



ISSN Print: 2664-844X
ISSN Online: 2664-8458
NAAS Rating (2026): 4.97
IJAFS 2026; 8(3): 348-360
www.agriculturaljournals.com
Received: 07-01-2026
Accepted: 09-02-2026

Aditi Sharma

Department of Post-Harvest
Process and Food Engineering,
College of Technology Govind
Ballabh Pant University of
Agriculture and Technology,
Pantnagar, Udham Singh
Nagar, Uttarakhand, India

Sachin Kumar

Department of Post-Harvest
Process and Food Engineering,
College of Technology Govind
Ballabh Pant University of
Agriculture and Technology,
Pantnagar, Udham Singh
Nagar, Uttarakhand, India

Mohd Abbas

Department of Post-Harvest
Process and Food Engineering,
College of Technology Govind
Ballabh Pant University of
Agriculture and Technology,
Pantnagar, Udham Singh
Nagar, Uttarakhand, India

Aman Pal

Department of Post-Harvest
Process and Food Engineering,
College of Technology Govind
Ballabh Pant University of
Agriculture and Technology,
Pantnagar, Udham Singh
Nagar, Uttarakhand, India

Shivani Jangde

Department of Post-Harvest
Process and Food Engineering,
College of Technology Govind
Ballabh Pant University of
Agriculture and Technology,
Pantnagar, Udham Singh
Nagar, Uttarakhand, India

Corresponding Author:

Aditi Sharma

Department of Post-Harvest
Process and Food Engineering,
College of Technology Govind
Ballabh Pant University of
Agriculture and Technology,
Pantnagar, Udham Singh
Nagar, Uttarakhand, India

Advances in the development of functional, heat-stable cocoa confectionery chocolate bar fortified with millet-derived nutrients and natural sweeteners: A comprehensive review

Aditi Sharma, Sachin Kumar, Mohd Abbas, Aman Pal and Shivani Jangde

DOI: <https://www.doi.org/10.33545/2664844X.2026.v8.i3e.1267>

Abstract

Chocolate's distinct sensory qualities and bioactive makeup make it one of the most popular confections consumed globally. However, traditional chocolate formulations have drawbacks like high refined sugar content and poor thermal stability, which limit their applicability to warm climates and health-conscious consumers. The creation of functional and heat-stable cocoa confections through ingredient modification and process optimization has garnered more research attention in recent years. Millets have become a promising ingredient for fortifying chocolate products because of their rich nutritional profile, ability to withstand climate change, and functional qualities. Similarly, because of their mineral content and practical benefits, natural sweeteners like jaggery have become more popular as substitutes for refined sugar. The development of heat-stable cocoa confections enhanced with natural sweeteners and nutrients derived from millet is thoroughly examined in this review. The review covers the mechanisms behind heat sensitivity, cocoa butter polymorphism, and the structural and thermal properties of chocolate. The importance of conching, tempering, particle size distribution, and demoulding conditions in enhancing heat resistance and product quality is emphasized. In the context of chocolate fortification, a critical analysis is conducted of the nutritional makeup, processing, and functional characteristics of millets, specifically finger millet. Additionally reviewed is the impact of natural sweeteners like jaggery on product functionality, antioxidant potential, and nutritional quality. These ingredients' effects on rheological behavior, melting properties, sensory quality, and shelf-life stability are also covered. In order to support the development of heat-stable, nutritionally enhanced cocoa confections that are appropriate for tropical climates and changing consumer demands, important research challenges and future directions are finally described.

Keywords: Functional chocolate, millets, jaggery, heat-stable confectionery, fiber enrichment, cocoa butter crystallization

1. Introduction

The main ingredients of chocolate, a complex confection, are sugar, cocoa butter, cocoa solids, and, in certain forms, milk solids. Its unique flavor, silky texture, and appealing melting

behavior all of which are primarily controlled by the physicochemical characteristics of cocoa butter are the reasons for its enormous appeal. Bioactive substances like flavanols and polyphenols, which have been linked to antioxidant activity and possible health advantages, are also abundant in cocoa (Araujo *et al.*, 2020) [3].

Despite these benefits, traditional chocolate products have built-in drawbacks, especially their high refined sugar content and poor thermal stability. Because cocoa butter melts at temperatures close to body temperature, usually between 30 and 34 °C, chocolate exposed to high ambient temperatures during storage and transit, particularly in tropical and subtropical areas, will soften, deform, and absorb fat (Beckett, 2008; Afoakwa, 2016) [4, 1]. Research into the creation of heat-stable chocolate systems has been prompted by these thermal issues, which present serious barriers to marketing and distribution in warm climates. Confectionery items with better nutritional value and less dependence on refined sugars are in greater demand because of consumers' growing knowledge of diet-related health problems.

The high glycemic load and calorie density of traditional chocolate formulations have sparked interest in functional additives that can improve nutritional value without sacrificing sensory pleasure. Because of their high dietary fiber content, mineral richness, and bioactive chemical content, millets have garnered a lot of attention in this area (Saleh *et al.*, 2013) ^[13]. Because of its high calcium content, antioxidant activity, and slowly digested starch, finger millet (*Eleusine coracana*) stands out among other millets and can be used to make functional food items (Shobana and Malleshi, 2007; Kumar *et al.*, 2016) ^[9, 14].

To improve nutritional quality and simultaneously affect the microstructure and thermal behavior of chocolate, the use of millet-derived compounds in chocolate formulations has been investigated. By increasing solid content and limiting fat mobility, millet flour and its derivatives can serve as structural fillers and perhaps increase heat stability (Taylor and Emmambux, 2008) ^[16]. Additionally, using natural sweeteners like jaggery instead of refined sucrose has been suggested. Jaggery has been shown to have antioxidant properties and functional benefits in food systems, while also retaining minerals and phenolic compounds from sugarcane juice (Rao and Singh, 2022) ^[12]. Chocolate's stability and quality are also greatly influenced by its processing conditions. Rheological behavior, melting properties, and sensory qualities are strongly influenced by particle size distribution, conching time, tempering settings, and demoulding procedures (Afoakwa *et al.*, 2009; Prawira and Barringer, 2009; Keijbets *et al.*, 2010) ^[1, 2, 11]. In composite chocolate systems that comprise unconventional ingredients like millet and natural sweeteners, it is even more important to optimize these parameters.

Thus, this review's goal is to critically assess current developments in the creation of functional, heat-stable cocoa confections enhanced with natural sweeteners and nutrients obtained from millet. In order to provide a thorough scientific foundation for upcoming research and product development in this field, the review summarizes the body of literature on millet nutrition and functionality, processing technologies, chocolate structure and thermal behavior, and the function of natural sweeteners.

2. Structure and thermal behaviour of chocolate

2.1 Chocolate as a multiphase food system

Chocolate is categorized as a complex multiphase food system, with solid ingredients like milk solids (in milk chocolate), sugar crystals, and cocoa solids scattered over a continuous fat phase made mostly of cocoa butter. The final product's mechanical strength, flow characteristics, melting properties, and thermal stability are determined by the distribution, interaction, and stabilization of these phases

(Beckett, 2008; Afoakwa, 2016) ^[1, 4].

To prevent grittiness and guarantee a smooth mouthfeel, the solid particles in chocolate are usually reduced to sizes below 25 to 30 μm during refining. To create a stable dispersion and lessen interparticle friction, cocoa butter must be evenly applied to these particles. Excessive viscosity, poor molding behavior, and heightened vulnerability to heat-induced deformation result from any imbalance between solid loading and fat content (Afoakwa *et al.*, 2009) ^[2].

2.2 Role of cocoa butter in structural integrity

In chocolate, cocoa butter serves as a structural component as well as a continuous phase. It is in charge of holding solid particles together and, when cooled, creating a crystalline network. The crystalline structure, distribution of crystal sizes, and connection of fat crystals all affect this network's mechanical strength (Afoakwa, 2016) ^[1].

The main ingredient in chocolate, cocoa butter, gives it favorable sensory qualities including snap at room temperature and quick melting in the tongue since it melts near body temperature. But because of this similar characteristic, chocolate is susceptible to heat stress, particularly when outside temperatures rise above 30 °C (Beckett, 2008) ^[4].

2.3 Cocoa butter polymorphism and its structural consequences

Polymorphism is the ability of cocoa butter to crystallize into different shapes based on temperature history, shear, and cooling conditions. According to Afoakwa (2016) ^[1], these polymorphs vary in stability, melting temperature, and molecular packing, all of which have an impact on the quality of chocolate.

