International Journal on Science and Technology (IJSAT)
E-ISSN: 2229-7677 ● Website: www.ijsat.org ● Email: editor@ijsat.org

Chocolates with Millet Infusion: Views on Technology, Nutrition, and Sensory Experience

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Background

Millets such as finger, pearl, foxtail, Kodo, proso, little, and barnyard varieties are nutrient-rich grains that contain high levels of fibre, slowly digestible starches, well-balanced proteins, essential minerals, and bioactive phenolics. Adding millets to chocolate products presents an opportunity to boost their nutritional value, lower glycaemic response, and support sustainability due to millets' resilience to climate change and minimal water requirements.

Methods

This review consolidates existing knowledge regarding the compositional and functional characteristics of millets that are pertinent to chocolate manufacturing. It explores methods for including millets in dark, milk, and compound chocolates while assessing their impacts on rheological behaviour, microstructural properties, polymorphic forms, shelf-life stability, sensory qualities, nutritional benefits, and regulatory factors.

Results

Research suggests that incorporating millet enhances the nutritional and functional characteristics of chocolates. However, notable formulation challenges remain, especially concerning particle size distribution, controlling water activity, and preserving a continuous fat phase. There are still research gaps in understanding long-term fat bloom behaviour, clinical validation of glycaemic effects, and the flavour impacts of roasted millets in cocoa matrices.

Conclusion

Millets hold significant promise as a functional ingredient for creating innovative chocolate products, delivering health and sustainability advantages. Future studies should concentrate on refining formulations and processing methods at both laboratory and pilot stages, while also addressing critical knowledge gaps to facilitate their effective commercial use.

Abstract
Keywords: Millets, Cocoa, Flow properties, Phenolic compounds, Grain size, Fat bloom phenomenon, Taste evaluation, Blood sugar index, Environmental impact, Entire grain.

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1. Introduction

Chocolate is commonly understood to be a complex fat-based dispersion system where sugar crystals and cocoa or cocoa-milk solids are finely suspended in a continuous fat phase mainly made up of cocoa butter, often with added milk fat. The unique texture, shine, and characteristic "snap" of high-quality chocolate result from the crystallization behaviour of cocoa butter, which must be tempered with precision to achieve the desired β(V) polymorphic form. This careful management of fat crystallization is crucial for maintaining the stability, mouthfeel, and attractiveness of chocolate products. In recent years, there has been an increasing focus on enhancing chocolate with whole grains to boost its nutritional content and attract health-conscious consumers. Traditionally, such enhancement approaches have utilized cereals like rice, wheat, or oats, typically introduced as inclusions (for example, puffed or crisped grains), flours, or particulate dispersions within the chocolate mix. These additions offer a variety of textures, nutritional benefits, and opportunities for product differentiation. Nevertheless, beyond conventional cereals, millets present a highly attractive option for enriching chocolate. Millets are small-seeded, drought-resistant grains that have historically been consumed in many regions of Africa and Asia, and they are currently receiving renewed global interest for their superior nutritional profile and environmental sustainability. Compared to refined cereals, millets are abundant in dietary fibre, micronutrients such as iron, calcium, and magnesium, as well as bioactive compounds that may offer health benefits. Their cultivation aids climate resilience and biodiversity, owing to their low input needs and adaptability to poor soils and semi-arid conditions. Consumer interest in "ancient grains" has surged recently, mirroring broader trends towards natural, minimally processed, and nutrient-rich foods. Despite this rising interest, systematically incorporating millets into chocolate has not been thoroughly investigated. Unlike straightforward inclusions, the integration of millet-based ingredients into chocolate requires careful attention, as factors such as particle size distribution, water-binding capacity, and fat interaction can significantly affect essential quality characteristics like tempering, gloss, viscosity, and melt-in-mouth performance. Striking a delicate balance between nutritional enhancement and maintaining the sensory and physicochemical qualities of chocolate poses a technical challenge that necessitates both scientific insight and innovative processing techniques. This paper, therefore, aims to assess the current understanding of formulation, processing, and quality considerations linked to the creation of millet-enriched chocolates. By exploring the science of fat crystallization, ingredient compatibility, and textural refinement, the paper seeks to provide systematic guidance for incorporating millet flours, crisps, or other derivatives into chocolate without compromising the industry quality standards characteristic of premium products. The review underscores opportunities, challenges, and prospects for advancing millet chocolates as a new category of functional, sustainable, and consumer-attractive confectionery items.

