TEKNOBUGA Vol. 14 No.1 (2026)

p-ISSN 2085 4056
e-ISSN 2528 7087

JURNAL TEKNOLOGI BUSANA DAN BOGA

https://journal.unnes.ac.id/journals/teknobuga/index

Trends in Sustainable Bakery: A systematic Review of Alternative Ingredients Derived from Tubers, Legumes, and Insects in Indonesia

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ABSTRACT - The global shift toward sustainable and functional foods has encouraged the development of innovative alternative ingredients in bakery products. In Indonesia, the high dependence on imported wheat flour poses challenges to food security, driving the exploration of local substitutes. This systematic literature review aims to analyze the potential, characteristics, and challenges of utilizing alternative ingredients derived from tubers, legumes, and insects for sustainable bakery production in Indonesia. The study reviewed 25 national and international scientific publications from 2015–2025, focusing on nutritional composition, sensory acceptance, and technological applications. Findings indicate that tuber-based flours (such as modified cassava flour and taro) and legume-based flours (soybean, mung bean) can replace up to 30% of wheat flour without significantly affecting product quality. In contrast, insect-based flours particularly cricket flour offer high protein and micronutrient potential but still face consumer acceptance barriers. This review contributes by consolidating multidisciplinary evidence and proposing a practical framework for reducing wheat dependency through local ingredient utilization offering actionable insights for researchers, policymakers, and the bakery industry toward a more sustainable food system in Indonesia.

Keywords: Sustainable bakery, alternative ingredients, tubers, legumes, insects.

INTRODUCTION

The past decade has witnessed a marked global shift in consumer preferences toward foods that not only satisfy sensory expectations but also deliver health benefits and reduced environmental impact. This paradigm shift driven by awareness of non-communicable diseases, climate concerns, and food security has placed bakery products at a crossroads: traditionally energy dense and highly dependent on imported wheat, the bakery sector must now reconcile taste, affordability, nutrition, and sustainability. In Indonesia, where wheat imports exceed several million tonnes annually, the reliance on imported wheat flour creates economic vulnerability and limits opportunities for value adding local agricultural commodities. According to the National Food Agency (Bapanas, 2023), Indonesia's wheat flour consumption continues to increase by around 4–5% per year, reinforcing the urgency to develop local flour alternatives derived from tubers, legumes, and insect-based sources. The present review positions alternative, locally available ingredients particularly tubers (e.g., cassava, sweet potato, taro), legumes (e.g., soybean, mung bean, chickpea), and edible insects (e.g., crickets, mealworms) as strategic levers to address these interrelated challenges.

Several lines of evidence motivate this review. First, agronomic and supply chain data indicate that many root and tuber crops are climate resilient, widely cultivated across Indonesian provinces, and amenable to post harvest processing into flours with acceptable functional properties (Helilusiatiningsih, 2023; Lestari & Widodo, 2021). Second, legume crops offer protein enrichment and can improve nutritional profiles of cereal-based products while supporting soil fertility through nitrogen fixation an agronomic co-benefit (Rahman et al., 2022). Third, the Food and Agriculture Organization (FAO, 2023) and emerging studies spotlight insects as dense sources of high quality protein and micronutrients with far lower greenhouse gas and water footprints than livestock (FAO, 2020; Hassan, 2024). For bakery applications specifically, recent experimental studies report that partial substitution of wheat flour with tuber or legume flours (commonly in the 15–30% range) can preserve sensory acceptability and deliver nutritional gains, whereas insect flours function well as fortificants at lower inclusion rates (5–15%) due to sensory and regulatory constraints (Ayustaningwarno, 2024; Marta, 2023).

Despite these promising findings, multiple knowledge and practice gaps remain. First, many studies focus on single ingredient substitutions and laboratory-scale trials; there is limited synthesis of cross cutting evidence to guide composite formulations (e.g., tuber + legume or legume + insect blends) that could simultaneously address functional, sensory, and nutritional trade offs. Second, consumer acceptance research in Indonesia particularly examining cultural drivers, labeling interventions, and sensory education strategies is still sparse and fragmented. Third, regulatory clarity about novel foods (insect-based ingredients) and industrial scalability (consistent flour quality from tubers or legumes) is incomplete, creating barriers for commercialization. Finally, techno economic assessments comparing life cycle impacts, production costs, and market willingness to pay for fortified/enriched bakery products are limited.