The βV polymorphism form is said to be the best as, when stored properly, it offers the best gloss, firmness, and bloom resistance. Conversely, fat bloom and surface browning result from the conversion of βV into the more stable βVI form during storage (Talbot, 2011) ^[15].

2.4 Thermal sensitivity and deformation mechanisms

When the outside temperature gets close to or above the melting point of cocoa butter crystals, chocolate becomes thermally sensitive. The crystalline network is weakened by partial melting of fat crystals, which results in increased surface oiling, decreased snap, and form loss. Bloom growth may be accelerated by recrystallization in less desired polymorphic forms upon cooling (Afoakwa, 2016) ^[1].

Frequent temperature changes, especially in poorly tempered chocolates, intensify these effects by encouraging fat migration and polymorphic metamorphosis. Thus, preserving structural integrity throughout processing, storage, and distribution requires regulating temperature exposure (Beckett, 2008) ^[4].

Table 1: Cocoa butter polymorphs and their relevance to chocolate stability

Polymorph	Melting range (°C)	Stability	Effect on chocolate	Source
γ / α	16-23	Very unstable	Soft, poor structure	Beckett (2008) ^[4]
β' forms	23-28	Metastable	Intermediate quality	Afoakwa (2016) ^[1]
βV	32-34	Stable	Desired commercial form	Talbot (2011) ^[15]
βVI	34-36	Very stable	Fat bloom formation	Afoakwa (2016) ^[1]

Source: Beckett (2008) ^[4]; Afoakwa (2016) ^[1]; Talbot (2011) ^[15]

2.5 Effect of particle size distribution on thermal behaviour

The distribution of particle sizes affects chocolate's temperature responsiveness and rheological behavior.

Efficient fat coating and consistent stress distribution throughout the chocolate matrix are guaranteed by a restricted particle size distribution. While excessively tiny particles impact stability by increasing surface area and fat demand,

excessively big particles disturb the fat network (Afoakwa *et al.*, 2009) ^[1].

The significance of refining in the production of heat-stable chocolate was highlighted by Afoakwa *et al.* (2009) ^[2], who showed that chocolates with an optimized particle size distribution showed better melting uniformity and resistance to structural collapse under thermal stress.

2.6 Influence of processing operations on structure

Conching, tempering, cooling, and demoulding are processing procedures that have a direct impact on the structure and thermal behavior of chocolate. According to Prawira and Barringer (2009) ^[11], conching improves viscosity and structural coherence by enhancing particle-fat interactions and reducing moisture. Controlled crystallization into the βV polymorphic form is ensured by proper tempering, which improves resistance to thermal deformation and bloom (Talbot, 2011) ^[15]. Surface quality and internal stress distribution are also influenced by the circumstances of the demolded product. According to Keijbets *et al.* (2010) ^[8], chocolate contraction behavior and surface flaws are greatly influenced by chilling pace and mold temperature.

2.7 Process flow affecting structural stability

Structure and thermal stability are influenced by the phases of chocolate preparation.

the stages of chocolate processing that affect its structure and thermal stability

crucial phases include roasting, grinding, refining, conching, tempering, molding, cooling, demolding, and packaging.

- Refinement: control of particle size
- Conching: moisture extraction and fat coating
- Polymorphism of cocoa butter due to temperature
- Surface integrity through cooling and demolding

Source: Beckett (2008) ^[4]; Afoakwa (2016) ^[1]; Prawira and

Barringer (2009) ^[11]; Keijbets *et al.* (2010) ^[8]

2.8 Relevance of structural understanding for heat-stable chocolate

Designing heat-stable formulations requires a thorough understanding of chocolate structure and thermal behavior; changes to ingredient composition, processing parameters, and solid-fat interactions must be informed by knowledge of cocoa butter crystallization and microstructural stability to prevent sacrificing sensory quality (Afoakwa, 2016) ^[2].

3. Cocoa butter polymorphism, fat bloom and heat stability

3.1 Polymorphism of cocoa butter: molecular basis

Symmetrical triglycerides, specifically 1,3-dipalmitoyl-2-oleoyl-glycerol (POP), 1-palmitoyl-2-oleoyl-3-stearoyl-glycerol (POS), and 1,3-distearoyl-2-oleoyl-glycerol (SOS), make up the majority of cocoa butter. The crystalline structure and polymorphic shape that are adopted during solidification are determined by the molecular packing and arrangement of these triglycerides (Beckett, 2008; Afoakwa, 2016) ^[1, 4].

The ability of cocoa butter to crystallize into several solid forms with distinct melting temperatures, thermodynamic stability, and crystal lattices is known as polymorphism. When making chocolate, the following factors affect these polymorphic transitions: cooling pace, shear history, thermal cycling, and tempering conditions (Talbot, 2011) ^[15]. The resistance to melting and vulnerability to transformation during storage vary throughout polymorphs.

3.2 Classification of cocoa butter polymorphs

According to their melting temperature and increasing order of stability, cocoa butter polymorphs are often divided into six forms (Forms I-VI). The texture, appearance, and thermal resistance of chocolate are directly impacted by the development of these polymorphs (Beckett, 2008; Afoakwa, 2016) ^[1, 4].

Table 2: Cocoa butter polymorphs and their implications for heat stability

Polymorphic form	Crystal form	Melting range (°C)	Relative stability	Effect on chocolate quality	Source
Form I	γ	~16-18	Very unstable	Soft, dull surface	Beckett (2008) ^[4]
Form II	α	~17-23	Unstable	Poor snap, rapid transformation	Beckett (2008) ^[4]
Form III	$\beta'2$	~23-25	Metastable	Moderate firmness	Afoakwa (2016) ^[1]
Form IV	$\beta'1$	~25-28	Metastable	Improved texture, still unstable	Afoakwa (2016) ^[1]
Form V	βV	~32-34	Stable	Glossy, firm, desired	Talbot (2011) ^[15]
Form VI	βVI	~34-36	Most stable	Fat bloom formation	Afoakwa (2016) ^[1]

Source: Beckett (2008) ^[4]; Afoakwa (2016) ^[1]; Talbot (2011) ^[15]

Form V (βV) is the preferred polymorphic form for commercial chocolate because it strikes a balance between quick melting at body temperature and structural integrity. However, fat bloom may result from βV crystals changing into the more stable βVI form due to heat stress or extended storage (Afoakwa, 2016) ^[1].

3.3 Mechanism of fat bloom formation

A whitish or greyish covering on the surface is a sign of fat bloom, one of the most prevalent quality flaws in chocolate. Although there is no safety risk, it greatly lowers consumer acceptability. Polymorphic transformation and fat migratory processes are the main causes of fat bloom (Beckett, 2008) ^[4]. Partially melting cocoa butter crystals and then recrystallizing them into bigger, more stable crystals (βVI) on the surface is the predominant mechanism. By encouraging multiple

melting and recrystallization cycles, which improve lipid mobility within the chocolate matrix, temperature changes quicken this process (Afoakwa, 2016) ^[1].

3.4 Influence of temperature and thermal cycling

One important factor affecting the growth of fat blooms is storage temperature. Particularly vulnerable to polymorphic transition are chocolates kept at temperatures around or above the melting point of βV crystals. Thermal cycling improves crystal rearrangement and boosts molecular mobility, even within a limited temperature range (Beckett, 2008) ^[4].

According to Afoakwa (2016) ^[16], compared to storage at a constant temperature, exposure to temperature fluctuations dramatically accelerates the production of fat blooms. This research emphasizes how crucial thermal control is for

distribution and storage, especially in hotter climates where it might be difficult to maintain a cold chain.

3.5 Role of processing conditions in polymorphic stability

3.5.1 Tempering

The technique of tempering involves carefully heating, chilling, and reheating chocolate in order to create stable βV crystals. According to Talbot (2011) ^[15], proper tempering minimizes the possibility of polymorphic transformation during storage and guarantees a homogeneous distribution of crystal sizes.

Under thermal stress, unstable crystal formations that are the product of improper tempering act as nuclei for polymorphic transition and bloom generation (Beckett, 2008) ^[4].

3.5.2 Conching and its indirect effect on bloom

Conching affects fat distribution, moisture removal, and particle-fat interactions, all of which have an indirect impact on crystal stability even though it does not directly govern polymorphism. Conching time affects smoothness and sensory preference, which are linked to better fat phase continuity and particle coating, as Prawira and Barringer (2009) ^[11] showed. Improved fat coating limits fat migratory pathways that lead to bloom formation by lowering localized gradients in fat content (Prawira and Barringer, 2009) ^[11].

