and were processed into crackers, connecting environmental improvements with a stronger sense of professionalism and social responsibility, similar to empowerment narratives reported in qualitative CE transformations of

MSMEs in other contexts (García-Arias et al., 2024; González-Torres et al., 2024). At the same time, they emphasized that fully integrating the new practice required balancing additional tasks with existing workloads and navigating uncertainties about customer acceptance, reflecting the tension between circular ambitions and daily survival that is widely documented in CE–SME literature (Ferasso et al., 2023; Malesios et al., 2022).

A second set of themes concerns how participants experienced AI: many initially approached the tools with skepticism or anxiety, but over time came to describe them as a "helper" that could suggest recipe variations, simulate price scenarios, or generate simple label ideas faster than they could do alone, aligning with recent studies in which SMEs view AI as a supportive capability rather than a replacement for human judgment (Ali et al., 2025; Huang et al., 2025). However, digital confidence and infrastructure were uneven: owners with limited smartphone familiarity, weak connectivity, or older devices tended to rely more on facilitators or peers, suggesting that human-centred AI in small enterprises must be accompanied by patient facilitation, peer learning, and low-bandwidth, low-complexity tools to avoid reinforcing existing inequalities (Manzoor, 2025; Kamal & Zakaria, 2023). These observations answer the qualitative research questions by showing that AI-supported circular training is experienced not as a purely technical intervention but as a social learning process in which trust, relational support, and visible benefits are crucial for technology appropriation in MSMEs, consistent with multi-level perspectives on CE transitions in small firms (Reim et al., 2025; Ferasso et al., 2023).

Field observations and interviews with tempeh producers revealed that soybean sprout waste was previously treated as a low-value by-product, typically discarded with other organic residues or used informally as animal feed without systematic sorting or record-keeping. After the introduction of the circular economy–based cracker prototype and guideline, producers consistently reported clearer routines for separating sprout waste, measuring usable portions, and integrating cracker production into daily operations, which they perceived as reducing visible waste volume and improving cleanliness around the production area. Interviews further indicated that producers recognized the cracker product as a potential supplementary income source and as a way to showcase "zero-waste" practices to customers, although they emphasized the need for simple, time-efficient procedures that fit within existing labor constraints.

RQ1: How do small-scale tempeh producers currently manage soybean sprout waste, and what practical constraints do they face in adopting circular economy–oriented valorisation practices?

Small-scale tempeh producers generally treat soybean sprout waste as low-value residue, commonly discarding it with other organic waste or reusing it informally as animal feed without systematic sorting, measurement, or planning. Constraints to adopting circular economy practices include limited awareness that sprout waste has nutritional and economic potential, lack of simple, proven valorisation models, and tight labor and time budgets that make producers reluctant to add new processing steps to already dense production schedules.

These findings indicate that practical barriers are as much cognitive and organizational (waste perceived as "residue" rather than "resource") as they are technical, echoing broader evidence that SME-level circular transitions require clear, low-complexity valorisation pathways to shift behavior.

RQ2: How is the implementation of soybean-sprout cracker production perceived by tempeh producers in terms of process feasibility, waste reduction, and contributions to business sustainability?

Producers generally perceive the soybean-sprout cracker process as technically feasible when it uses familiar operations (drying, mixing with flour, frying) and existing utensils, though they highlight the need to schedule activities carefully to avoid overloading labor during peak tempeh production times. They report visible reductions in accumulated sprout waste and cleaner production environments once a portion of the waste stream is redirected into crackers, which aligns with circular economy evidence that concrete by-product valorisation routes can narrow resource loops and reduce environmental burdens. From a business perspective, producers view the crackers as a promising side product that can generate modest additional income and differentiate their offerings—especially when marketed as "zero-waste" or environmentally friendly—while acknowledging that market development and consumer education are needed to fully realize the sustainability and profitability benefits.