This systematic literature review addresses these gaps by synthesizing 25 peer reviewed studies (2015–2025) focusing on the use, functionality, sensory effects, and adoption barriers of tuber, legume, and insect derived flours in bakery contexts, with emphasis on implications for Indonesia. The review objectives are to: (1) map the current evidence regarding nutritional and technological impacts of alternative flours in breads, cakes, and cookies; (2) evaluate sensory acceptance thresholds and consumer perception issues; (3) identify formulation strategies that balance functionality and acceptability; and (4) propose a prioritized research and policy agenda for accelerating sustainable bakery innovation in Indonesia. By consolidating diverse findings into evidence based recommendations, this review aims to support academics, product developers, and policymakers seeking to reduce wheat dependency while promoting nutritious and culturally acceptable bakery products.

Despite these advancements, existing research in Indonesia remains fragmented, with limited integration between nutritional, technological, and socio-cultural perspectives. In particular, there is a lack of comprehensive synthesis that connects the functional performance of alternative flours with consumer perception and policy readiness.

Research gap: Few studies evaluate tuber, legume, and insect based ingredients holistically from the standpoint of sustainability, product feasibility, and cultural acceptability in bakery applications.

Objectives: Therefore, this review aims to (1) synthesize evidence on nutritional and sensory impacts of alternative flours; (2) compare their technological feasibility across bakery products; and (3) develop a framework to guide sustainable ingredient adoption in Indonesia's bakery industry.

Research questions:

1) To what extent can tuber, legume, and insect based flours substitute wheat flour without compromising product quality?
2) What sensory and consumer acceptance barriers influence the adoption of these alternative ingredients?
3) What strategies can effectively accelerate their integration into Indonesia's bakery sector?

METHOD

This systematic review followed a narrative synthesis approach adapted from (Snyder, 2019) and aligned with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Although no formal PRISMA flow diagram is presented, the core stages of identification, screening, eligibility, and inclusion were applied narratively to ensure transparency and replicability of the literature selection process.

Structured searches were conducted in bibliographic databases (ScienceDirect, Scopus, SpringerLink, DOAJ) and national repositories (Garuda, ResearchGate) using the following keyword combinations: "alternative flour bakery", "tuber flour bread", "legume flour cookies", "insect flour bakery", and "sustainable bakery Indonesia".

Inclusion criteria were: (1) peer-reviewed empirical studies or reviews published between 2015 and 2025; (2) explicit focus on bakery products (bread, cake, biscuits/cookies); and (3) provision of quantitative or semi-quantitative data on substitution levels, proximate composition, sensory scores, or processing parameters.

Exclusion criteria included non–peer-reviewed articles, studies without bakery product applications, and purely exploratory chemical analyses.

From an initial pool of retrieved records, 25 studies met all criteria and were analyzed. Extracted data fields included author/year, ingredient type, product type, substitution level, nutritional outcomes, sensory acceptance metrics, and processing notes. The analytical framework followed the approach proposed by (C. Liu et al., 2024), which categorizes bakery-related research into three evaluation dimensions: nutritional properties, sensory performance, and technological feasibility. Data synthesis was organized thematically into nutritional/functional properties, sensory outcomes, processing strategies, and adoption barriers.

RESULTS AND DISCUSSION

This section synthesizes empirical findings across the 25 reviewed studies and organizes them into four thematic subsections: (1) tuber-based flours, (2) legume-based flours, (3) insect-based flours, and (4) comparative synthesis including composite formulation strategies. For clarity and reproducibility, each subsection presents: (a) key nutritional and functional outcomes, (b) common processing or formulation parameters reported in the literature, (c) sensory and consumer-acceptance results, and (d) practical recommendations for product development and scale-up. Where possible, quantitative ranges (substitution levels, hydration adjustments, hydrocolloid usage) are reported so the reader gains actionable guidance. After the narrative, two summary tables (**TABLE 1** and **TABLE 2**) consolidate representative study outcomes and a comparative synthesis respectively.

FIGURES 1 and **2** illustrate the conceptual and quantitative synthesis derived from the reviewed studies, complementing **TABLES 1** and **2** for clearer visualization of substitution trends and sustainability implications.