1.1 Millets: Classification and Nutritional Content

The main types of millets include pearl (Pennisetum glaucum), finger (Eleusine coracana), foxtail (Setaria italica), proso (Panicum millicum), Kodo (Paspalum Scrobiculatum), little (Panicum Sumatrense), and barnyard (Echinochloa spp.). Common characteristics consist of total dietary fibre ranging from 7% to 15% (which is higher in whole meal), resistant starch components, slowly digestible starch, and protein content of 7% to 14%, with a relatively higher level of lysine compared to other grains. They are also rich in minerals, particularly calcium in finger millet, and contain phenolic compounds like ferulic and caffeic acids, along with tannins found in certain varieties. The endogenous lipids, comprising 2% to 6%, are predominantly unsaturated, and the presence of lipase activity can affect the flavour during the roasting process.

1.2 What Makes Millets Great in Chocolate?

Millet-based ingredients offer distinct benefits in terms of nutrition, functionality, and sustainability, positioning them as an appealing choice for innovation in product development. From a nutritional standpoint, millet flours and extracts boast higher concentrations of dietary fibre and minerals when compared to refined sugars. When incorporated as a partial substitute for sucrose, millet has the potential to lower postprandial glycaemic responses, providing consumers with a healthier carbohydrate alternative. The combination of both soluble and insoluble fibres promotes satiety and supports digestive health, while the richness of micronutrients adds benefits beyond mere energy supply.

In terms of functionality, millet adds unique roasted Flavors, often referred to as nutty and malty, which complement cocoa-based products like chocolates, beverages, and baked goods. These flavour pairings can improve sensory appeal while minimizing the need for artificial additives. Moreover, the insoluble fibre content in millet affects particle arrangement within complex food structures, thereby altering rheological characteristics such as viscosity and yield stress. These properties can be utilized to enhance texture, mouthfeel, and stability in formulations without relying on synthetic stabilizers.

From an ecological perspective, millet presents considerable sustainability benefits. Its ability to withstand drought, shorter growth cycle, and lower resource requirements (such as fertilizers, pesticides, and water) render it more adaptable to shifting climate conditions than traditional cereals like rice and wheat. Additionally, encouraging the cultivation of millet helps diversify farming systems and offers farmers new income opportunities, thereby promoting agricultural sustainability and supporting rural economies. Ultimately, the incorporation of millet into food systems responds to consumer preferences for nutritious, functional, and environmentally conscious products.

2. Formats and strategies for incorporation

2.1 Formats

Millets can be processed into various ingredient types, each providing distinct functional and sensory attributes to food products. Finely milled whole-grain flours, ground to ≤20–25 µm (D90), can be blended with sugar and cocoa to create a smooth mouthfeel in chocolate or confectionery applications while preserving fibre and micronutrients. Puffed or crisped pieces (0.5–3 mm) act as crunchy additions in enrobed or moulded bars, enhancing textural variation and consumer attraction. Sprouted millet malts, extracts, or syrups offer natural sweetness, complex Flavors, and serve as partial sugar substitutes, imparting nutty or malty notes that complement cocoa. Pre-gelatinized flakes or microgranules aid in providing satiety and improving texture, making them suitable for use in bars, cereals, and beverages. Lastly, protein concentrates or fractions derived from millet play essential roles in aeration, especially in whipped or filled products, enhancing structure and mouthfeel. Collectively, these ingredient formats broaden the potential for nutritional, functional, and sensory advancements in millet-based product development.

2.2 Strategies for Incorporation

Millet can be integrated into chocolate formulations through various processing methods, each resulting in unique functional and sensory characteristics.

