

Composite Millet Flours in Cookie Systems: Rheological Characteristics, Baking Performance and Future Perspectives-A Review

Happy Narang¹, Sunil², Khan Chand³ and Gargi Shekhar⁴

^{1&2}School of Agricultural Sciences and Engineering, IFTM University, Moradabad (U.P.)
India

³Department of Agricultural Engineering, School of Agricultural Sciences, Nagaland
University, Medziphema, Nagaland

⁴School of Agriculture, Dev Bhoomi Uttarakhand University, Dehradun, Uttarakhand

Corresponding author: kc@nagalanduniversity.ac.in & happynarang.nov18@gmail.com

Abstract

Millets have emerged as nutritionally rich and climate-resilient cereals with significant potential in the development of functional bakery products. This review critically examines the application of composite millet flours in cookie systems, with a focus on their rheological behaviour, baking performance, and prospects. Millets such as finger millet, pearl millet, and sorghum offer superior nutritional benefits, including high dietary fibre, essential minerals, and bioactive compounds. However, their lack of gluten presents technological challenges, particularly in dough formation and structural stability. The study synthesizes findings from recent literature to evaluate how millet incorporation influences dough rheology, including viscosity, elasticity, and water absorption characteristics. It further explores the impact on cookie quality attributes such as spread ratio, texture, color, and sensory acceptability. While millet enrichment enhances nutritional value, higher substitution levels often compromise texture and consumer preference. Strategies such as optimized blending ratios, use of hydrocolloids, and advanced processing techniques are discussed as effective approaches to improve product quality. Overall, this review highlights the need for balanced formulation and standardized methodologies to fully utilize millet potential in bakery applications. It also identifies research gaps and emphasizes future opportunities in gluten-free and functional food development.

Keywords: Nutraceutical properties, Dough microstructure, Antioxidant activity, Gluten-free formulation, Sensory optimization

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Introduction

Millets have gained renewed attention in recent years as resilient, climate-smart crops with strong nutritional potential. These small-seeded cereals, including

finger millet, pearl millet, and sorghum, are rich in dietary fiber, essential amino acids, minerals, and bioactive compounds such as polyphenols. Their ability to thrive under low-input and drought-prone conditions makes them highly suitable for sustainable

agriculture, particularly in regions facing climate variability and resource constraints. Studies have highlighted that millets not only contribute to food security but also support nutritional security by addressing micronutrient deficiencies and improving overall diet quality (Kumar et al., 2018; Saleh et al., 2013). Additionally, the presence of antioxidants and slowly digestible starch in millets has been associated with reduced risks of chronic diseases, making them valuable ingredients in functional food development (Devi et al., 2014; Alamdar Husain et al., 2023).

Despite these advantages, wheat continues to dominate bakery industries due to its unique gluten-forming ability, which imparts desirable viscoelastic properties to dough. However, increasing incidences of gluten intolerance, such as celiac disease, and the growing consumer demand for gluten-free products have intensified the need for alternative flours. Millets present a promising substitute, yet their lack of gluten poses technological challenges in bakery applications. As noted in earlier research, gluten plays a critical role in structure formation, gas retention, and texture development in baked goods, especially cookies and biscuits (Pareyt & Delcour, 2008; Gallagher et al., 2004). Therefore, replacing wheat entirely or partially requires careful formulation strategies to maintain product quality.

The concept of composite flours has emerged as an effective approach to address these challenges. Composite flour systems involve blending millet flours with wheat or other non-gluten flours such as legumes, tubers, or pseudocereals to enhance both nutritional and functional attributes. This strategy not only improves protein quality

and fiber content but also helps balance the rheological properties required for dough handling and baking performance. Research has demonstrated that incorporating millets into composite flours can significantly improve the nutritional profile of cookies while maintaining acceptable sensory characteristics (Hussain et al., 2020; Ikade et al., 2024). Furthermore, the use of complementary ingredients such as hydrocolloids and emulsifiers can help mimic the structural role of gluten, thereby improving dough stability and product texture (Lazaridou et al., 2007; Sabanis & Tzia, 2011).