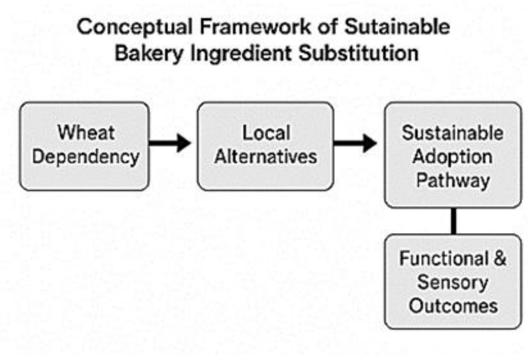

FIGURE 1. Conceptual framework illustrating the transition from wheat dependency toward sustainable bakery formulations using tuber, legume, and insect-based ingredients.

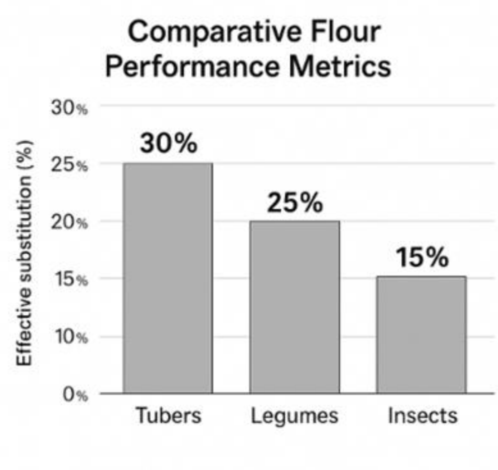

FIGURE 2. Comparative effective substitution levels of tuber-, legume-, and insect-based flours in bakery products.

Nutritional and Technological Aspects of Tuber Based Flours

Tuber flours (modified cassava flour or MOCAF, taro, sweet potato) predominantly contribute starch based structure, dietary fiber, and certain micronutrients (e.g., provitamin A in orange fleshed sweet potato). The reviewed studies consistently report that these flours increase total dietary fiber and lower predicted glycemic index when substituted for wheat flour at partial levels. Mechanistically, MOCAF and roasted sweet potato flours tend to have smaller particle size and higher water absorption index (WAI) compared to wheat flour; these physical properties increase batter viscosity and alter gas retention during proofing, producing a crumb that is often softer but with modest reduction in specific volume.

Processing & formulation parameters (practical, from literature)

- Effective substitution range: 20–30% for bread and cake without major sensory penalty. Above 30% the crumb tends to become denser and loaf volume decreases markedly.
- Hydration adjustment: Increase water addition by approximately 3–8% (absolute w/w) relative to control wheat recipes to account for higher WAI of tuber flours. Example: if original recipe uses 60% dough hydration, tuber substitution at 25% may require 62–65% effective hydration.
- Use of hydrocolloids/emulsifiers: Xanthan gum at 0.2–0.5% w/w or guar gum 0.3–0.6% can partially mimic gluten network elasticity in high-tuber blends. Lecithin (0.5–1.0%) improves gas cell stability and extends shelf-life.
- Pre-treatment: Fermentation (e.g., natural or starter-based) and enzymatic modification (α-amylase treatment) improve dough handling and crumb structure by modifying starch gelatinization and retrogradation profiles. Pre-roasting tuber flour (120–150 °C for 5–10 min) reduces enzymatic off-notes and develops nutty aroma.

Sensory Outcomes and Variability

Sensory panels (both consumer and trained) in multiple studies commonly reported hedonic scores ≥6/9 for up to 25–30% substitution in sweet breads and cakes. Important sensory changes include slight color shifts (crumb becomes more yellow or slightly brown depending on tuber), reduced oven spring (volume), and subtle flavor differences (earthy or sweet notes). Acceptability improves when tuber flours are blended with flavor enhancers (e.g., vanilla, roasted nut inclusions) or composited with small amounts of legume protein to improve mouthfeel.

TABLE 1 summarizes representative experimental outcomes for tuber based flour substitutions, detailing product types, substitution levels, and key sensory/technological findings reported in selected studies.

TABLE 1. Summary of tuber based flour utilization in bakery.

No	Author & Year	Type of Tuber Flour	Bakery Product	Substitution (%)	Key Findings
1	(Helilusiatiningsih, 2023)	MOCAF	White Bread	30	Soft crumb; increased fiber; slight volume loss mitigated by xanthan 0.3%
2	(Marta, 2023)	MOCAF + Banana Flour	Cookies	20-30	Improved aroma & color; water addition +5% recommended
3	(Gularte et al., 2023)	Cassava Flour	Gluten-free Bread	25	Retained elasticity with enzyme treatment; lower GI

TABLE 1 highlights a consistent pattern: MOCAF and composite tuber flours produce acceptable sensory profiles up to 30% substitution while improving fiber content and lowering predicted glycemic responses. However, the data

also indicate an operational trade off formulations require hydration management and often benefit from hydrocolloid addition to maintain crumb structure and shelf stability.