Route A (co-grinding) involves combining sugar, cocoa liquor, and millet flour, and then refining it to achieve a desired particle size distribution (PSD). The resulting mixture is then conched, after which fats and emulsifiers are incorporated before tempering and Molding. This method guarantees an even distribution of millet flour, which adds fibre and minerals while keeping a smooth mouthfeel. However, care must be taken to manage starch damage during refining to prevent viscosity problems.

Route B (post-refining addition) involves adding pre-milled millet flour (D90 ≤ 20 µm) during the later stages of conching. By avoiding thorough refining, this method reduces starch damage and better retains functional properties while still ensuring appropriate integration within the chocolate mixture. It may be necessary to adjust the emulsifier levels to uphold flow and stability.

Route C (inclusion) utilizes puffed or crisped millet particles, typically added at a rate of 5–15% to the tempered chocolate. To maintain their crunchiness, inclusions should have low water activity (aw ≤ 0.30) and might need oil barrier coatings to prevent fat migration or sogginess throughout their shelf life. This method enhances textural variety and visual appeal, catering to consumer preferences for multisensory experiences in chocolate.

2.3 Parameters for processing

To process chocolate containing millet, it is essential to carefully manage unit operations to maintain both quality and functionality.

Roasting millet grains or flours generally occurs at temperatures of 120–150 °C for 5–15 minutes. This process enhances nutty and malty Flavors through Maillard reactions, while also decreasing antinutritional components and inactivating lipase to prevent spoilage. Optimizing this step is important: overly prolonged roasting can lead to increased redness (a*) and bitterness, which negatively impacts flavour.

The refining stage subsequently lowers particle size, aiming for a distribution where D90 is at or below 25 µm, D50 is around 15–18 µm, and D10 is no less than 1–3 µm.

Meeting these specifications helps avoid a gritty texture while maintaining enough body for an appealing mouthfeel. Effective refining also guarantees that millet flour is uniformly integrated into the cocoa matrix.

Conching, performed at temperatures between 60–80 °C for 6–12 hours depending on the size of the batch, requires that residual moisture be kept below 0.6% while also minimizing volatile acidity. This process creates a smoother texture, rounds out flavour, and improves overall viscosity management.

The fat phase, along with emulsifiers, significantly influences flow properties. In dark chocolate, cocoa butter generally comprises 28–34%, or 26–32% when cocoa butter equivalents (CBEs) are utilized. Sunflower lecithin (300–500 ppm) or polyglycerol polyricinoleate (PGPR, 100–300 ppm) can be used to adjust the Casson plastic viscosity (ηC) and yield stress (τ0), facilitating efficient Molding and coating.

Lastly, tempering organizes fat crystals into the stable β(V) polymorph, which provides chocolate with its characteristic snap, shine, and resistance to bloom. Both seed point and continuous tempering methods are effective, with temper index values ideally ranging from 2.5 to 5.5. To verify the crystalline structure, measurements can be taken using thermometers, differential scanning calorimetry (DSC), or X-ray diffraction (XRD).

3. Design of formulations and limitations

3.1 Core formulations (standards)

Chocolate recipes can be modified to include millet while preserving appealing sensory and processing qualities.

dark chocolate containing (comprising 70% cocoa solids), a standard formulation consists of 40% cocoa liquor, 30% sugar, 30% cocoa butter, and 0.3% lecithin. In variations that incorporate millet, 5–15% of the sugar can be substituted with fine whole-grain millet flour. To maintain optimal flow properties, cocoa butter may need to be increased by 0.5–1.5%, and lecithin can be adjusted up to 0.5% to compensate for changes in viscosity. This replacement improves fibre and mineral levels while maintaining the texture.

In the formulation of milk chocolate, the typical recipe includes 12% cocoa liquor, 18% milk powder, 50% sugar, 20% cocoa butter, and 0.3% lecithin. Millet flour or sprouted-malt powder can replace 5–12% of sugar and/or milk solids, enhancing nutritional value while adding malty flavour nuances. However, this may increase yield stress ($\tau 0$), requiring the addition of polyglycerol polyricinoleate (PGPR) to ensure suitable flow and processing efficiency.