However, gluten-free and composite dough systems are inherently complex and present multiple challenges. Unlike wheat dough, millet-based dough lacks elasticity and cohesiveness, leading to issues such as poor machinability, reduced spread control, and undesirable texture in final products. The absence of a continuous protein network affects water absorption, dough viscosity, and gas retention. Studies on gluten-free formulations indicate that achieving optimal dough rheology requires precise control of ingredient interactions, particle size distribution, and processing conditions (Belorio et al., 2019; Mancebo et al., 2015). Additionally, variations in millet type, flour composition, and substitution levels can lead to inconsistent baking outcomes, making standardization difficult.

Given these complexities, understanding the rheological behavior of composite flours is essential for successful product development. Rheology provides insights into dough flow, deformation, and viscoelastic properties, which directly influence cookie spread, texture, and overall quality. Instruments such as

farinographs, mixolabs, and rheometers are commonly used to evaluate these properties and predict baking performance (Dobraszczyk & Morgenstern, 2003; Pandey & Gujral, 2024). Moreover, cookie quality is not solely dependent on flour characteristics; interactions with sugar, fat, and water also play a significant role in determining final product attributes (Pareyt et al., 2009). Therefore, a comprehensive evaluation of both rheological properties and baking performance is necessary to optimize millet-based cookie formulations.

The rationale for focusing on composite millet flours in cookie systems lies in the growing demand for healthier, gluten-free snacks that do not compromise on sensory appeal. Cookies serve as an ideal model product due to their relatively simple structure and widespread consumption. Unlike bread, cookies require less gluten development, making them more adaptable to alternative flour incorporation. Previous studies have shown that millet-based cookies can achieve acceptable texture, flavor, and shelf stability when appropriate formulation techniques are applied (Aljobair, 2022; Anggraini et al., 2021). However, there remains a need for critical evaluation of existing research to identify gaps, inconsistencies, and opportunities for innovation.

Therefore, this review aims to critically analyse the role of composite millet flours in cookie systems, with a specific focus on rheological characteristics and baking performance. It seeks to synthesize current knowledge on functional properties, dough behaviour, and quality attributes of millet-based cookies while highlighting the limitations of existing studies. Furthermore, the review explores emerging strategies for

improving product quality and outlines future research directions to support the development of nutritionally enhanced and commercially viable millet-based bakery products.

2. Methodology

The present critical review was designed to systematically gather, evaluate, and synthesize existing scientific literature on the use of composite millet flours in cookie systems, with particular emphasis on rheological behaviour and baking performance. A structured and transparent methodology was adopted to ensure reliability, reproducibility, and depth of analysis. A comprehensive literature search was conducted using major academic databases, including Scopus, Web of Science, and Google Scholar, as these platforms provide access to high-quality peer-reviewed journals in food science and cereal technology. Additional relevant sources were identified through cross-referencing and citation tracking of key articles and review papers. Foundational texts on cookie processing and dough rheology were also consulted to strengthen the theoretical framework (Manley, 2011; Dobraszczyk and Morgenstern, 2003).

To maintain relevance and scientific rigor, clear inclusion and exclusion criteria were established prior to the review process. Studies published primarily between 2000 and 2025 were considered, with particular attention given to recent advances (post-2015) in gluten-free and millet-based bakery systems. Only peer-reviewed journal articles, review papers, and authoritative book chapters were included. Research focusing specifically on millet flours (such as finger millet, pearl millet, and sorghum) and their application in

cookies or similar baked products was prioritized. Studies addressing rheological properties, functional characteristics, sensory quality, and baking performance were selected for detailed analysis.

Conversely, articles lacking experimental evidence, non-English publications, and studies unrelated to bakery applications were excluded to maintain focus and consistency.



Figure 2.1 Processing interventions to improve quality in composite food systems

A strategic keyword-based search approach was employed to ensure comprehensive coverage of the topic. Keywords and combinations such as “composite flour,” “millet cookies,” “gluten-free baking,” “dough rheology,” “functional properties of millet flour,” and “baking performance of composite flours” were used. Boolean operators (AND, OR) were applied to refine search results and retrieve relevant studies. This approach enabled the identification of diverse research works examining both traditional and innovative formulations (Hussain et al., 2020; Ikade et al., 2024; Pandey & Gujral, 2024). This processing

intervention is illustrated in a three-tier strategy for enhancing product quality of figure 2.1 and the pre-treatment techniques—germination, fermentation, and roasting—are applied to improve enzymatic activity and flavour, enhance digestibility, and develop desirable aroma, respectively. Ingredient optimization focuses on the incorporation of functional additives, where hydrocolloids improve dough cohesiveness, enzymes modify starch functionality, and protein isolates compensate for structural deficiencies. Advanced technologies such as extrusion processing and nano-encapsulation of

functional ingredients represent emerging approaches for improving physicochemical and nutritional attributes. Despite these the need for scale-up and process standardization.