3.5.3 Cooling and Demoulding

After molding, cooling rate affects internal stress distribution and crystal size. While gradual cooling encourages greater crystal growth, rapid cooling may trap unstable crystals, both of which might affect bloom development. According to Keijbets *et al.* (2010) ^[8], chocolate's surface quality and contraction behavior both of which are correlated with interior crystal structure are greatly impacted by the conditions during the demoulding process.

3.6 Relationship between polymorphism and heat stability

The stability of chocolate's fat crystal network is directly correlated with its heat stability. Under mild heat exposure, chocolates dominated by βV crystals show greater resistance to softening and deformation. On the other hand, chocolates that contain large quantities of unstable polymorphs are more likely to bloom and soften quickly (Afoakwa, 2016) ^[1].

To delay polymorphic transition and structural collapse at high temperatures, strategies to increase heat stability frequently concentrate on limiting fat mobility and increasing the stiffness of the crystalline network (Beckett, 2008) ^[4].

3.7 Implications for development of heat-stable chocolate

Designing heat-stable chocolate systems requires an understanding of bloom mechanisms and cocoa butter polymorphism. Important tactics to improve heat resistance include regulating tempering, reducing temperature swings,

and maximizing fat-solid interactions. These ideas serve as the scientific foundation for adding functional additives such as natural sweeteners and millets, which, when prepared correctly, may further reduce fat mobility and enhance heat stability (Afoakwa, 2016; Beckett, 2008) ^[1, 4].

4. Processing parameters affecting heat stability of chocolate

4.1 Importance of processing conditions in chocolate stability

The production process has a significant impact on the overall quality and heat stability of chocolate, and formulation alone does not determine these factors. The microstructure, fat crystallization behavior, and distribution of solid particles within the cocoa butter matrix are all impacted by the several unit operations of refining, conching, tempering, cooling, and demoulding (Beckett, 2008; Afoakwa, 2016) ^[1, 4]. Rheology, melting properties, bloom susceptibility, and resistance to thermal deformation can all differ significantly depending on the processing parameters used.

When functional ingredients like natural sweeteners or cereal flours are added, processing becomes even more important since these chemicals change the interactions between particles and fats and may have an impact on the formation of crystal networks and fat mobility. Thus, the creation of heat-stable chocolate systems requires an understanding of the impact of different processing steps (Afoakwa *et al.*, 2009) ^[2].

4.2 Refining and particle size reduction

4.2.1 Role of refining in chocolate manufacture

To guarantee smooth texture and even dispersion within the fat phase, sugar crystals, cocoa solids, and other solid components undergo a mechanical size-reduction procedure called refining. To prevent grittiness and enhance mouthfeel, refining usually lowers particle size to less than 25-30 μm (Beckett, 2008) ^[4].

The amount of cocoa butter needed to sufficiently coat solid particles depends on the particle size distribution created during refining. While too much fat may weaken the crystalline network and decrease heat resistance, too little coating increases interparticle friction, leading to high viscosity and poor flow behavior (Afoakwa *et al.*, 2009) ^[2].

4.2.2 Effect of particle size distribution on heat stability

Chocolates with an ideal particle size distribution showed better rheological characteristics and more consistent melting behavior, as shown by Afoakwa *et al.* (2009) ^[2]. The development of a continuous fat crystal network that is resistant to deformation under mild heat stress is encouraged by fine and narrow particle size distributions, which also improve packing efficiency. On the other hand, wide particle size distributions could result in localized weak spots in the structure and an uneven distribution of fat, which could cause melting and deformation at high temperatures (Afoakwa *et al.*, 2009) ^[2].

Table 3: Influence of particle size distribution on chocolate properties

Particle size characteristic	Effect on rheology	Effect on melting & heat stability	Source
Coarse particles (>30 μm)	Grittiness, uneven flow	Weak structure, early deformation	Afoakwa <i>et al.</i> (2009) ^[2]
Optimal range (20-25 μm)	Smooth flow, balanced viscosity	Uniform melting, better stability	Afoakwa <i>et al.</i> (2009) ^[2]
Excessively fine (<15 μm)	High viscosity	Increased fat demand, possible instability	Beckett (2008) ^[4]

Source: Beckett (2008) ^[4]; Afoakwa *et al.* (2009) ^[2]

4.3 Conching and its influence on heat stability

4.3.1 Purpose and mechanism of conching

Conching, a high-temperature mixing and shearing procedure, is essential to chocolate's particle-fat interaction, moisture removal, and flavor creation. Cocoa butter distributes across solid particles during conching, enhancing flow characteristics and lowering friction (Beckett, 2008) ^[4].

According to Prawira and Barringer (2009) ^[11], conching time has a major impact on sensory qualities including flavor and smoothness, which are signs of better particle coating and structural homogeneity.

4.3.2 Effect of conching time on chocolate properties

Improved viscosity and texture are the results of prolonged conching, which also improves the fat coating of particles and lowers moisture content and volatile acids. Overly lengthy conching, however, can lead to overprocessing, the loss of favorable volatile chemicals, and modifications in the

distribution of fat that may affect thermal behavior (Prawira and Barringer, 2009) ^[11].

Medina-Mendoza *et al.* (2025) ^[10] also showed that conching time affects chocolate's microstructural development and antioxidant qualities, emphasizing the necessity of ideal processing conditions when adding functional additives.

4.4 Tempering and controlled crystallization

4.4.1 Role of tempering in heat stability

A regulated heat treatment called tempering is used to encourage the development of stable βV cocoa butter crystals. Heat stability is directly linked to gloss, snap, and resistance to fat bloom, all of which are enhanced by proper tempering (Talbot, 2011) ^[15].

Unstable polymorphs that melt readily and change during storage due to improper tempering increase vulnerability to thermal deformation (Afoakwa, 2016) ^[1].

Table 4: Effect of conching time on chocolate quality attributes

Conching time	Observed effects on chocolate	Source
Short	Incomplete fat coating, higher viscosity	Prawira & Barringer (2009) ^[11]
Optimal	Improved smoothness, balanced flavour	Prawira & Barringer (2009) ^[11]
Extended	Enhanced antioxidant attributes (with additives)	Prawira & Barringer (2009) ^[11]

Source: Prawira and Barringer (2009) ^[10]; Medina-Mendoza *et al.* (2025) ^[11]

4.4.2 Influence of tempering conditions

Heating to dissolve preexisting crystals, freezing to cause crystal nucleation, and reheating to get rid of unstable forms are the steps in the tempering process. The distribution of crystal sizes and the strength of the network are determined by the temperature profile and shear used during tempering (Beckett, 2008) ^[4].

βV -dominated chocolates are more resistant to softening and retain their structural integrity at higher temperatures than chocolates with poor tempering (Talbot, 2011) ^[15].

4.5 Cooling and demoulding conditions

4.5.1 Cooling rate and structural integrity

The rate at which crystals grow, and internal stress develops in chocolate is determined by cooling after molding. Heat stability can be impacted by both extremely slow cooling, which can encourage the production of massive crystals, and rapid cooling, which can trap unstable crystal formations (Beckett, 2008).

4.5.2 Demoulding effects

According to Keijbets *et al.* (2010) ^[8], the conditions of the demolded chocolate affect its structural homogeneity, surface quality, and contraction behavior. Surface flaws, which are frequently linked to inadequate heat resistance, are decreased and uniform contraction is made possible by properly controlling the mold's temperature and cooling gradients.

4.6 Integrated process flow affecting heat stability

Chocolate processing stages and their influence on heat stability

- **Refining:** Controls particle size distribution
- **Conching:** Improves fat coating and reduces moisture
- **Tempering:** Induces stable βV crystals

- **Cooling & Demoulding:** Determines surface quality and internal stress

- **Source:** Beckett (2008); Afoakwa (2016); Prawira and Barringer (2009); Keijbets *et al.* (2010) ^[1, 8, 11]

4.7 Relevance of processing optimization for functional chocolate

When creating heat-stable chocolate formulations, especially those that incorporate beneficial ingredients, it is crucial to optimize processing conditions. Refinement, conching duration, and tempering profile adjustments can help preserve desired rheological and thermal properties and offset changes in solid composition (Afoakwa *et al.*, 2009; Medina-Mendoza *et al.*, 2025) ^[2, 10].

5. Rheological behaviour and melting characteristics of chocolate systems

5.1 Importance of rheology in chocolate quality and stability

Processability, sensory quality, and heat stability are all significantly influenced by rheology, which characterizes the flow and deformation behavior of chocolate under applied stress. Chocolate has a quantifiable yield stress, plastic viscosity, and shear-thinning, non-Newtonian behavior. In addition to influencing structural integrity under heat stress, these rheological factors control crucial processes such as pumping, mixing, molding, enrobing, and demoulding (Beckett, 2008; Afoakwa, 2016) ^[1].