For compound coatings, where cocoa butter is partially substituted with cocoa butter equivalents (CBEs), special attention must be given when adding millet flour. The flour needs to be ground to a very fine particle size to prevent a gritty or waxy mouthfeel. When processed correctly, millet can enhance flavour, increase nutrition, and expand the variety of chocolate products available.

3.2 Water resource management

Millets provide bound water through their fibre and starch components, which can affect the processing of chocolate. To maintain texture and flow, it’s crucial to keep the total moisture content below 0.6% following conching. Excess moisture can lead to sugar bloom, increased viscosity, and inadequate tempering. If conventional conching fails to lower moisture sufficiently, vacuum conching can be utilized to speed up drying and the removal of volatiles. Although hygroscopic syrups serve as effective sweeteners, they should generally be avoided as they raise water activity and affect shelf stability—unless polyols are also used to mitigate aw. Thus, careful management of water is vital for ensuring stable millet-enriched chocolate.

3.3 Rheology objectives

Controlling rheology is essential when creating chocolate enhanced with millet. Based on the Casson model, optimal flow characteristics for Molding and tableting require a plastic viscosity ranging from 2.5 to 4.0 Pa·s and a yield stress ($\tau 0$) between 5 and 20 Pa. In enrobing scenarios, lower $\tau 0$ values (1–5 Pa) are favoured to facilitate uniform and efficient coating. The addition of millet flour brings in fibrous and irregularly shaped particles, which can increase $\tau 0$ by interfering with flow and particle arrangement. To mitigate this effect, formulators can modify the fat phase by slightly raising cocoa butter content, fine-tune emulsifier systems (such as lecithin and PGPR) to reduce interparticle friction, and carefully refine the particle size distribution (PSD) for a smoother texture and reliable processing performance.

3.4 Consistency and Growth

Fat bloom, a significant stability issue in chocolate, is caused by fat movement and transitions between different crystal forms. Various methods can be utilized to address this challenge in millet-enriched products. The most important method is proper tempering, which ensures the creation of the stable β(V) polymorph that imparts gloss, snap, and helps resist recrystallization. Furthermore, ensuring adequate fat coverage on particle surfaces prevents the formation of clusters of hydrophilic fines (like millet fibre or starch), which can draw in moisture and disturb the cocoa butter matrix, leading to potential bloom initiation.

The conditions under which chocolate is stored are also crucial. It should be maintained at a temperature of 16–18 °C with a relative humidity below 50% to prevent temperature variations and condensation, both of which can accelerate the blooming process. For products that include elements like puffed or crisped millet, applying barrier coatings (either fat- or sugar-based) can help reduce moisture absorption and limit fat migration from the chocolate into the inclusions.

Additional techniques to combat blooming include the addition of small amounts of milk fat, which interferes with the recrystallization of cocoa butter, or choosing compatible cocoa butter alternatives (CBEs) that have triglyceride compositions rich in POP (1,3-dipalmitoyl-2-oleoylglycerol) and Post (1-palmitoyl-3-stearoyl-2-oleoylglycerol) to align with cocoa butter behaviour. Small crystallization modifiers may also be utilized to enhance stability.

3.5 Balance and flourish

Fat bloom in chocolate is a frequent quality issue resulting from the movement of fat and unstable crystallization. It manifests as a white film on the surface, diminishing both the visual appeal and texture. To mitigate fat bloom caused by migration, several strategies are vital. First, ensuring proper tempering is essential to form the stable β(V) polymorph of cocoa butter, as this structure is less likely to convert into the unstable β(VI) polymorph that encourages bloom. Additionally, applying fat to the surfaces of particles during the refining and conching processes helps prevent the formation of clusters of hydrophilic fines, which otherwise serve as pathways for migrating fats. The conditions under which chocolate is stored are also critical: it should be kept at a temperature of 16–18 °C with a relative humidity of less than 50% to minimize condensation, recrystallization, and fat migration. For products that include add-ins like nuts or wafers, employing barrier layers—such as sugar or fat coatings—can help stop the migration of oils into the chocolate. Finally, methods to prevent bloom include adding small quantities of milk fat, which disrupts the crystal network of cocoa butter; using cocoa butter equivalents (CBEs) that have triacylglycerol profiles high in POP and Post for better compatibility with cocoa butter; or introducing minor crystallization modifiers to slow down fat diffusion. Collectively, these approaches can prolong shelf life and maintain the sensory quality of chocolate.