The analysis of selected literature followed a comparative and thematic framework. Studies were first categorized based on key focus areas, including (i) functional and compositional attributes of millet flours, (ii) rheological behaviour of composite dough systems, and (iii) cookie quality and sensory performance. Within each category, findings from different studies were systematically compared to identify patterns, consistencies, and contradictions. For instance, variations in dough viscosity and elasticity reported across studies were critically examined in relation to differences in millet type, particle size, and processing conditions (Belorio et al., 2019; Monthe et al., 2018).

A critical synthesis approach was further employed to move beyond simple summarization. This involved evaluating the strengths and limitations of individual studies, identifying methodological gaps, and assessing the practical applicability of reported findings. For example, while

advancements, most interventions remain confined to laboratory-scale studies with limited industrial validation, highlighting

several studies demonstrated improved nutritional quality with millet incorporation, inconsistencies in sensory acceptance and textural attributes highlighted the need for formulation optimization (Aljobair, 2022; Bala et al., 2015). Similarly, the role of hydrocolloids in improving gluten-free dough structure was analysed by integrating findings from multiple sources (Lazaridou et al., 2007; Sabanis & Tzia, 2011).

In addition, the review considered variability in experimental designs, such as differences in substitution levels, baking conditions, and analytical techniques. This variability was critically examined to explain discrepancies in reported results and to highlight the need for standardized methodologies in future research. The inclusion of both experimental studies and review articles allowed for a balanced perspective, combining empirical evidence with broader scientific interpretations.