Functional Role of Legume Flours

Legume flours (soybean, mung bean, chickpea) are primarily leveraged for protein enrichment and fiber content. Compared to tubers, legumes provide complementary amino acid profiles that can correct the protein poor nature of high tuber formulations. When legume flour is introduced at 15–25%, the typical outcomes include a 15–40% increase in crude protein content (depending on the legume and its protein concentration), improved water holding capacity, and enhanced nutritional score (PDCAAS proxy metrics).

Processing and Formulation Considerations

- **Flavor mitigation:** Roasting (120–160 °C for 5–15 min) reduces the beany/aromatic off notes by inactivating lipoxygenase enzymes. Fermentation (e.g., lactic acid bacteria) further diminishes undesirable volatiles and can improve sensory acceptance.
- **Texture control**: Legume proteins interact with starch and residual gluten; substitution at >20% often yields a firmer crumb. To counteract density, formulators can: (a) increase mechanical dough development time, (b) add enzymes (transglutaminase at 0.02–0.05%) to improve protein network, or (c) combine with tuber flours for lighter texture.
- **Nutritional synergy:** Combining legume + tuber flours allows simultaneous fiber and protein improvements without major sensory penalties (e.g., 20% MOCAF + 10% roasted soy yields balanced texture and 25–30% protein increase compared to control).

Sensory and Consumer Segmentation

Consumer acceptance of legume rich bakery tends to be higher among health conscious segments and in savory product categories. In sweet bakery, masking strategies (spices, sweet inclusions) increase acceptance. Many studies used 9 point hedonic scales with trained panels (n=20–40) and consumer panels (n=50–200); statistically significant declines in overall liking emerge typically above 25–30% legume inclusion ($p < 0.05$, ANOVA/Tukey comparisons reported in primary studies).

Practical Application Notes

- For product developers: trial 10–20% legume inclusion first, using roasted legume flour and small amounts of enzymatic or hydrocolloid aids.
- For nutrition claims: a 20% soybean substitution may justify "source of protein" labeling depending on national regulation thresholds check local labeling law before claims.

Insect Based Flour as Emerging Protein Fortification

Insect flours (notably crickets Acheta domesticus and mealworms Tenebrio molitor) present concentrated protein (commonly 50–70% on dry basis), beneficial fatty acid profiles, and essential micronutrients such as iron and zinc. Life cycle assessments reported in the literature indicate insect farming emits substantially lower greenhouse gases and requires less land and water relative to conventional livestock, making it attractive within sustainability narratives.

Functional & processing aspects

- Particle size & lipid content: Fine milling (<150 µm) and defatting (partial solvent or mechanical pressing to reduce free lipids) can reduce off-aroma and improve blend uniformity. Defatted insect meal is often preferred for bakery inclusion to limit oxidative rancidity.

- Inclusion levels: Sensory-acceptable ranges reported are 5–15% depending on the product and reformulation strategies. At >15% inclusion, color darkening and savory/umami notes become prominent and may reduce acceptability.
- Safety & regulatory: Authors emphasize the need for allergen labeling (chitin and cross-reactivity with crustaceans) and microbial control during insect processing (thermal drying >80 °C or blanching prior to drying). Regulatory frameworks vary by jurisdiction; product developers should document traceability and hazard analyses (HACCP / GMP).

Consumer acceptance & marketing

Consumer resistance is the major bottleneck. Studies show that acceptance improves when insect ingredients are presented as invisible (powdered fortificant), when taste tests occur in controlled sampling with informative labeling, and when products are positioned as premium functional foods (protein bars, specialty cookies). Education campaigns, sensory trials with labeling variations, and pilot commercialization in niche markets are recommended.

Comparative Synthesis of Alternative Ingredients

The relative strengths and limitations of each ingredient class are summarized in Table 2. Tubers excel in textural contributions and scalability (high feasibility given existing supply chains), but are limited in protein contribution. Legumes deliver protein and essential amino acids, yet require processing to mitigate sensory issues. Insects provide unmatched protein density and micronutrients but face acceptance and regulatory hurdles. Recent studies by (Y. Liu et al., 2023) emphasized that integrating local starches and novel proteins through composite flour formulations can significantly enhance both the sustainability and nutritional quality of bakery products. Table 2 presents a concise comparative synthesis of effective substitution ranges, principal nutritional impacts, consumer acceptance levels, and industrial feasibility for tuber, legume, and insect flours.