4. Characterization through analysis

4.1 Particle size distribution

Laser diffraction techniques, such as the Malvern Mesmerizer, are utilized to analyse particle size distribution in a medium that does not contain solvents and is compatible with cocoa butter, ensuring proper dispersion of cocoa solids. This approach yields important percentile values—D10, D50, and D90—that represent the fine, median, and coarse particle fractions, respectively. Of these values, D90 is particularly significant because it signifies the upper end of the distribution, which is directly associated with mouthfeel. Sensory evaluations reveal that chocolate starts to feel gritty when particles are larger than approximately 25–30 µm. Therefore, managing D90 to remain under this limit is essential for achieving a smooth texture, while D10 and D50 are instrumental in refining processing methods and ensuring quality consistency.

4.2 Rheology properties

Apparent viscosity can be assessed at 40 °C using a rotational rheometer fitted with either concentric cylinder or parallel plate configurations, which ensures that the shear conditions for chocolate or fat-based mixtures are representative. Flow curves are produced over a range of shear rates and are modelled with rheological equations such as Casson or Herschel–Bulkley to characterize shear-thinning behaviour. Yield stress, a vital factor that affects flow and mouthfeel, can be evaluated through a stress ramp or by determining the point where tangents intersect on the flow curve. These measurements offer valuable information on processing efficiency, pumpability, and sensory experience, aiding in the optimization of formulations and consistency in manufacturing.

4.3 Thermal properties and polymorphic forms

Differential Scanning Calorimetry (DSC) evaluates the thermal characteristics of cocoa butter and chocolate, including the temperatures at which melting begins and peaks. For well-tempered dark chocolate, the ideal β(V) polymorph exhibits a distinct peak in the range of 33–34 °C, which guarantees an appropriate snap, shine, and melting behaviour. Additionally, X-ray diffraction (XRD) complements this by confirming the crystalline structure and validating the presence of β(V) patterns. In storage studies, XRD can monitor the gradual transition from β(V) to the more stable β(VI) form, which is linked to fat bloom and degradation in quality. By using both DSC and XRD, a comprehensive method is established for assessing tempering quality, polymorphic stability, and the longevity of the product.

4.4 Microstructure

Confocal laser scanning microscopy or scanning electron microscopy (SEM) can be utilized to observe interactions between particles and fat, showcasing wetting performance and agglomeration behaviour within chocolate compositions. The evaluation of fat coverage can be accomplished through a blend of solvent extraction and image analysis, offering insights into the surface visibility of particles. Such measurements are essential for comprehending dispersion quality, refining processing parameters, and guaranteeing favourable texture, stability, and sensory qualities in final chocolate products.

4.5 Colour and shine

The CIELAB system (L*, a*, b*) can be used to assess colors and appearance under standard D65 lighting, yielding objective measurements of lightness, redness, and yellowness. A glossmeter calibrated to 60° measures surface sheen, which reflects the quality of tempering and visual attractiveness. Tracking changes in ΔL* over time allows for the observation of oxidative darkening or fat/sugar bloom, both of which can diminish consumer appeal. In combination, colorimetry and gloss evaluation offer complementary insights into the visual quality, storage longevity, and overall shelf-life performance of chocolate.

4.6 Moisture and Water Activity

Moisture content can be determined through oven drying or Karl Fischer titration for accurate measurements, whereas water activity (aw) is evaluated using an aw meter. The desired values are ≤0.30 for dry inclusions to avoid microbial growth and texture deterioration, and ≤0.40 for fillings to maintain stability and prolong shelf-life.