Rheology indicates the strength of the internal particle-fat network from the standpoint of heat stability. While chocolate systems with a well-structured fat crystal network and balanced viscosity exhibit stronger resistance to thermal deformation, those with lower yield stress and excessive fat mobility tend to melt and deform quickly at high temperatures (Afoakwa *et al.*, 2009) ^[2].

5.2 Rheological models used for chocolate characterization

Empirical flow models like the Herschel-Bulkley and Casson models are frequently used to characterize chocolate rheology. These models take into consideration plastic viscosity and yield stress, two important markers of fat phase continuity and particle-particle interactions (Afoakwa, 2016) ^[1].

- Yield stress, which is related to the particle network's strength, is the lowest stress necessary to start flowing.
- Once movement has begun, plastic viscosity, which is impacted by fat content, particle size distribution, and degree of fat coating, represents resistance to flow.

Excessively low values may suggest inadequate structural integrity, resulting in poor heat resistance, whereas high yield

stress and viscosity may impede processing (Beckett, 2008) ^[2].

5.3 Influence of particle size distribution on rheology

One of the most important elements influencing the rheology of chocolate is the distribution of particle sizes. Refining increases surface area, decreases particle size, and increases the amount of cocoa butter needed to coat the particles. Insufficient fat content causes higher viscosity and yield stress because of increased interparticle friction (Afoakwa *et al.*, 2009) ^[2].

Chocolates with an ideal particle size distribution showed balanced rheological characteristics, a smooth texture, and better melting uniformity, as shown by Afoakwa *et al.* (2009) ^[2]. While overly fine particles increased viscosity because of their higher surface area and fat requirement, excessively coarse particles caused discontinuities in the fat matrix.

Table 5: Effect of particle size distribution on rheological behaviour of chocolate

Particle size characteristic	Yield stress	Plastic viscosity	Implication for heat stability	Source
Coarse distribution	Moderate	Low to moderate	Weak structure, early softening	Afoakwa <i>et al.</i> (2009) ^[2]
Optimized (20-25 µm)	Balanced	Balanced	Improved structural stability	Afoakwa <i>et al.</i> (2009) ^[2]
Very fine (<15 µm)	High	High	Restricted flow, possible instability	Beckett (2008) ^[2]

Source: Beckett (2008) ^[2]; Afoakwa *et al.* (2009) ^[2]

5.4 Effect of fat content and fat phase structure

Cocoa butter strongly influences chocolate rheology. By improving particle lubrication and decreasing friction, a higher fat content typically results in lower yield stress and viscosity. But too much fat might damage the network of fat crystals, making them more prone to melting and distortion when heated (Afoakwa, 2016) ^[1].

Rheology is also influenced by the crystalline form of cocoa butter. In contrast to chocolates with unstable polymorphs, those with stable βV crystals have stronger internal networks and greater resistance to deformation (Talbot, 2011) ^[15]. Thus, tempering quality and cocoa butter polymorphism are intimately related to rheology.

5.5 Role of conching in rheological development

Conching promotes fat coating of particles and lowers moisture content, which has a substantial impact on rheological characteristics. Eliminating moisture improves flow behavior and reduces viscosity by reducing capillary forces between particles (Beckett, 2008) ^[2].

According to Prawira and Barringer (2009) ^[11], longer conching times resulted in smoother and more preferred sensory experiences, which are associated with better particle coating and better rheological behavior. Heat stability is indirectly supported by a more uniform fat crystal network, which is a result of improved fat distribution during conching. Medina-Mendoza *et al.* (2025) ^[10] also demonstrated that conching time affects microstructural development and antioxidant characteristics, indicating that, under carefully regulated processing conditions, rheological optimization and the introduction of functional ingredients can coexist.

5.6 Relationship between rheology and melting behaviour

The rheological structure of chocolate is intimately related to its melting behavior. When exposed to high temperatures, chocolates with weaker particle networks and lower yield stress tend to melt quickly and lose their structure. On the

other hand, systems with a strong particle-fat network exhibit better shape retention and slower softening (Afoakwa *et al.*, 2009) ^[2].

Melting entails enhanced molecular mobility and a slow deterioration of the fat crystal network rather than a straightforward phase change. Rheology is a valuable predictor of heat stability since it sheds light on how chocolate will react to heat stress (Afoakwa, 2016) ^[1].

5.7 Effect of processing on melting characteristics

The size, distribution, and polymorphic form of crystals are determined by processing stages including tempering and cooling, which have a significant impact on melting behavior. While improperly tempered chocolates melt unevenly and collapse too soon, properly tempered chocolates melt uniformly and have a narrow melting range (Talbot, 2011) ^[15].

By affecting internal stress distribution and crystal orientation, deforming and cooling conditions also have an impact on melting behavior. Inappropriate demolded conditions can result in surface flaws and structural weaknesses, which might hasten melting and deformation, according to Keijbets *et al.* (2010) ^[8].

5.8 Interrelationship between rheology, melting and heat stability

The microstructure of chocolate controls the associated characteristics of rheology, melting behavior, and heat stability. A stable rheological structure that withstands melting and deformation under heat is the result of a combination of optimized particle size distribution, balanced fat content, efficient conching, and regulated tempering (Beckett, 2008; Afoakwa, 2016) ^[1, 2].

Since additional solid elements may change the rheology and melting behavior of chocolate, it is especially crucial to comprehend these interactions when creating useful chocolate systems with them. Therefore, careful processing optimization is necessary to preserve thermal stability as well as functional benefits.

6. Millets: nutritional composition and functional properties relevant to chocolate fortification

6.1 Overview of millets as functional food ingredients

Traditionally used in many regions of Asia and Africa, millets are a type of small-seeded cereal grains that are becoming increasingly well-known for their environmental, functional, and nutritional benefits. Because of their high dietary fiber content, mineral richness, bioactive chemical content, and appropriateness for use in functional meals, millets have attracted renewed attention in recent years (Saleh *et al.*, 2013; Gull *et al.*, 2014) ^[6, 13].

Millets have higher quantities of vitamins and phytochemicals because they maintain a sizable amount of their bran and germ parts, in contrast to processed cereals. Because of their makeup, they are especially appealing for

enhancing meals high in energy, like chocolate, which would otherwise have low levels of minerals and dietary fiber (Saleh *et al.*, 2013) ^[13]. Furthermore, millets are low-water-demanding, climate-resilient crops that enable their incorporation in sustainable food systems (Taylor and Emmambux, 2008) ^[16].

6.2 Nutritional composition of millets

Millets are distinguished by a high concentration of micronutrients and a balanced macronutrient profile. They offer significant amounts of dietary fiber, especially insoluble fiber, complex carbohydrates, and moderate protein levels. Compared to other grains, finger millet (*Eleusine coracana*) stands out for having a remarkably high calcium content (Shobana and Malleshi, 2007; Kumar *et al.*, 2016) ^[9, 14].

Table 6: General nutritional composition of millets (per 100 g, dry basis)

Component	Typical range	Nutritional relevance	Source
Carbohydrates (%)	65-75	Energy source, slow digestibility	Saleh <i>et al.</i> (2013) ^[13]
Protein (%)	7-12	Structural and functional role	Saleh <i>et al.</i> (2013) ^[13]
Dietary fiber (%)	8-15	Glycemic moderation, gut health	Gull <i>et al.</i> (2014) ^[6]
Fat (%)	1-5	Low lipid contribution	Saleh <i>et al.</i> (2013) ^[13]
Ash (%)	2-4	Mineral indicator	Kumar <i>et al.</i> (2016) ^[16]

Source: Saleh *et al.* (2013) ^[13]; Gull *et al.* (2014) ^[6]; Kumar *et al.* (2016) ^[16]

Given that fiber can affect the structural characteristics of the chocolate matrix as well as its nutritional value, millets' comparatively high fiber content is especially pertinent to chocolate fortification.

6.3 Mineral composition with emphasis on finger millet

One of the best plant sources of calcium among grains is

finger millet, according to numerous reports. It has significant levels of calcium as well as iron, phosphorus, and magnesium all of which are frequently lacking in diets made from refined cereals (Shobana and Malleshi, 2007; Kumar *et al.*, 2016) ^[9, 14]. For the development of nutritionally enhanced chocolate products targeted at children, adolescents, and the elderly, finger millet's high calcium content is very beneficial.