TABLE 2. Comparative potential of alternative flours in bakery applications.

Ingredient Type	Effective Substitution (%)	Nutritional Impact	Consumer Acceptance	Industrial Feasibility
Tubers	20–30	Increased fiber; lower predicted GI	Good–Moderate	High (existing supply)
Legumes	15–25	Increased protein & amino acids	Moderate	High (processing needed)
Insects	5–15	High protein, micronutrients	Low–Moderate	Emerging (requires regulation)

TABLE 2 underscores a practical pathway: begin with tuber legume composites for short term, scalable wheat reduction while simultaneously investing in regulatory clarity, safety protocols, and consumer education to enable wider adoption of insect based fortification in the medium term.

From a cultural perspective, acceptance of non-wheat bakery products in Indonesia is shaped by familiarity, labeling, and exposure. Studies such as (Marta, 2023; Raharja & Putri, 2023) highlight that consumer behavior is strongly influenced by educational interventions and visibility of local narratives (e.g., “beras dari singkong”, “protein serangga lokal”). Integrating cultural values and sensory education (Tan & Stieger, 2021) is therefore essential to bridge innovation and acceptance.

Comparative analysis further indicates that while tuber- and legume-based formulations are technologically mature, insect-based innovations remain at an experimental stage primarily due to psychological and regulatory barriers. These differences emphasize the need for staged policy implementation and consumer literacy programs to foster gradual market adaptation.

Practical Implications

The combined use of tuber, legume, and insect flours supports local resource utilization, nutritional enhancement, and reduction of wheat import dependency. Future innovation should emphasize consumer education, formulation optimization, and collaboration between academia and industry for scaling up production.

The evidence supports a staged strategy for industry and policy actors:

- **Immediate actions (0–2 years)**: Promote tuber legume composite formulations for small and medium bakeries. Technical packages should include recommended substitution ranges (e.g., 20% tuber + 10% roasted legume), hydration adjustments (+3 - 6% water), and simple hydrocolloid or emulsifier additions to stabilize crumb and extend shelf life. Government extension programs can facilitate MOCAF quality standards and supply chain linkages to bakeries.
- **Medium-term actions (2–5 years):** Invest in pilot scale insect protein fortification projects targeting functional foods and sports/health niches. Establish regulatory pathways, develop allergen labeling protocols, and fund consumer education and sensory experiments to normalize acceptance.
- **Research & development:** Fund comparative life cycle assessments (LCA) and techno economic analyses to quantify the environmental and cost benefits of alternative flours relative to imported wheat. Standardize analytical protocols (proximate analysis, WAI, particle size) to enable cross study comparability.

Limitations of the Evidence Base

Although the reviewed studies provide useful direction, several methodological limitations constrain generalizability: (a) small and non representative sensory panels, (b) inconsistent reporting of processing parameters (e.g., moisture content, particle size distribution), (c) lack of long term shelf life and staling kinetics data for various formulations, and (d) limited economic analysis on cost implications for small scale bakers. Addressing these gaps requires coordinated multi disciplinary trials combining sensory science, food engineering, and market research.

Summary Transition to Conclusion

Overall, the results indicate clear and actionable pathways for deploying alternative flours in bakery products. Tubers and legumes are immediately actionable with minimal investment in processing; insect flours are strategically valuable but require complementary investments in regulation, safety assurance, and consumer engagement. The concluding section synthesizes these insights into concise recommendations.

CONCLUSION

This review confirms that tuber, legume, and insect-based ingredients hold strong potential for sustainable bakery innovation in Indonesia. Tuber and legume flours can substitute up to 30% of wheat flour, improving nutrition and supporting local agriculture. Insect-based flours provide superior protein quality but require cultural adaptation and regulatory frameworks. To translate these findings into practice, the adoption of composite flour (tuber–legume) should be promoted for SMEs through technical and financial incentives. In addition, public education programs on insect-based food safety and sustainability need to be developed. Furthermore, collaboration between academia, industry, and government should be encouraged to standardize flour quality and labelling. By implementing these strategies, Indonesia can progressively reduce wheat dependency and strengthen its local food system through sustainable bakery innovation.

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