4.7 Nutritional components and bioactive substances

Proximate analysis reveals the fundamental composition of chocolate and its inclusions, including moisture, protein, fat, ash, and carbohydrates. The quantification of dietary fibre is carried out using official AOAC methods (991.43 or 2009.01) to evaluate its nutritional value. Mineral analysis is conducted with ICP-MS, allowing for accurate identification of essential elements such as calcium, iron, zinc, and magnesium. The content of polyphenols is assessed through the Folin–Ciocalteu assay, while antioxidant capacity is measured using DPPH, ABTS, or ORAC methodologies. In-vitro starch digestibility assessments are performed according to established static digestion protocols, permitting the calculation of both rapidly and slowly digestible fractions. Based on this information, the predicted glycaemic index is calculated, offering important insights into the metabolic effects, functionality, and potential health advantages of chocolate-based products.

4.8 Shelf-life

Accelerated storage experiments are carried out at 25 °C/50% RH and 30 °C/65% RH for periods of 6 to 12 weeks to evaluate the stability of chocolate. The development of bloom is tracked by assessing ΔL* color variations, which are further verified through microscopy. The levels of oxidative rancidity are measured using peroxide value (PV) and p-anisidine tests. Changes in texture are analysed through a three-point bend test to determine hardness and brittleness. Additional sensory evaluations offer insights into how consumers perceive alterations in flavour, texture, and appearance, aiding in the prediction of shelf-life and overall product quality.

5. Sensory Evaluation

A two-phase sensory evaluation method is suggested to encompass both expert analysis and consumer feedback. In the initial phase, trained panellists perform a descriptive analysis, identifying critical sensory traits related to flavour (cocoa richness, roasted millet, malt, bitterness, astringency), texture (smoothness, grittiness, snap, melt rate), and appearance (gloss, bloom). This creates a comprehensive sensory profile for each product. In the second phase, consumer acceptance testing is conducted with a minimum of 100 participants, utilizing a 9-point hedonic scale to assess overall liking and Just-About-Right (JAR) scales to evaluate sweetness and crunchiness, which are especially significant for products containing inclusions. Additionally, purchase intent is recorded to connect sensory perceptions with market significance. The samples are presented using a Williams design to reduce order and carryover effects. Statistical evaluations include mixed-effects ANOVA, where product is treated as a fixed factor and subject as a random factor, followed by Tukey's HSD for pairwise comparisons. Penalty analysis is used on the JAR data to pinpoint sensory factors that are either too low or too high, adversely impacting overall liking. Ultimately, descriptive attributes are correlated with consumer liking scores through partial least squares (PLS) regression, helping to identify essential drivers of preference. This comprehensive methodology offers practical insights for optimizing formulations, ensuring quality control, and developing consumer-focused products.

6. Safety and compliance factors

When creating chocolate products that include millet, it is crucial to consider various regulatory and nutritional factors to ensure compliance and maintain consumer trust.

Most types of millet are naturally gluten-free, making them ideal for those with gluten sensitivities and individuals with celiac disease. Nevertheless, it is vital to prevent cross-contamination in facilities that also handle wheat, barley, or rye. For items labelled as "gluten-free," testing must confirm gluten levels are below 20 ppm, following Codex guidelines and local regulations.

Ingredients must be clearly disclosed, using phrases like "whole-grain millet flour" or naming the specific type of millet to facilitate effective communication. In India, products should adhere to the Food Safety and Standards Authority of India (FSSAI) regulations regarding chocolate identity, which includes requirements for minimum cocoa solids. In other regions, such as the EU or US, it is important to differentiate between products that can officially be termed "chocolate" and those that are required to be labelled as "compound chocolate" or "chocolatey" if they include cocoa butter substitutes (CBEs) or other vegetable fats.