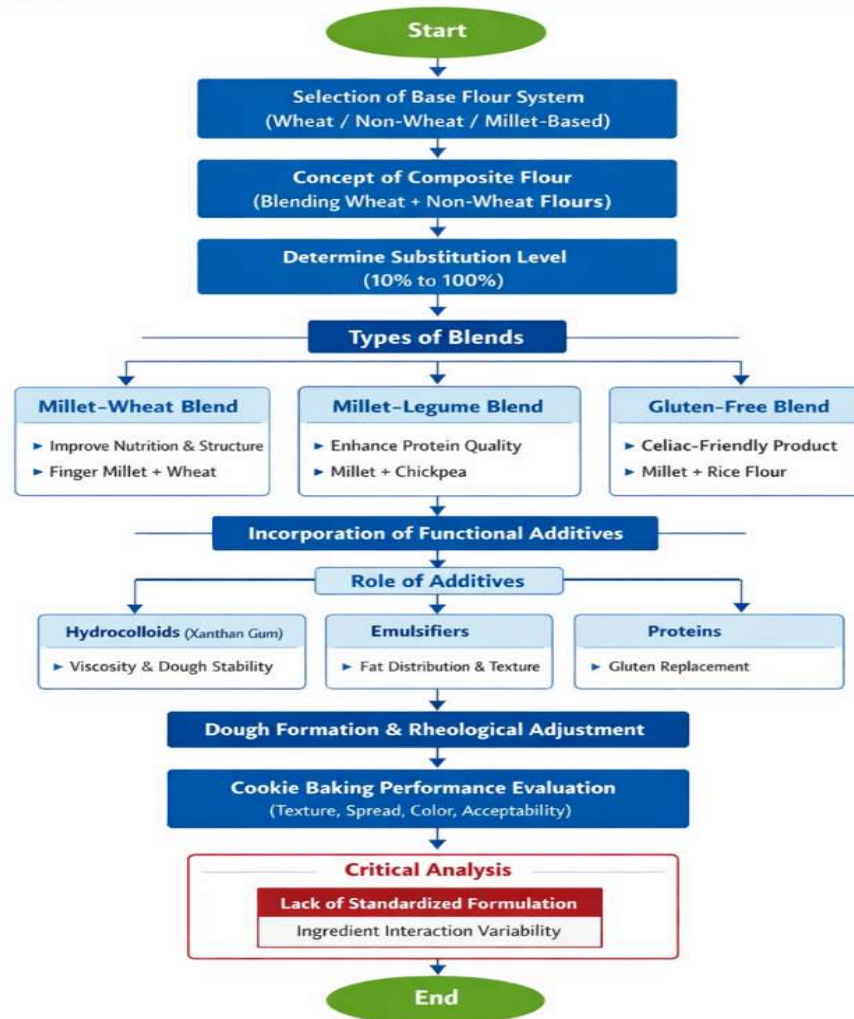


Figure 2.1 Flowchart of composite flour systems in cookie formulation and functional optimisation

Overall, this methodological approach ensured a comprehensive, balanced, and critical evaluation of the available literature. By integrating findings across multiple studies and identifying existing research gaps, the review provides a solid foundation for understanding the complex interactions governing composite millet flour systems in cookie production, while also guiding future research directions in this evolving field.

3. Critical Analysis and Results with Discussion

While millet incorporation undeniably improves nutritional quality, its impact on rheology and baking performance remains a key challenge. The success of composite millet cookies largely depends on achieving a balance between functional performance and sensory acceptability.

3.1 Composition and Functional Properties of Millets

Millets have attracted considerable attention as functional ingredients due to their superior nutritional profile compared to refined wheat flour. They are naturally

rich in dietary fiber, essential amino acids, minerals such as calcium, iron, and zinc, and bioactive compounds including polyphenols (Saleh et al., 2013; Devi et al., 2014). Finger millet, for instance, is particularly noted for its high calcium

content, while pearl millet provides significant iron levels. These nutritional advantages make millet-based composite flours highly suitable for developing health-oriented bakery products.

Table 3.1 Case Study: Composition and Functional Properties of Millets in Cookie Systems

Study	Millet Type / Composite Flour	Key Compositional Traits	Functional Properties Observed	Implications for Cookie Systems
Saleh et al. (2013)	Multiple millets	High fibre, minerals, polyphenols	Strong antioxidant activity	Enhances nutritional value and functional appeal
Devi et al. (2014)	Finger millet	High calcium and dietary fibre	Improved hydration and health benefits	Suitable for functional cookies but affects texture
Krishnan et al. (2011)	Finger millet seed coat flour	High fibre content	Increased water absorption	Reduced spread ratio, harder texture
Hussain et al. (2020)	Wheat–millet composite	Balanced nutrients	Improved antioxidant capacity	Acceptable sensory quality at moderate substitution
Belorio et al. (2019)	Maize (GF system, comparable)	Variable particle size	Fine flour improves uniformity	Better cookie structure and mouthfeel
Yenasew & Urga (2023)	Germinated finger millet	Enhanced enzyme activity	Improved solubility and digestibility	Better functional performance in dough
Gautam & Perumal (2022)	Millet-based foods	Rich micronutrients	High water and oil absorption	Influences dough consistency and baking behavior
Kathuria et al. (2021)	Composite cereal flour	Balanced macronutrients	Improved emulsification and hydration	Enhanced dough handling properties
Kristanti & Setiaboma (2022)	Composite flour blends	Improved protein balance	Increased oil absorption capacity	Improved texture and mouthfeel
Pandey & Gujral (2024)	Millet dough systems	Variable starch properties	Altered pasting and rheology	Direct impact on cookie spread and structure

From a functional standpoint, millet flours exhibit higher water absorption capacity and oil-binding properties than wheat flour (Gautam & Perumal, 2022). This is largely due to their fiber-rich composition and the presence of non-starch polysaccharides. However, unlike wheat, millets lack gluten-forming proteins, which are critical for structural development in dough systems. Consequently, while millet incorporation enhances nutritional value, it compromises viscoelastic behaviour and handling properties.