Table 7: Mineral content of finger millet compared with common cereals (mg/100 g)

Mineral	Finger millet	Wheat	Rice	Source
Calcium	300-350	30-40	10-20	Kumar <i>et al.</i> (2016) ^[9]
Iron	3-5	3-4	1-2	Gull <i>et al.</i> (2014) ^[6]
Phosphorus	250-300	280-300	90-100	Saleh <i>et al.</i> (2013) ^[13]
Magnesium	120-140	110-130	30-40	Kumar <i>et al.</i> (2016)

Source: Saleh *et al.* (2013); Gull *et al.* (2014) ^[6]; Kumar *et al.* (2016) ^[9]

6.4 Dietary fiber and glycemic response

One of millets' main functional ingredients, dietary fiber, is crucial for controlling the glycemic response and maintaining digestive health. Both soluble and insoluble fiber fractions found in millets help to lower postprandial blood glucose levels and delay the digestion of starches (Gull *et al.*, 2014) ^[6].

By adding fiber-rich millet ingredients to chocolate recipes, satiety can be increased and the product's glycemic impact reduced. Technologically speaking, dietary fiber raises the solid volume fraction of chocolate and, by limiting fat mobility within the matrix, can affect rheological behavior and thermal stability (Taylor and Emmambux, 2008) ^[16].

6.5 Bioactive compounds and antioxidant properties

Additionally, millets contain bioactive substances that support antioxidant activity, including flavonoids, tannins, and phenolic acids. Depending on the level of processing, these chemicals are partially maintained and are mostly concentrated in the grain's outer layers (Saleh *et al.*, 2013) ^[13]. The addition of millet may improve the antioxidant capacity

of chocolate products when paired with cocoa, which is naturally high in polyphenol. The incorporation of millet-derived phenolics may enhance the health-promoting benefits of cocoa polyphenols, which were emphasized by Araujo *et al.* (2020) ^[3].

6.6 Functional properties of millet flours relevant to chocolate systems

Millet flour's performance in composite food systems is influenced by its functional qualities, which include its ability to absorb water and oil, as well as its swelling and pasting characteristics. Processing techniques including decortication and milling have a major impact on the functional behavior of finger millet flour, according to Shobana and Malleshi (2007) ^[14].

Particles of millet flour function as extra solid ingredients that interact with the fat phase in chocolate systems. According to Taylor and Emmambux (2008) ^[16], their capacity to absorb moisture and interact with lipids can affect viscosity, fat distribution, and particle packing all of which are crucial elements for processing behavior and heat stability.

6.7 Effect of millet processing on nutritional and functional properties

The nutritional and functional qualities of millets are altered by processing methods such as decortication, milling, and heat treatment. By removing a piece of the outer layer, decortication reduces antinutritional substances while preserving a sizable amount of fiber and minerals (Shobana and Malleshi, 2007) ^[14].

Thermal treatments can affect phenomenon and functional qualities in addition to improving flavor and decreasing enzymatic activity. Therefore, when millet is meant to be incorporated into chocolate formulations, choosing the right processing techniques is crucial (Saleh *et al.*, 2013) ^[13].

6.8 Relevance of millets for heat-stable chocolate development

From a structural point of view, elements made from millet give chocolate a higher solid content and help to create a more robust network of particles. When paired with ideal processing conditions, this network may improve heat stability by limiting fat flow and delaying softening at high temperatures (Taylor and Emmambux, 2008) ^[16].

Excessive millet flour incorporation, however, may worsen sensory quality and increase viscosity. Therefore, striking a balance between consumer acceptance, processing viability, and nutritional enhancement continues to be a major problem.

7. Processing of millets for application in chocolate systems

7.1 Importance of millet processing prior to chocolate fortification

The proper pre-processing of the grains is crucial to the optimal integration of millet-derived ingredients into chocolate systems. If consumed unmodified, raw millets' natural qualities such as their coarse texture, high fiber content, and antinutritional factors may negatively impact processing behavior, rheology, and sensory quality (Saleh *et al.*, 2013; Shobana & Malleshi, 2007) ^[13, 14]. Therefore, to increase compatibility with chocolate matrices, processing processes like cleaning, decortication, milling, and thermal treatment are crucial.

Processing alters functional characteristics such as particle size, water absorption, and interaction with lipids, all of which are essential for producing stable chocolate dispersions, in addition to increasing the nutritional bioavailability of millet components (Taylor and Emmambux, 2008) ^[16].

7.2 Cleaning and Decortication

7.2.1 Role of decortication

The process of decorticating millets entails removing the outer seed covering entirely or partially. This process preserves a significant number of micronutrients and

endosperm components while lowering the amount of coarse fiber and antinutritional substances (Shobana and Malleshi, 2007) ^[14]. When compared to whole-grain flours, decorticated millet flours have better color, less bitterness, and more useful qualities. Decortication is especially crucial when it comes to chocolate fortification since too many bran particles can generate a harsh mouthfeel and obstruct the fat coating process during refining (Taylor and Emmambux, 2008) ^[16].

7.3 Milling and particle size reduction

7.3.1 Milling requirements for chocolate applications

One of the most important processing stages for converting millet to chocolate systems is particle size reduction. For chocolate to have a smooth mouthfeel and even dispersion throughout the cocoa butter matrix, the solid particles must be refined, usually below 25 to 30 μm (Beckett, 2008; Afoakwa *et al.*, 2009) ^[2, 4]. As a result, millet flour meant for chocolate integration needs to be finely ground and occasionally secondary refined along with sugar and cocoa solids. According to Shobana and Malleshi (2007) ^[14], the functional characteristics of finger millet flour, such as its ability to absorb water and its pasting behavior, are considerably changed by milling. While fine milling increases surface area and decreases grittiness and enhances dispersibility, it may also increase the requirement for fat during the chocolate-making process.

7.4 Thermal processing of millets

7.4.1 Roasting and Heat treatment

Millets are frequently processed using thermal techniques like roasting to improve flavor, lower moisture content, and deactivate enzymes. Roasting produces pleasing nutty flavors that can lessen the taste of raw cereal and enhance the flavor of cocoa (Saleh *et al.*, 2013) ^[13]. The stability of phenolic chemicals and millet flour's beneficial qualities may also be impacted by heat treatment. Roasted millet elements may enhance flavor compatibility in chocolate formulations, but they must be carefully managed to prevent excessive browning or the deterioration of nutrients that are sensitive to heat (Saleh *et al.*, 2013) ^[13].

7.5 Effect of millet processing on nutritional quality

The nutritional makeup and bioavailability of millet components are changed during processing. While milling and decortication may decrease some mineral fractions, they also increase digestibility and lessen antinutritional elements. According to Shobana and Malleshi (2007) ^[14], processed finger millet flour showed enhanced functional performance while retaining a large amount of calcium and dietary fiber. According to Saleh *et al.* (2013) ^[13], processing conditions must strike a balance between functional appropriateness and nutrient retention, especially when millet is employed as an ingredient in composite food systems like chocolate.

Table 8: Effect of milling on functional properties of finger millet flour

Property	Coarse flour	Fine flour	Implication for chocolate	Source
Particle size	High	Low	Improved smoothness	Shobana & Malleshi (2007) ^[14]
Water absorption	Moderate	High	Affects viscosity	Shobana & Malleshi (2007) ^[14]
Oil absorption	Lower	Higher	Influences fat requirement	Taylor & Emmambux (2008) ^[16]

Source: Shobana and Malleshi (2007); Taylor and Emmambux (2008) ^[14, 16]

7.6 Interaction of processed millet ingredients with chocolate matrix

As solid fillers, processed millet particles mainly interact with the cocoa fat phase. Their rheological behavior and fat distribution are influenced by their surface characteristics, particle size, and oil absorption capability. According to Taylor and Emmambux (2008) ^[16], millet-derived solids may raise the solid volume percentage of chocolate, which would increase its viscosity and yield stress. If particle size and processing conditions are optimized, a higher solid content may limit fat mobility and postpone softening under heat from the standpoint of thermal stability (Afoakwa *et al.*, 2009) ^[12].

7.7 Compatibility of millet processing with chocolate manufacturing steps

When making chocolate, millet ingredients are usually added during the mixing or refining process. Their incorporation needs to work with later processing stages like tempering and conching. Poor tempering behavior, higher viscosity, or uneven dispersion can all be consequences of improper integration. To preserve processability and structural stability, Beckett (2008) ^[2] emphasized that the addition of solid ingredients needs to be carefully balanced with fat content and emulsification.