Millets contain antinutrients like phytates and tannins, which can hinder mineral absorption. This issue may be alleviated through processing methods such as malting, sprouting, fermentation, or using enzymatic treatments with phytase.

Nutritional claims such as "source of fiber," "source of iron," or "source of calcium" need to be validated with analytical evidence and must comply with local regulatory standards. Adhering to both compositional guidelines and allowable nutrient content claims enhances product credibility and reinforces its image as a functional, health-focused indulgence.

7. Sustainability and the supply chain

Millets are identified as grains that can withstand climate fluctuations due to their minimal water needs, brief growth cycle, and adaptability to less fertile and drought-affected areas. Incorporating them into food systems not only promotes climate-smart agricultural practices but also enhances the resilience of livelihoods when sourced through networks of smallholder farmers, especially in semi-arid zones. The addition of millet to chocolate recipes presents an opportunity to diversify supply chains while bolstering the sustainability profile of the product. To maximize effectiveness, it is essential to pair millet integration with certified sources of cocoa, such as those recognized by Rainforest Alliance or Fairtrade, ensuring ethical lab or practices, protection of biodiversity, and adherence to sustainability standards at the farm level. Clear mapping of supply chains improves traceability, enabling consumers and stakeholders to confirm responsible sourcing practices. Furthermore, performing a life cycle assessment (LCA) is vital for measuring the environmental advantages. Specifically, substituting refined sugar with whole-grain millet components can help decrease greenhouse gas (GHG) emissions and reduce water usage while also enhancing nutritional quality. In combination, these approaches align sustainable ingredient selections with tangible environmental results, positioning millet-based chocolate as both eco-friendly and socially responsible.

8. Suggested experimental strategy (laboratory–pilot scale)

8.1 purpose

This research seeks to assess how the integration of millet affects the quality and functionality of chocolate. Initially, the study will explore the effects of different levels of millet flour (0, 5, 10, 15%) in both dark and milk chocolates, concentrating on their rheological properties, tempering behaviours, and sensory characteristics. Next, a comparison will be made between two different forms of inclusion—flour and puffed millet crisps—to evaluate their impact on texture, microstructure, and bloom formation during storage. Lastly, the nutritional benefits will be measured through compositional analysis, and in-vitro starch digestibility tests will be conducted to estimate the glycemic response, offering insights into the health advantages of millet-infused chocolate formulations.

8.2 Research methodology

The research will assess the incorporation of millet into chocolate by examining four primary factors: the percentage of millet (0, 5, 10, 15%), the variety of millet (finger, pearl, foxtail), the type of chocolate (dark 60%, milk 35%), and the format (flour versus crisp). A fractional factorial design will first analyze these variables, followed by response surface methodology (RSM) utilizing a central composite design to fine-tune the significant factors. Important responses include Casson viscosity (ηC), yield stress ($\tau 0$), particle size (D90), $\beta(V)$ polymorph index, and color change (ΔE^*). Other outcomes will include sensory preference, dietary fiber content, mineral enrichment (Fe, Ca), and estimated glycemic index, aiding in the optimization of the formulation.

8.3 Method

Millet processing starts with roasting at 135 °C for 10 minutes, followed by milling with a pin mill and classification to achieve a particle size distribution with D90 $\leq$ 25 µm. The flour is ground together with sugar and cocoa liquor to obtain the desired chocolate particle size. Conching is conducted at 70 °C for 8 hours, with lecithin (0.4%) and polyglycerol polyricinoleate (PGPR) added as necessary to enhance flow properties. The chocolate is tempered using the seed method, then shaped into 5 g thins and 100 g bars. Samples are stored at 18 °C for 7 days before undergoing analytical, structural, and sensory assessments.

8.4 Data analysis

The data analysis will utilize ANOVA with batch blocking to address production variability, followed by Tukey's HSD for subsequent pairwise comparisons. The rheological data will be modelled using the Casson and Herschel–Bulkley equations, and multi-response optimization will adopt a desirability method: minimizing viscosity, aiming to keep yield stress within acceptable limits, and enhancing sensory preference. A power analysis ($\alpha = 0.05$, power = 0.8) suggests that around 30–50 consumers per product will suffice for initial screening studies, whereas confirmatory validation should include at least 100 consumers to guarantee strong statistical confidence and the generalizability of sensory acceptance results.