Table 3.2: Comparative Functional Properties of Wheat and Millet Flours

Property	Wheat Flour	Millet Flour (Finger/Pearl/Sorghum)	Critical Interpretation	Key References
Water Absorption Capacity	Moderate	High due to fiber content	High WAC in millets improves hydration but may lead to dense dough	Gautam & Perumal (2022); Yenasew & Urga (2023)
Oil Absorption Capacity	Moderate	High	Enhances flavor retention in millet products	Aderinola & Adeoye (2022)
Gluten Formation	Present (gliadin + glutenin)	Absent	Major limitation in millet dough structure	Dobraszczyk & Morgenstern (2003); Gallagher et al. (2004)
Dough Rheology	Elastic and extensible	Weak, less cohesive	Requires hydrocolloids for improvement	Lazaridou et al. (2007)
Bulk Density	Uniform	Variable	Influences packaging and texture	Kathuria et al. (2021)
Pasting Properties	Stable gelatinization	Variable gelatinization	Affects cookie spread and texture	Pandey & Gujral (2024)
Fiber Content	Low to moderate	High	Improves nutritional value but affects texture	Devi et al. (2014)
Antioxidant Activity	Low	High (polyphenols)	Adds functional health benefits	Ragae et al. (2006)

Cookie Spread Ratio	Optimal	Reduced at high substitution	Indicates poorer dough flow	Hussain et al. (2020)
Texture (Hardness)	Soft to crisp	Often harder	Needs optimization strategies	Krishnan et al. (2011)

3.2 Rheological Characteristics of Composite Dough

The absence of gluten presents a major challenge in forming cohesive dough when millet flours are incorporated. Gluten proteins in wheat create a viscoelastic network responsible for dough elasticity and gas retention (Dobraszczyk & Morgenstern, 2003). In composite systems, this network is weakened, leading to reduced elasticity and increased dough fragility.

