AI-Enhanced Capacity Building for Tempeh MSMEs: Training on Processing Soybean Sprout Waste into Crackers as a Circular Economy Implementation

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ABSTRACT

Tempeh micro, small, and medium enterprises (MSMEs) generate substantial soybean sprout waste that is typically discarded or used informally as low-value feed, contributing to environmental burdens and lost economic potential (Mujayyanah et al., 2026). This community service program aimed to empower tempeh MSMEs through AI-enhanced training on processing soybean sprout waste into crackers as a practical application of circular economy principles. The service design combined on-site workshops with the use of artificial intelligence tools for recipe refinement, costing simulations, packaging and branding design, and simple demand-forecast scenarios tailored to local markets. Evaluation using pre–post questionnaires, observation, and product trials showed increased knowledge of circular economy and AI applications, improved skills in waste-based cracker production, and the emergence of new product prototypes ready for local commercialization. This program demonstrates that integrating AI into capacity building for traditional food MSMEs can accelerate the adoption of circular practices and support more sustainable, resilient micro-enterprises in the tempeh sector.

I. INTRODUCTION

Tempeh MSMEs in Indonesia play a vital role in providing affordable protein, yet their production processes generate liquid and solid wastes, including soybean sprouts, that are often unmanaged or underutilized (Mujayyanah et al., 2026). Circular economy concepts offer a way to transform such by-products into value-added products, reducing environmental impact while generating new income streams for small producers (Roy et al., 2025). Previous studies have shown that soybean processing residues such as okara can be successfully valorized into crackers and other snack products, supporting both waste reduction and sustainable product development for small enterprises (Anggraini et al., 2026; Pallavi et al., 2025). At the same time, emerging literature highlights the potential of artificial intelligence to support circular food economies by optimizing resource use, improving process design, and enabling data-driven decision-making in food systems (Batra, 2026; Ellen MacArthur Foundation & McKinsey, 2019).

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).

However, AI applications are often perceived as complex and distant from the realities of micro-scale food enterprises, even though recent work indicates that AI-driven tools can be downscaled to support SMEs in areas such as basic demand forecasting, inventory planning, and simple product design (de Lucas López, 2026; Chen, 2026). In the tempeh context, there is still a gap in community service initiatives that simultaneously introduce circular economy practices and demonstrate accessible, low-cost uses of AI to enhance product development and business planning for MSMEs. This community service program responds to that gap by designing and implementing AI-enhanced training for tempeh MSMEs on processing soybean sprout waste into crackers, with a focus on practical skills, simple digital tools, and context-appropriate circular economy implementation.

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).

The research community service program was designed with the following objectives: to increase tempeh MSMEs' understanding of circular economy principles and the potential of soybean sprout waste as a raw material for value-added products, to build practical skills for processing soybean sprout waste into crackers that meet basic quality and safety criteria, to introduce MSMEs to simple, accessible AI tools that support recipe development, cost simulation, packaging/branding design, and basic demand estimation, and to strengthen business sustainability by helping MSMEs integrate waste-based cracker production into their existing operations in a realistic and data-informed way.

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

The program was implemented in a tempeh MSME cluster in Pacet district small city in Mojokerto, Indonesia, involving 5–10 MSME owners and key workers who routinely handle soybean processing and manage day-to-day business operations (Mujayyanah et al., 2026). Participants were selected purposively based on their willingness to innovate with by-product utilization and their access to basic digital devices (smartphones or laptops) that could support the use of AI-based tools during and after training (Batra, 2026).

Service Design and Stages

The community service followed four main stages:

1. Preparation and needs assessment The team conducted brief interviews and observations to map existing waste management practices, levels of digital literacy, and MSME expectations regarding new products and technology use (Nurseto, 2023). Simple baseline questionnaires captured knowledge of circular economy, current uses of sprout waste, and prior experience with digital or AI-based applications.

2. Development of AI-enhanced training modules Based on the assessment, the team developed training materials covering: Circular economy basics for tempeh MSMEs (waste hierarchy, repurposing strategies, economic and environmental benefits); Standard operating procedures (SOPs) for processing soybean sprout waste into crackers, adapted from existing research on soy by-product crackers and local culinary preferences (Anggraini et al., 2026; Pallavi et al., 2025); Guided use of AI tools for: (a) Generating and refining recipe variations (e.g., flavoring, texture, portion sizes), (b) Simulating cost structures and simple pricing scenarios, (c) Producing draft labels, brand names, and simple promotional content. (d) Exploring basic what-if scenarios for demand and production planning (Chen, 2026; Batra, 2026).