7.8 Process flow for millet incorporation into chocolate

Generalized processing flow for millet incorporation into chocolate

Cleaning→ Decortication→ Milling (fine flour) → Optional roasting→ Mixing with cocoa mass and sugar→ Refining→ Conching→ Tempering→ Moulding and cooling
Source: Beckett (2008); Shobana and Malleshi (2007); Saleh *et al.* (2013); Taylor and Emmambux (2008) ^[2, 13, 14, 16]

7.9 Implications for heat-stable chocolate development

for millets to be successfully used in heat-stable chocolate systems, proper processing is necessary. Compatibility, nutritional value, and structural strengthening can all be improved by fine grinding, controlled heat treatment, and optimal integration into chocolate production. However, rheology and sensory quality may suffer from overprocessing or improper processing management. As a result, millet processing needs to be customized for chocolate applications while taking processing limitations and nutritional goals into

account (Saleh *et al.*, 2013; Taylor and Emmambux, 2008) ^[13, 16].

8. Natural sweeteners in chocolate systems with emphasis on jaggery

8.1 Rationale for replacing refined sugar in chocolate

Refined sucrose is the main sweetener used in conventional chocolate formulas, which greatly increases calorie density and total carbohydrate load. Due to the lack of micronutrients and bioactive substances, sucrose's nutritional contribution to chocolate is limited, despite its significant technological significance in adding volume, texture, and sweetness (Beckett, 2008; Afoakwa, 2016) ^[1, 2]. The investigation of substitute sweeteners that can offer sweetness and other nutritional advantages has been prompted by growing consumer awareness of diet-related health issues. The mineral content and functional qualities of natural sweeteners made from minimally processed sources have garnered interest. Jaggery is one of these that has shown promise for usage in confections made with cocoa (Rao and Singh, 2022; Hirpara *et al.*, 2020) ^[7, 12].

8.2 Jaggery: origin, processing and composition

Boiling clarified sugarcane juice until a solid or semi-solid mass forms is how jaggery, a traditional non-centrifugal sweetener, is made. Jaggery preserves a significant amount of naturally occurring minerals, vitamins, and phenolic compounds found in sugarcane juice, in contrast to refined sugar (Rao and Singh, 2022) ^[12]. The components of molasses, which are mostly eliminated during the creation of refined sugar, are retained during the production of jaggery due to the lack of crystallization and centrifugal separation. The unique nutritional and functional qualities of jaggery in comparison to sucrose are caused by this compositional difference (Hirpara *et al.*, 2020) ^[7].

8.3 Nutritional composition of jaggery

Minerals including calcium, iron, potassium, magnesium, and phosphorus are said to be present in jaggery, along with trace levels of phenolic chemicals that support antioxidant action. The micronutrient profile of jaggery sets it apart from refined sugar in terms of nutrition, even if it is still an energy-dense sweetener (Rao and Singh, 2022) ^[12].

For chocolate products with added nutrients meant for those with micronutrient deficits, the iron and calcium content of jaggery is especially important.

Table 9: Nutritional composition of jaggery compared with refined sugar (per 100 g)

Component	Jaggery	Refined sugar	Nutritional implication	Source
Total sugars (%)	80-85	~99	Similar sweetness contribution	Rao & Singh (2022) ^[12]
Calcium (mg)	40-100	<10	Bone health relevance	Rao & Singh (2022) ^[12]
Iron (mg)	10-13	<1	Anaemia prevention	Hirpara <i>et al.</i> (2020) ^[7]
Potassium (mg)	100-140	Trace	Electrolyte balance	Rao & Singh (2022) ^[12]
Phenolics	Present	Absent	Antioxidant potential	Rao & Singh (2022) ^[12]

Source: Rao and Singh (2022) ^[12]; Hirpara *et al.* (2020) ^[7]

8.4 Functional properties of jaggery relevant to chocolate systems

Jaggery adds bulk and participates in the solid phase of chocolate in addition to adding sweetness. Rheology and

shelf stability may be impacted by its mineral content and hygroscopic character, which also affect moisture interactions (Beckett, 2008) ^[2].

The efficiency of fat coating during refining and conching may be impacted by the surface properties of jaggery particles, which differ from refined sugar.

From a functional standpoint, the phenolic chemicals that are preserved in jaggery may help to increase antioxidant activity in chocolate systems. The viability of incorporating functional sweeteners was supported by Medina-Mendoza *et al.*'s (2025) ^[10] demonstration that adding bioactive substances during chocolate processing can improve antioxidant qualities without necessarily lowering product quality.

8.5 Effect of jaggery on rheological behaviour of chocolate

When jaggery is used in place of refined sugar, the particle composition changes and rheological characteristics including viscosity and yield stress may be affected. If not offset by changes in fat content or emulsification, the presence of mineral salts and non-sugar components in jaggery might increase solid-solid interactions and perhaps increase viscosity (Afoakwa, 2016) ^[1].

Therefore, proper conching and refining are necessary to guarantee that the jaggery particles have a sufficient fat coating. Conching time affects fat distribution and smoothness, which is crucial when using non-traditional sweeteners, according to Prawira and Barringer (2009) ^[11].

8.6 Influence of jaggery on melting and heat stability

By altering the makeup of the solid phase and limiting lipid mobility, jaggery inclusion may affect how chocolate melts. When properly designed, higher solid content and changed particle interactions can help delay softening at high temperatures, which could improve heat stability (Afoakwa *et al.*, 2009) ^[2]. On the other hand, poor processing or over-substitution can result in uneven dispersion, higher viscosity, and diminished sensory quality. Therefore, to strike a balance between heat resistance and nutritional enhancement, formulation and processing optimization are required.

8.7 Interaction of jaggery with cocoa butter crystallization

Jaggery's presence as a solid filler affects the particle packing and spatial distribution of fat crystals even if it does not directly contribute to the crystallization of cocoa butter. By limiting fat migratory pathways, increased solid loading may indirectly lower the pace at which fat blooms occur (Beckett, 2008; Afoakwa, 2016) ^[1, 2].

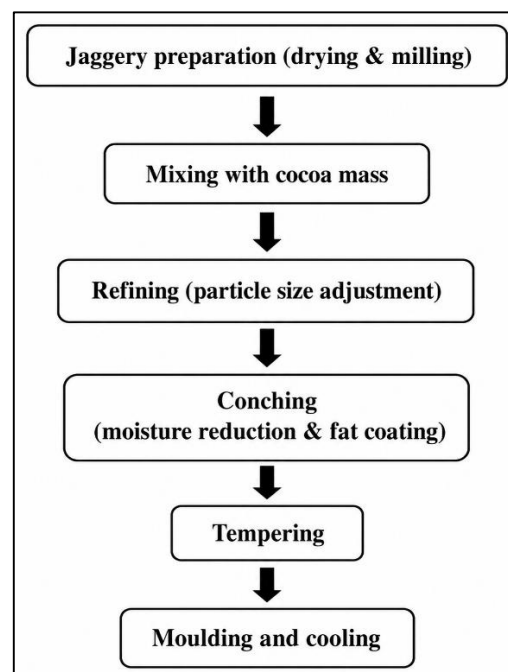
To guarantee the dominance of β V cocoa butter crystals, tempering settings must be carefully controlled, especially in formulations that contain other sweeteners that could change the thermal behavior.

8.8 Processing considerations for jaggery-based chocolate

When making chocolate, jaggery is usually added during the mixing or refining process. To prevent processing problems like agglomeration or excessive viscosity, its moisture content and particle size need to be properly regulated. According to Beckett (2008) ^[2], moisture content exceeding critical thresholds can seriously affect the flow characteristics of chocolate.

Conching is essential for eliminating any remaining moisture and encouraging a consistent fat coating on the jaggery particles. In contrast to traditional sugar-based formulations, prolonged conching could be necessary to attain a satisfactory rheology and texture (Prawira and Barringer, 2009) ^[11].

8.9 Conceptual process flow for jaggery-based chocolate



Source: Beckett (2008); Prawira and Barringer (2009); Rao and Singh (2022) ^[2, 11]

Processing flow for chocolate formulation using jaggery as a natural sweetener

8.10 Relevance of jaggery for functional and heat-stable chocolate development

Jaggery's mineral richness and antioxidant qualities make it a potentially beneficial natural sweetener for functional chocolate. Jaggery-based chocolates may have better nutritional content while retaining acceptable rheological, sensory, and thermal properties when paired with ideal processing conditions and suitable formulation modifications (Rao and Singh, 2022) ^[12].

To fully utilize the functional advantages of jaggery without sacrificing product quality, more research is necessary to determine the ideal substitution levels and processing conditions.