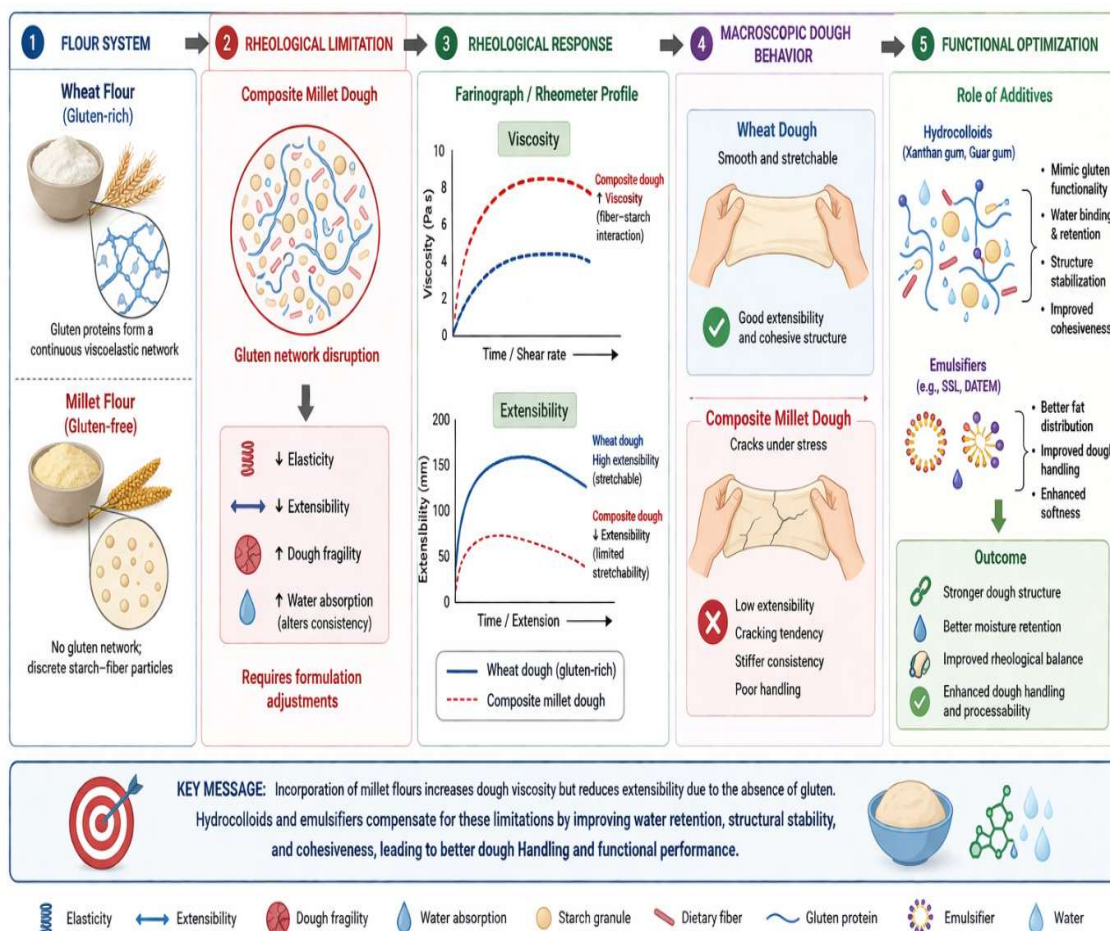


Figure 3.1 Rheological Characteristics of composite Millet Dough Systems in absence of gluten

Rheological studies using instruments such as farinographs and rheometers indicate that millet-enriched doughs exhibit increased viscosity but reduced extensibility (Pandey & Gujral, 2024). This results in doughs that are less stretchable and more prone to cracking. Additionally, increased water absorption alters dough consistency, often requiring formulation adjustments.

To compensate for these limitations, hydrocolloids such as xanthan gum and guar gum are frequently incorporated. These additives mimic gluten functionality by improving water retention, stabilizing dough structure, and enhancing cohesiveness (Lazaridou et al., 2007). Emulsifiers further contribute by improving fat distribution and dough handling properties.

3.3 Impact on Cookie Baking Performance

The incorporation of millet flours significantly influences cookie quality parameters, including spread ratio, texture, and color. Generally, an increase in millet content leads to higher spread ratios due to weaker dough structure and reduced gluten strength (Hussain et al., 2020). While moderate spread is desirable, excessive spreading may result in thin and fragile cookies.

Texture analysis shows that millet-based cookies tend to be harder and more brittle, primarily due to high fiber content and reduced gluten matrix (Sudha et al., 2007). Additionally, darker coloration is often observed, attributed to Maillard reactions involving higher protein and phenolic content.

Sensory evaluation studies reveal mixed outcomes. While millet incorporation enhances nutritional appeal, high substitution levels (>40%) often reduce consumer acceptability due to changes in taste and texture (Aljobair, 2022). However, optimized formulations with 20–30% substitution generally achieve a balance between nutrition and sensory quality. A comparative visualization of wheat and millet-based cookies (Figure 3.1) highlights the superior nutritional and functional attributes of millet composites, although a decline in texture and elasticity is evident.

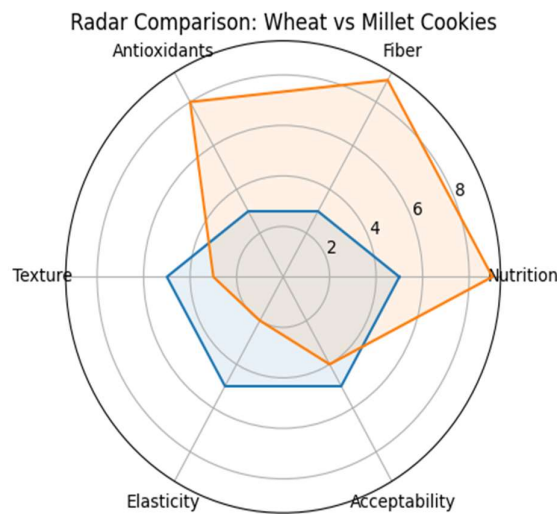


Figure 3.2: Radar chart comparing quality attributes of millet composites

Table 3.2: Case Studies on Millet-Based Cookies

Study	Millet Type	Substitution (%)	Key Findings
Hussain et al. (2020)	Mixed millet	20–40%	Improved antioxidant activity; acceptable sensory scores at 30%
Aljobair (2022)	Sorghum/Millet	25–50%	Increased hardness; reduced spread at higher levels
Ikade et al. (2024)	Multi-millet	30%	Balanced texture and good acceptability
Anggraini et al. (2021)	Millet flour	20–40%	Enhanced shelf life but reduced taste at higher substitution

3.4 Optimization Strategies

To overcome functional limitations, several optimization strategies have been explored. Blending millets with wheat or other gluten-free flours (such as rice or cassava) helps improve dough properties and final product quality. Studies suggest that partial substitution (20–30%) yields the best results in terms of both functionality and acceptability (Chaudhary et al., 2024).