9. Expected outcomes and analysis

We expect that replacing up to approximately 10% of the flour with millet flour can result in acceptable viscosity and mouthfeel when the D90 is less than or equal to 25 μm and the fat content is modified by about 1%. Exceeding this replacement may lead to a significant increase in τ_0 due to fiber-driven bridging flocculation, which may require the addition of PGPR or extra cocoa butter. Roasting is likely to enhance nutty and malty flavors that complement cocoa; however, varieties high in tannins might increase astringency, which could necessitate partial decortication or the use of milk chocolate bases. The addition of puffed millets can provide a pleasant crunch and enhance perceived health benefits, but also raises the risk of bloom without the use of oil barriers. From a nutritional standpoint, these formulations can increase dietary fiber content by 2–4 g per 100 g and provide minerals (especially calcium from finger millet) with a minimal effect on energy density. The anticipated glycemic index is projected to be lower than that of sucrose-matched controls due to the presence of slowly digestible starch and fiber, though this requires clinical testing for confirmation.

10. Constraints and areas needing further investigation

Future investigations should focus on the long-term kinetics of bloom formation in chocolate matrices enriched with millet, considering realistic storage and distribution scenarios to more accurately assess shelf-life stability. Another critical area of research involves exploring the interactions between phenolics derived from millet and cocoa polyphenols, particularly in terms of their possible synergistic effects on antioxidant properties and their impact on flavour perception. Research involving human subjects is necessary to confirm in vitro results, especially concerning the glycemic response and satiety advantages linked to the inclusion of millet. Lastly, trials aimed at scaling up the processes of continuous conching and tempering should be conducted, emphasizing how increased fiber content affects rheology, processability, and the quality of the finished product in industrial production settings.

11. Conclusion

Millets represent a valuable avenue for creating chocolate products that blend greater nutrition with enhanced sustainability, while maintaining the essential qualities that consumers associate with chocolate. Their inherent gluten-free nature, significant fiber content, and wealth of minerals render them effective functional ingredients. Nevertheless, their successful incorporation relies on meticulous particle size manipulation to eliminate grittiness, strict moisture management to mitigate microbial risks, and careful control of rheological properties to ensure processability and a desirable mouthfeel. It is essential to optimize roasting parameters to reveal attractive cereal and nut-like flavor characteristics while reducing any bitterness and astringency. The outlined methodological framework—which includes particle size assessment, rheological evaluation, thermal and structural analysis, nutritional assessment, and sensory testing—offers a thorough guide for research and development. Collectively, these strategies arm product developers, academic researchers, and industry collaborators with the resources needed to create millet-based chocolates that meet consumer desires for indulgence, health, and sustainability, ultimately expanding the horizons for innovation in functional confectionery.

Acknowledgment

The author sincerely appreciates the support and resources offered by Kamdhenu University, which were crucial for the successful completion of this research. Access to laboratory facilities, technical support, and analytical equipment played a crucial role in conducting the experimental work, gathering data, and analyzing the results, thereby significantly enhancing the quality and accuracy of the presented findings.

Author Contributor

Conceptualization was conducted by Pavan Prajapati; the methodology was developed by Krunal Meghwal; the original draft was prepared by Pavan Prajapati; revisions and editing were undertaken by Krunal Meghwal, Sangam Prajapati, and Parthiv Prajapati; and supervision was provided by Pavan Prajapati. Every author has reviewed and consented to the final version of the manuscript. The team's collaborative efforts guaranteed that the research presented in this publication is accurate, clear, and maintains its integrity.

Funding

This research received no external funding

Institutional Review Board statement

Not applicable

Informed Consent Statement

Not applicable

Ethical approval

This article does not include any research involving human subjects or animals conducted by any of the authors.

Conflict of Interest

no conflict of interest.

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