9. Combined effects of millet-derived ingredients and natural sweeteners on chocolate quality and heat stability

9.1 Rationale for combined ingredient modification

The creation of functional, heat-stable chocolate necessitates a comprehensive strategy that takes processing circumstances and ingredient composition into account. While natural sweeteners like jaggery offer sweetness along with minerals and bioactive substances, millets offer nutritional boost and structural strengthening. When millet-derived substances and jaggery are added to chocolate formulations at the same time, complex interactions are introduced within the cocoa butter-solid particle matrix, affecting thermal stability, rheology, melting behavior, and sensory quality (Beckett, 2008; Afoakwa, 2016) ^[2].

Prior research on the structure and processing of chocolate shows that the solid volume fraction, fat crystallization, and particle size distribution all influence how chocolate behaves under heat stress (Afoakwa *et al.*, 2009). These properties change simultaneously when millet solids and jaggery are added; therefore careful formulation and processing optimization are required.

9.2 Influence on solid volume fraction and particle network formation

Because millet flour has a high fiber and carbohydrate content, it raises the solid volume percentage of chocolate. Similarly, because jaggery retains its non-sugar components, it delivers more solid particles than refined sugar. When sufficiently coated with cocoa butter, a higher solid volume fraction improves particle-particle interactions and can fortify the internal particulate network (Taylor and Emmambux, 2008) ^[16].

According to Afoakwa *et al.* (2009), rheological characteristics including viscosity and yield stress are impacted by an increase in solid content. Particles made from millet may help create a more robust particle network that limits fat mobility and postpones softening at high temperatures if they are finely ground and evenly distributed.

9.3 Effects on rheological behaviour

The rheological characteristics of chocolate are greatly impacted by the combined presence of millet flours and

jaggery. If fat content and emulsification are not changed, millet particles especially those high in dietary fiber increase the capacity to absorb water and oil, which could raise viscosity and cause yield stress (Shobana and Malleshi, 2007; Taylor and Emmambux, 2008) ^[14, 16].

Because of their mineral content and hygroscopic nature, jaggery particles may have an additional impact on particle cohesion and moisture interactions. Therefore, adequate fat coating and homogeneous dispersion of both millet and jaggery particles depend on proper refining and conching (Prawira and Barringer, 2009) ^[11].

9.4 Impact on melting behaviour and heat stability

Changes in fat mobility and particle packing affect how chocolate containing millet and jaggery melts. A higher solid concentration may hinder the cocoa butter's ability to flow throughout the matrix, delaying its softening when heated. When the chocolate is suitably tempered to create stable βV cocoa butter crystals, this impact may help increase heat stability (Afoakwa, 2016) ^[1].

Table 10: Combined influence of millet ingredients and jaggery on chocolate rheology

Ingredient modification	Rheological impact	Processing implication	Source
Millet flour addition	Increased yield stress	Requires fat/emulsifier adjustment	Shobana & Malleshi (2007) ^[14]
Jaggery substitution	Increased viscosity	Extended conching needed	Prawira & Barringer (2009) ^[11]
Combined addition	Higher solid loading	Careful refining & tempering	Afoakwa <i>et al.</i> (2009)

Source: Afoakwa *et al.* (2009); Shobana and Malleshi (2007); Prawira and Barringer (2009) ^[11, 14]

However, uneven melting behavior and a degraded texture could be the result of either too much solid loading or insufficient fat coating. Thus, maintaining a continuous fat crystal network while incorporating solids must be balanced to achieve better heat stability (Beckett, 2008) ^[2].

9.5 Interaction with cocoa butter crystallization and bloom development

Although they do not directly contribute to the crystallization of cocoa butter, millet-derived solids and jaggery have an impact on the spatial arrangement of fat crystals. The development of fat blooms and polymorphic metamorphosis may be slowed by increased particle density, which may limit fat migration paths (Afoakwa, 2016) ^[1].

Regardless of ingredient adjustment, however, incorrect tempering or temperature changes can still cause βV crystals to change into the more stable βVI form, which results in bloom. Thus, even in chocolate systems that have undergone nutritional modification, processing management is still essential (Talbot, 2011) ^[15].

9.6 Effects on sensory attributes

One important factor influencing customer adoption of functional chocolate products is sensory quality. Color, flavor, and texture can all be affected by the addition of millet, especially if there are gritty particles or notes of raw cereal. To reduce sensory flaws and guarantee compatibility with cocoa flavor, processing procedures including roasting and fine milling are crucial (Saleh *et al.*, 2013) ^[13].

The distinct caramel-like flavor that jaggery adds may go well with cocoa, but it must be carefully balanced to prevent overbearing chocolate overtones. Conching duration is critical to flavor development and smoothness, especially in composite chocolate systems, according to Prawira and Barringer (2009) ^[11].

9.7 Nutritional enhancement through combined fortification

By boosting dietary fiber, mineral richness, and antioxidant potential, the combination of millet-derived substances with jaggery improves chocolate's nutritional profile. Jaggery offers iron, potassium, and other phenolics, while millets offer fiber, calcium, and phenolic chemicals (Saleh *et al.*, 2013; Rao and Singh, 2022) ^[12, 13].

As noted by Araujo *et al.* (2020) ^[3] in their study of cacao and human health, these ingredients may work in concert with cocoa polyphenols to boost antioxidant potential.

9.8 Processing challenges and optimization strategies

Adding both millet and jaggery creates several processing issues, such as higher viscosity, a greater need for fat, and possible tempering issues. Modifications to tempering profiles, emulsifier use, conching duration, and refining intensity can all help overcome these difficulties (Beckett, 2008; Afoakwa, 2016) ^[1, 2].

The viability of integrating functional ingredients was supported by Medina-Mendoza *et al.*'s (2025) ^[10] demonstration that meticulous management of conching conditions can improve antioxidant properties while preserving acceptable microstructure.

9.9 Conceptual framework for combined ingredient incorporation

Conceptual framework showing combined effects of millet and jaggery in chocolate systems

Millet flour + Jaggery

→ increased solid content

→ modified rheology

→ restricted fat mobility

→ delayed melting

→ potential improvement in heat stability

Source: Beckett (2008); Afoakwa *et al.* (2009) ^[2]; Taylor and Emmambux (2008) ^[2, 16]

9.10 Summary of combined effects

A possible method for creating useful, heat-stable chocolate products is the combination of natural sweeteners like jaggery and nutrients derived from millet. Although these components improve nutritional value and might help with increased heat resistance, their effective use requires careful formulation balance and processing parameter management. A solid scientific basis for additional study into optimal composite chocolate systems is provided by the body of existing literature.

10. Challenges, limitations and future research directions

10.1 Technological challenges in developing heat-stable functional chocolate

There are still several technological obstacles in the way of creating heat-stable functional chocolate, even with the encouraging promise of millet-based ingredients and natural sweeteners like jaggery. Rheology, crystallization behavior, and sensory quality are all greatly impacted by even minor formulation or processing modifications in chocolate, which is a delicately balanced system (Beckett, 2008; Afoakwa, 2016) ^[1, 2].

In addition to increasing the solid volume percentage, millet flour adds non-starch polysaccharides and dietary fiber, which can enhance viscosity and yield stress. Poor flow behavior, trouble molding, and higher processing energy needs could result from improper management through fat modification and refining (Afoakwa *et al.*, 2009; Taylor and Emmambux, 2008) ^[2, 16].

10.2 Processing limitations related to millet incorporation

Achieving particle size compliance with traditional chocolate systems is one of the main obstacles to millet integration. For chocolate to have a smooth mouthfeel, the particles must be polished below the threshold of sensory perception. If more fat is not sufficiently organized within the cocoa butter network, heat stability may be jeopardized. This is because fine-milling millet flours increases surface area and fat demand (Shobana and Malleshi, 2007; Afoakwa *et al.*, 2009) ^[2, 14].

Furthermore, depending on the type of grain, level of processing, and milling conditions, millet-derived substances may introduce diversity in functional characteristics. According to Saleh *et al.* (2013) ^[13], processing techniques have a significant impact on the nutritional and functional qualities of millets, suggesting that consistent processing procedures are necessary when using millets to make chocolate.

10.3 Challenges associated with jaggery as a sweetener

Although jaggery is more nutritious than refined sugar, there are several drawbacks when using it in chocolate systems. Compared to refined sucrose, jaggery has higher moisture and mineral content, which could affect hygroscopicity and moisture interactions during the chocolate-making process (Rao and Singh, 2022) ^[12].

Because even trace levels of moisture can significantly increase viscosity by encouraging sugar agglomeration and capillary forces between particles, moisture is especially harmful to chocolate rheology (Beckett, 2008) ^[2]. To guarantee moisture reduction and consistent fat coating,

jaggery must be sufficiently dried and finely ground before integration. Conching conditions may also need to be prolonged (Prawira and Barringer, 2009) ^[11].