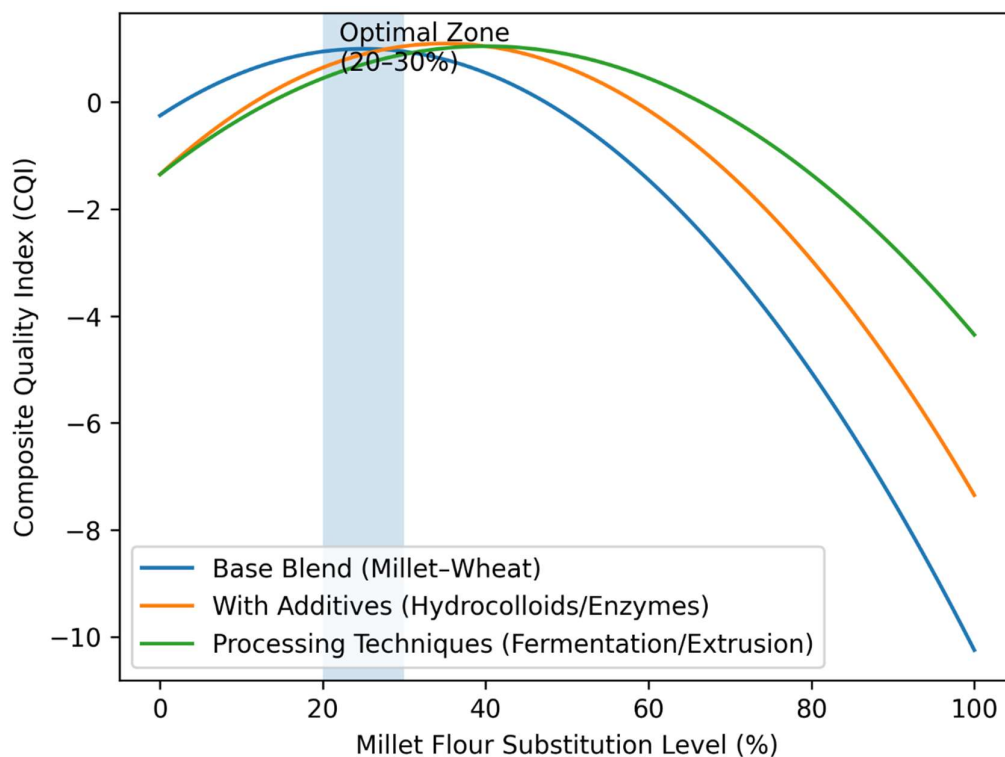


Figure 3.3: Optimization of composite millet flour in cookie system

The use of additives such as enzymes, hydrocolloids, and emulsifiers plays a crucial role in enhancing dough stability. For example, hydrocolloids improve moisture retention and reduce cookie hardness, while enzymes can modify starch behaviour and improve texture. Processing

techniques such as fermentation and extrusion have also shown promise. Fermentation enhances bioavailability of nutrients and improves flavour, while extrusion modifies starch structure, leading to better functional performance (Monthe et al., 2018).

3.5 Comparative Evaluation Across Studies

A critical comparison of existing literature reveals inconsistencies in reported findings. While some studies report improved cookie texture with millet incorporation, others highlight increased hardness and reduced acceptability. These discrepancies can be attributed to variations in millet type, particle size, processing methods, and formulation differences.

Table 3.4: Comparative Evaluation of Selected Studies on Millet-Based Composite Cookies

Study	Flour Composition	Key Findings (Rheology & Baking)	Sensory Outcome	Limitations Identified
Hussain et al. (2020)	Wheat + Millet blends	Reduced elasticity; increased hardness with higher millet levels	Acceptable up to ~30% substitution	Limited optimization of additives
Aljobair (2022)	Sorghum–Millet composite	Improved nutritional profile; decreased spread ratio	Moderate acceptability	Texture deterioration at high levels
Ikade et al. (2024)	Multi-millet composite flour	Balanced rheology when blends optimized	High acceptability with proper ratios	Lack of standard formulation
Pandey & Gujral (2024)	Millet-based dough systems	Altered thermo-mechanical behavior; weaker gluten network	Not primary focus	Limited sensory correlation
Belorio et al. (2019)	Maize gluten-free flour	Particle size significantly affects texture and spreads	Improved with finer flour	Focus limited to maize, not millets
Krishnan et al. (2011)	Finger millet seed coat composite	Increased fiber and antioxidant content; altered dough structure	Acceptable but denser texture	Limited commercial applicability
Anggraini et al. (2021)	Millet-based cookies	Improved nutrition and shelf life	Good consumer acceptance	Limited rheological analysis