3. Implementation: Workshops and practice sessions The implementation consisted of two integrated components: Hands-on production workshop: participants practiced sorting and preparing soybean sprout waste, mixing ingredients, shaping, frying/baking crackers, and evaluating basic sensory quality; AI mini-lab sessions: participants worked in small groups with

facilitators to input their own cost data, local ingredient prices, and desired selling prices into simple AI-supported spreadsheets or web tools; they also generated draft packaging designs and short marketing texts tailored to their local markets (de Lucas López, 2026).

4. Monitoring, evaluation, and follow-up mentoring, Pre–post questionnaires and checklists were used to assess changes in knowledge, attitudes, and confidence related to circular economy, waste-based production, and AI usage. Facilitators observed production sessions and AI mini-labs to document skill acquisition, difficulties, and adaptations. Follow-up mentoring (online or on-site) focused on troubleshooting production issues, refining recipes based on customer feedback, and supporting repeated use of AI tools for ongoing decision-making (Batra, 2026; Rabbi et al., 2024).

IV. RESULTS AND DISCUSSION

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 (Mujayyanah et al., 2026). 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 (Pandey et al., 2025; Roy et al., 2025). 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 (Pallavi et al., 2025).

The main qualitative variables identified in the analysis and the key themes attached to each variable. 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).

The program results indicated a marked increase in participants' understanding of circular economy concepts, particularly the idea of repurposing and valorizing soybean sprout waste within the tempeh value chain (Roy et al., 2025; Yulistika et al., 2023). Many MSME owners reported that prior to the training they had never considered sprout waste as a potential input for human food products, and they expressed surprise at the positive sensory evaluation of the resulting crackers during the workshop. This finding aligns with earlier evidence that awareness and concrete examples are pivotal in shifting SME behavior from linear "dispose" practices toward circular reuse and repurposing (Pandey et al., 2025; Khatami et al., 2024).

Practically, all participating MSMEs were able to produce at least one acceptable batch of soybean-sprout crackers following the provided SOPs, with several groups experimenting with local flavors (e.g., spicy, herb-based) during the session. This confirms that waste-based cracker production can be technically feasible at micro-enterprise scale when the process is simplified and aligned with existing kitchen equipment and skills, echoing earlier valorization work on soy by-products (Anggraini et al., 2026; Pallavi et al., 2025). In addition, AI-assisted recipe refinement helped participants quickly explore variations in ingredient proportions and seasonings, making the experimentation process less intimidating and more structured for those with limited formal culinary training (Batra, 2026).

On the business side, MSMEs reported that AI-driven cost and pricing simulations were particularly helpful for visualizing how ingredient choices, batch sizes, and selling prices affect their margins, even if their digital skills were initially modest (Chen, 2026; Rabbi et al., 2024). Some participants used AI-generated label text and simple logo concepts as starting points for discussions with local designers or printing shops, indicating that AI can lower the entry

barrier to basic branding and marketing tasks for small producers (de Lucas López, 2026; Ellen MacArthur Foundation & McKinsey, 2019). These outcomes resonate with broader findings that AI can support circular business models by improving design, operational planning, and information flows, even when used in light-touch, non-technical ways in SMEs (de Lucas López, 2026; Batra, 2026).

Nevertheless, the program also revealed limitations and challenges. Some MSME owners expressed concern about the time needed to consistently produce crackers alongside their core tempeh operations, highlighting the need for careful scheduling and possibly shared or rotational production among cluster members. Others were enthusiastic about AI tools during the workshops but unsure how frequently they would use them without ongoing mentoring or improved internet connectivity, echoing documented barriers such as digital skills gaps and infrastructure constraints in SME-level digital transitions (Chen, 2026; Manzoor, 2025). These findings suggest that AI-enhanced community service must be accompanied by realistic follow-up support and consideration of structural constraints if circular innovations are to be sustained and scaled (Sagitova, 2026; Rabbi et al., 2024).

V. CONCLUSION

This community service program demonstrates that integrating artificial intelligence into capacity-building for tempeh MSMEs can strengthen circular economy implementation by making waste-based product innovation more accessible, data-informed, and attractive for small producers. Training on processing soybean sprout waste into crackers, combined with AI-based support for recipe development, costing, and basic marketing design, enabled MSMEs to reframe waste as a resource and to prototype new products with realistic business considerations. For practitioners and local governments, the experience suggests that community service initiatives in food-producing clusters can be enriched by including simple, guided AI components alongside technical skills, provided that materials are tailored to local digital literacy levels and infrastructural realities (Batra, 2026; de Lucas López, 2026). Future programs should explore cooperative models for shared production and AI access within MSME clusters, as well as mixed-method evaluations that quantify environmental and economic impacts of AI-supported circular innovations in traditional food sectors.

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