10.4 Sensory acceptance and consumer perception

Maintaining taste acceptance while enhancing nutritional and thermal qualities presents another significant obstacle. Color, texture, and flavor can all be affected by millet integration, especially if there are coarse particles or notes of raw cereal. In a similar vein, jaggery adds a distinct caramel-like flavor that, if present in large quantities, would not be enjoyed by everyone (Saleh *et al.*, 2013; Rao and Singh, 2022) ^[12, 13].

Conching time has a considerable impact on sensory preference, as shown by Prawira and Barringer (2009) ^[11], underscoring the significance of flavor development and smoothness in composite chocolate systems. Therefore, careful balancing of ingredient quantities and processing conditions is necessary to achieve consumer acceptability.

10.5 Limitations related to heat stability enhancement

The inherent thermal sensitivity of cocoa butter cannot be eliminated by ingredient modification alone, even though modified particle networks and increased solid content may help to delay softening under heat. The primary element influencing melting behavior and bloom creation is still cocoa butter polymorphism (Afoakwa, 2016; Talbot, 2011) ^[1, 15].

For this reason, rigorous control over tempering and storage conditions is necessary to preserve the quality of even nutritionally enhanced chocolates. Instead of replacing appropriate processing control, ingredient-based methods to heat stability should be seen as complementary (Beckett, 2008) ^[2].

10.6 Scalability and industrial applicability

Scalability is a crucial factor from an industrial standpoint. Modifications to current processing lines, such as increased refining capacity, longer conching periods, and adjustments to tempering profiles, may be necessary to incorporate millet flour and jaggery. These modifications might result in longer processing times and higher energy usage, which needs to be assessed in light of commercial viability (Afoakwa, 2016) ^[1]. Keijbets *et al.* (2010) ^[8] emphasized the necessity of thorough scale-up research prior to commercial adoption, pointing out that even small modifications in processing conditions might affect surface quality and demoulding behavior.

10.7 Research gaps identified from existing literature

A survey of the literature indicates a number of holes that need to be filled. Although millet nutrition, natural sweeteners, and chocolate processing have all been the subject of distinct studies, little is known about how these three ingredients work together in cocoa-based confectionery systems. There are few systematic research assessing the relationship between cocoa butter crystallization, jaggery, and millet-derived solids (Taylor and Emmambux, 2008; Rao and Singh, 2022) ^[12, 16]. Furthermore, it is challenging to completely evaluate the stability and shelf life of composite chocolate products in real-world settings because of the paucity of long-term storage studies under various heat conditions (Afoakwa, 2016) ^[1].

10.8 Directions for future research

Future studies should concentrate on refining formulation and processing parameters to balance heat stability, sensory quality, and nutritional enhancement considering the reviewed literature.

It is necessary to conduct thorough research on the optimization of particle size, fat-solid interactions, and tempering behavior in chocolate systems enriched with millet and jaggery (Afoakwa *et al.*, 2009; Beckett, 2008) ^[2, 4].

The effective commercialization of functional, heat-stable chocolate products will also require research assessing consumer acceptance, storage stability, and industrial scalability (Saleh *et al.*, 2013; Prawira and Barringer, 2009) ^[11, 13].

Conclusion

A significant field of study at the nexus of food processing, nutrition, and product innovation is the creation of useful, heat-stable cocoa confections. Although conventional chocolate products are widely prized for their sensory appeal, their low thermal stability and dependence on refined sugar limit their applicability for consumers who are health-conscious and live in hotter areas. With a focus on the potential of millet-derived compounds and natural sweeteners like jaggery to overcome these constraints, the current review has critically analyzed developments in chocolate research and processing.

Melting properties, rheological behavior, and resistance to deformation at high temperatures are all influenced by cocoa butter polymorphism, particle size distribution, and processing parameters, according to an analysis of chocolate structure and thermal behavior. A steady network of fat crystals must be maintained, and quality flaws such as fat bloom must be reduced, by carefully managing the refining, conching, tempering, chilling, and demoulding processes. Any approach to enhancing heat stability in chocolate systems is based on these processing principles.

Because of their high dietary fiber content, mineral richness, and bioactive component composition, millets especially finger millet have been recognized as prospective functional ingredients. By increasing the solid volume fraction and altering the particle networks, their addition to chocolate formulations provides chances for both nutritional improvement and structural strengthening. In a similar vein, jaggery has become a popular natural sweetener that is different from refined sucrose in terms of nutrition. It offers sweetness as well as minerals and antioxidant chemicals.

When jaggery and millet-derived ingredients are used together, complex interactions are introduced into the chocolate matrix that affect thermal stability, rheology, melting behavior, and sensory quality. Although these substances may limit the mobility of fat and postpone its softening when heated, their effective use necessitates meticulous formulation and processing condition optimization. The quality of the product may be harmed by excessive solid loading, insufficient fat coating, or incorrect tempering, highlighting the necessity of a methodical and balanced approach.

Overall, the literature study shows that when component alteration is backed by a solid grasp of chocolate structure and processing chemistry, it is possible to create useful, heat-stable cocoa confections. A viable route toward nutritionally enhanced products appropriate for hotter climates and changing customer preferences is the use of millets and natural sweeteners in chocolate systems. To guarantee sensory acceptability on an industrial scale, assess long-term storage stability, and optimize processing techniques, more study is necessary. Translating laboratory-scale results into

chocolate products that are both useful, stable, and aesthetically pleasing would need such efforts.

References

1. Afoakwa EO. Chocolate science and technology. 2nd ed. Oxford: Wiley-Blackwell; 2016.
2. Afoakwa EO, Paterson A, Fowler M, Vieira J. Relationship between rheological, textural and melting properties of dark chocolate as influenced by particle size distribution and composition. *European Food Research and Technology*. 2009;228(3):425-435.
3. Araujo QR, Gattward JN, Almoosawi S, Silva MD, Dantas PA, De Faria LJG. Cacao and human health: From head to foot - A review. *Critical Reviews in Food Science and Nutrition*. 2021;61(1):1-27.
4. Beckett ST. The science of chocolate. 2nd ed. Cambridge: Royal Society of Chemistry; 2008.
5. Godos J, et al. Dietary polyphenols and health outcomes: An umbrella review of meta-analyses. *International Journal of Environmental Research and Public Health*. 2019;16(24):4960.
6. Gull A, Jan R, Nayik GA, Prasad K, Kumar P. Significance of finger millet (*Eleusine coracana*) in nutrition, health and value-added products: A review. *Journal of Environmental Science, Computer Science and Engineering*. 2014;3(3):1601-1608.
7. Hirpara P, Thakare N, Kele VD, Patel D. Jaggery: A natural sweetener. *Journal of Pharmacognosy and Phytochemistry*. 2020;9(5):3145-3148.
8. Keijbets EL, Chen J, Vieira J. Chocolate demoulding and effects of processing conditions. *Journal of Food Engineering*. 2010;98(1):133-140.
9. Kumar A, Metwal M, Kaur S, Gupta AK, Puranik S, Singh S, et al. Nutritional characterization and oxidative stability of finger millet (*Eleusine coracana*). *Journal of Food Science and Technology*. 2016;53(7):2924-2934.
10. Medina-Mendoza M, Mori-Mestanza D, Iliquin-Fernández RE, Colca ISC, Castro-Alayo EM, Balcázar-Zumaeta CR. Chocolate production: Effect of conching time, berry by-products, and sacha inchi oil on antioxidant attributes. *Journal of Agriculture and Food Research*. 2025;22:100430.
11. Prawira M, Barringer SA. Effects of conching time and ingredients on preference of milk chocolate. *Journal of Food Processing and Preservation*. 2009;33(5):571-589.
12. Rao PVK, Singh R. Nutritional, functional and health aspects of jaggery: A review. *Journal of Food Science and Technology*. 2022;59(6):2153-2165.
13. Saleh ASM, Zhang Q, Chen J, Shen Q. Millet grains: Nutritional quality, processing, and potential health benefits. *Comprehensive Reviews in Food Science and Food Safety*. 2013;12(3):281-295.
14. Shobana S, Malleshi NG. Preparation and functional properties of decorticated finger millet (*Eleusine coracana*) flour. *Journal of Food Engineering*. 2007;79(2):529-538.
15. Talbot G. Chocolate temper. In: *Industrial chocolate manufacture and use*. 4th ed. Oxford: Wiley-Blackwell; 2011. p. 261-275.
16. Taylor JRN, Emmambux MN. Products containing other speciality grains: Sorghum, millets and pseudocereals. In: *Technology of functional cereal products*. Cambridge: Woodhead Publishing; 2008.