Saini et al. (2025)	Pearl millet + Niger seed flour	Enhanced nutritional value; increased hardness	Acceptable at low substitution	Poor spread at higher levels
Bala et al. (2015)	Wheat + cassava + water chestnut	Improved functional properties but weaker structure	Acceptable with formulation adjustment	Not millet-specific but comparable
Lazaridou et al. (2007)	Gluten-free systems + hydrocolloids	Improved dough cohesiveness and stability	Enhanced texture	Additive dependency

For instance, finer flour particles tend to produce better texture and uniformity, whereas coarse particles may result in gritty mouthfeel (Belorio et al., 2019). Similarly, differences in baking conditions and ingredient ratios significantly influence outcomes. Therefore, lack of standardization makes direct comparison across studies challenging.

3.6 Limitations in Existing Research

Despite significant progress, several limitations persist in current research. One major issue is the lack of standardized methodologies for evaluating rheological and baking properties. Different studies employ varying instruments and parameters, making it difficult to draw consistent conclusions.

Additionally, most studies are conducted at laboratory scale, with limited focus on industrial applicability. Large-scale production challenges, including processing efficiency and cost implications, remain underexplored. Another critical gap is the lack of long-term storage and shelf-life studies. While some research indicates improved shelf stability due to low moisture content, comprehensive studies on microbial stability and packaging are scarce (Geetha et al., 2021).

3.7 Future Perspectives

The future of millet-based composite flours in cookie systems appears promising, particularly in the context of increasing demand for gluten-free and functional foods. Millets offer a sustainable and

nutritionally rich alternative to wheat, aligning with global food security goals (Kumar et al., 2018).

Emerging technologies such as artificial intelligence and machine learning can be utilized to optimize formulations and predict product quality. Additionally, advanced processing methods like extrusion and 3D food printing hold potential for creating customized and nutritionally enhanced bakery products. Furthermore, the integration of millets into nutraceutical and functional food markets presents significant opportunities. With growing consumer awareness regarding health and wellness, millet-based cookies can be positioned as value-added products with enhanced health benefits.

Conclusion

The incorporation of composite millet flours into cookie systems presents a compelling opportunity to enhance both the nutritional quality and sustainability of bakery products. Millets, with their rich composition of dietary fiber, minerals, and bioactive compounds, offer clear advantages over conventional wheat flour. However, their lack of gluten significantly

affects dough rheology and final product quality, making formulation a critical aspect of successful product development. This review highlights that while millet-based composite flours improve nutritional attributes, they often lead to challenges such as reduced dough elasticity, increased hardness, and variability in baking performance. The rheological behavior of such dough systems is complex and influenced by multiple factors, including water absorption, particle size, and ingredient interactions. Consequently, achieving an optimal balance between functional performance and sensory acceptability remains a key challenge. Evidence from various studies suggests that moderate substitution levels, typically between 20–30%, provide the best compromise between enhanced nutrition and acceptable texture and flavor. The use of hydrocolloids, enzymes, and emulsifiers has proven effective in mimicking gluten functionality and improving dough stability. Additionally, processing techniques such as fermentation and extrusion offer promising avenues for enhancing both functional and sensory properties. Despite these advancements, the review identifies several gaps in current research, including a lack of standardized evaluation methods, limited industrial-scale studies, and insufficient data on shelf life and storage stability. Addressing these gaps is essential for translating laboratory findings into commercial applications. Looking ahead, the integration of emerging technologies such as artificial intelligence and innovative processing methods could significantly advance the development of millet-based bakery products. With growing consumer demand for gluten-free and health-oriented foods, composite millet cookies hold strong potential as functional,

sustainable, and marketable alternatives in the global food industry.

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