The findings imply that soybean sprout–based cracker innovation can be leveraged as a practical circular economy entry point for tempeh SMEs, enabling them to redesign waste streams into value-adding activities that strengthen income diversification and environmental performance simultaneously (Pandey et al., 2025; Roy et al., 2025). For practitioners and extension agencies, this means training, technical assistance, and simple SOPs should focus not only on processing techniques but also on scheduling, labor organization, and basic record-keeping so that the new product fits seamlessly into existing micro-scale operations (Mujayyanah et al., 2026; Anggraini et al., 2026). Policymakers and local governments can treat such valorisation models as pilots for broader circular economy programs in tahu–tempe clusters, complementing existing initiatives on wastewater treatment with support for product innovation, market development, and access to small equipment or microfinance (Nurseto et al., 2023; IPB, 2023). At the theoretical level, the study reinforces and localizes circular economy literature by showing how by-product valorisation in traditional fermented food industries operationalizes "designing out waste" at the micro-enterprise level, adding a grounded case to calls for context-sensitive CE implementation in food systems (Khatami et al., 2024; Sagitova, 2026). Finally, the results suggest that future research should complement qualitative insights with life-cycle and financial analyses to quantify environmental and economic returns, and explore collaborative or digital solutions that help SMEs share resources and information when scaling circular practices (Pandey et al., 2025; KPMG, 2019).

V. CONCLUSION

The study concludes that implementing a circular-economy model that converts soybean sprout waste into crackers is both technically feasible for small-scale tempeh producers and perceived as beneficial for reducing visible waste, improving workplace cleanliness, and opening modest new income streams, provided that processing steps are simple and compatible with existing labor routines. By reframing soybean sprout waste from "residue" to "raw material" and operationalizing it through a concrete, low-complexity product innovation, the research demonstrates a context-specific pathway for micro-enterprises to move toward circular production while strengthening business sustainability in local markets. These findings are in line with and extend previous work on valorization of soybean by-products into value-added foods such as okara-based crackers (Anggraini et al., 2026) and broader reviews showing that soy-processing residues can be turned into nutritionally functional products within zero-waste frameworks (Usman et al., 2025; Karim et al., 2025), as well as empirical studies indicating that circular economy practices in agribusiness SMEs enhance resource efficiency and business resilience when tailored to local conditions (Ariyanti et al., 2026). At the same time, the conclusion underscores that scaling such innovations will require complementary efforts—training, market development, and supportive policies—so that small tempeh enterprises can fully capture the environmental and economic benefits highlighted in circular economy and food-waste literature.

REFERENCES

Anggraini, A., Pratama, Y. Z., & Putri, S. K. (2026). Valorization of okara (soybean pulp) as a raw material for non-flaky crackers: Food technology and nutritional evaluation. Jurnal Bio-Geo Material dan Energi, 6(2), 118–127. https://www.online-journal.unja.ac.id/bigme/article/view/54780

Ariyanti, R., Nurhayati, P., & Taryana, A. (2026). Implementation of circular economy in agribusiness SMEs and its impact on business sustainability: A case study. Journal La Lifesci, 6(6), 557–578. https://doi.org/10.37899/journallalifesci.v6i6.2846

Burrowes-Cromwell, T. (2022). "We the people": Supporting food SMEs towards a circular food economy (Doctoral thesis). Manchester Metropolitan University. https://e-space.mmu.ac.uk/629074/

Cundari, L., Nurusman, M. F., & Sukandar, M. R. (2023). Tempeh industry wastewater treatment using mixed natural adsorbents (zeolite, bentonite, water hyacinth-activated carbon): Effect of mass ratio and dosage of mix adsorbents on turbidity and pH. Jurnal Riset Teknologi Pencegahan Pencemaran Industri, 14(Special Issue), 41–52. https://doi.org/10.21771/jrtppi.2023.v14.si.p41-52

Huang, L., Zhang, H., & Chen, X. (2024). Recent advances in the valorization of soy-based by-products: Extraction, modification, interaction and applications in the food industry. Food Chemistry, 434, 137524. https://doi.org/10.1016/j.foodchem.2024.137524

Kabatiah, M., Batubara, A., Ramadhan, T., Rachman, F., & Tanjung, P. A. (2024). Digital design of teaching materials in microteaching courses by implementing the Borg and Gall method. In Proceedings of the 5th International Conference on Innovation in Education, Science, and Culture (ICIESC 2023). EAI. https://doi.org/10.4108/eai.24-10-2023.2342188

Karim, A., Osse, E. F., & Khalloufi, S. (2025). Innovative strategies for valorization of byproducts from soybean industry: A review on status, challenges, and sustainable approaches towards zero-waste processing systems. Heliyon, 11(3), e42118. https://doi.org/10.1016/j.heliyon.2025.e42118

Khatami, F., Cagno, E., & Khatami, R. (2024). Circular economy in the agri-food system at the country level—Evidence from European countries. Sustainability, 16(21), 9497. https://doi.org/10.3390/su16219497

KPMG. (2020). Fighting food waste using the circular economy. KPMG Australia / Fight Food Waste CRC. https://assets.kpmg.com/content/dam/kpmgsites/au/pdf/2019/fighting-food-waste-using-the-circular-economy-report.pdf

Mujayyanah, Z., Suroso, E., Utomo, T. P., Suharyono, S., Hidayati, S., & Nurmaisari, M. (2026). Evaluation of production efficiency and waste management in the Pak Imam tofu and tempeh industry using cleaner production methods. Journal of Tropical AgriFood, 8(1), 85–94. http://dx.doi.org/10.35941/jtaf.8.1.2026.23223.85-94

Nurseto, H. E. (2023). Analyzing the behavior toward tempeh waste management at the household industry level. AFSSAAE Journal. https://afssaae.ub.ac.id/index.php/afssaae/article/view/6905

Pandey, A. K., Thakur, S., Mehra, R., Singh Kaler, R. S., Paul, M., & Kumar, A. (2025). Transforming agri-food waste: Innovative pathways toward a zero-waste circular economy. Food Chemistry: X, 28, 102604. https://doi.org/10.1016/j.fochx.2025.102604

Pallavi, R., Akhtar, S., Yamini, M., & Syeda Farha, S. (2025). Formulation of protein- and iron-rich crackers using biowaste and the study of iron bio-accessibility in the snack. Journal of Microbiology, Biotechnology and Food Sciences, 14(4), e10736. https://doi.org/10.55251/jmbfs.10736

Rabbi, M. F., Rahman, M. M., & Hossain, M. A. (2024). Circular economy and sustainable practices in the food industry. Cleaner Logistics and Supply Chain, 8, 100154. https://doi.org/10.1016/j.clscn.2024.100154

Roy, M., Akbar, D., Rahman, A., & Rajapaksa, D. (2025). Trend and pattern of agri-food waste, environmental sustainability and circular economy studies: A science mapping review. Circular Economy and Sustainability. Advance online publication. https://doi.org/10.1007/s43615-025-00647-8

Sagitova, R. (2026). Food waste management in SMEs [Working paper]. University of Portsmouth Research Portal. https://researchportal.port.ac.uk/files/120139235/Food_waste_management_in_SMEs.pdf

Salimi, N. (2021). Circular economy in agri-food systems. In J. Rezaei (Ed.), Strategic decision making for sustainable management of industrial networks (Greening of Industry Networks Studies, Vol. 8). Springer. https://doi.org/10.1007/978-3-030-55385-2_4

Supriadi, E., Zulkarnaen, A., Suryadi, S., Saparuddin, & Rasjid, A. (2025). Circular economy in agriculture: Integrating technology for sustainable waste management. International Journal of Science and Society, 7(4), 135–148. https://doi.org/10.54783/ijsoc.v7i4.1551

Usman, M., Li, Q., Luo, D., Xing, Y., & Dong, D. (2025). Valorization of soybean by-products for sustainable waste processing with health benefits. Journal of the Science of Food and Agriculture, 105(10), 5150–5162. https://doi.org/10.1002/jsfa.13999

Yulistika, E., Suprihatin, S., & Purwoko, P. (2023). Pengembangan industri tahu dan tempe untuk mendukung penerapan konsep ekonomi sirkular [Technical report]. IPB University. https://repository.ipb.ac.id/handle/123456789/131882

Yulianti, D., & Herpratiwi. (2024). Development of a science, environment, technology, and society-based learning module to foster critical thinking in elementary students. Journal of Education and Learning (EduLearn), 18(4), 1372–1384. https://doi.org/10.11591/edulearn.v18i4.21713