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FORMULATION STRATEGIES FOR CHOCOLATE COUVERTURE UTILIZING COCOA BUTTER ALTERNATIVES: A SYSTEMATIC REVIEW

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Abstract:

This Systematic Literature Review (SLR) investigates formulation strategies for chocolate couverture utilizing Cocoa Butter Alternatives (CBA), addressing the growing demand for innovative chocolate formulations that cater to health and sustainability concerns. The problem centers on the challenges posed by the rising costs and ethical implications related to Cocoa Butter (CB) usage. Employing the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol, we systematically searched two databases, Scopus and ScienceDirect, identifying 27 primary studies relevant to our research focus. Our findings are organized into three key themes: (1) CBAs and Fat Modification, exploring various substitutes and their impact on sensory properties; (2) Nutritional and Functional Enhancement of Chocolate, assessing the implications of alternative ingredients on health benefits; and (3) Processing, Crystallization, and Analytical Techniques in Chocolate Formulation, highlighting the technological advancements that facilitate effective incorporation of CBAs. The review reveals significant opportunities for optimizing chocolate formulations while potentially improving nutritional profiles. Ultimately, the evidence suggests that although CBAs show promise, careful consideration of their effects on texture, stability, and consumer acceptance is critical for successful product development. This study provides valuable insights for researchers and manufacturers aiming to create innovative chocolate products that align with current market trends and consumer preferences.

Keywords:

Chocolate, Couverture, Cocoa Butter, Cocoa Butter Alternative, Cocoa Butter Equivalent, Cocoa Butter Replacer, Cocoa Butter Substitute

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Introduction

Chocolate couverture, a high-quality chocolate variant containing a significant proportion of Cocoa Butter (CB), plays a pivotal role in the confectionery industry due to its superior melting behavior, gloss, and snap. Traditionally used by chocolatiers and in fine patisserie, couverture chocolate must meet stringent compositional and rheological criteria to ensure optimal functionality in enrobing, molding, and decorative applications. However, the heavy reliance on CB, an expensive and geographically limited commodity, poses significant challenges related to cost volatility, supply sustainability, and ethical sourcing. In recent years, these concerns have intensified in light of climate change impacts on cocoa-producing regions, rising global demand, and increasing consumer awareness about sustainable food systems. As a result, the exploration and incorporation of Cocoa Butter Alternatives (CBAs) in couverture chocolate formulation have emerged as critical areas of innovation in food science and industrial chocolate manufacturing. Notably, CBAs offer potential solutions to issues of cost-efficiency, functional performance, and product stability while aligning with industry efforts toward sustainable and ethically produced chocolate products.

The formulation of chocolate couverture using CBAs, such as Cocoa Butter Equivalents (CBEs), Cocoa Butter Replacers (CBRs), and Cocoa Butter Substitutes (CBSs), has been the focus of various studies aimed at mimicking the physicochemical, rheological, and sensory properties of traditional CB. Key findings from recent literature suggest that specific CBEs derived from shea, illipe, or mango kernel fats can be blended with CB in limited proportions without significantly compromising crystallization behavior or tempering characteristics. Furthermore, carefully selected CBEs can yield acceptable polymorphic forms, particularly the desired β(V) form, while maintaining gloss and snap. However, CBSs and CBRs, typically lauric fats like palm kernel or non-lauric fats, present more pronounced challenges due to their incompatibility with CB, requiring complete substitution and often resulting in altered melting profiles and mouthfeel. Despite these advances, several unresolved issues persist. The literature remains fragmented with inconsistent methodological approaches, particularly regarding evaluation techniques for sensory and textural properties. There is also a lack of consensus on optimal fat blending ratios and their effects on crystallization kinetics and fat bloom stability over extended shelf life. Moreover, many studies fail to consider how CBAs interact with other couverture ingredients such as emulsifiers, milk solids, and sugar, which can significantly influence product quality. In addition, controversies remain over the regulatory classifications and labeling implications of using CBAs, especially in markets governed by strict chocolate compositional standards (e.g., European Union (EU), Food and Drug Adminstration (FDA)), further complicating the adoption of such alternatives at commercial scale.

Therefore, this article aims to synthesize the existing body of research on CBAs in couverture chocolate, critically evaluate the methodologies and findings of key studies, and identify knowledge gaps that hinder the development of optimized formulations. Note that by focusing on formulation strategies, including fat selection, blending ratios, tempering protocols, and Quality Assessment (QA) techniques, this review seeks to provide a comprehensive, evidence-based framework for the rational design of couverture chocolate using CBAs. Accordingly, it contributes to advancing academic knowledge and industrial practice in food formulation, with implications for cost reduction, sustainability, and product innovation in the global chocolate sector.

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Literature Review

In response to rising CB prices and sustainability concerns, the search for CBAs and CBEs in couverture chocolate has intensified. Researchers have increasingly focused on using diverse vegetable oils and their derivatives, owing to their availability and functional versatility. For example, physically modified oils like crystallized and emulsified sunflower oil have demonstrated potential in replacing palm fat, maintaining firmness and flavor in dark chocolate fillings (Schmid et al., 2025). Similarly, mahua oil fractions high in POS triacylglycerols (TAG) effectively mimicked CB's physical and rheological attributes, permitting substitution up to 20% without adverse effects (Thilakarathna et al., 2025). Structuring agents, such as Hydroxypropyl Methylcellulose (HPMC), have also enabled sunflower oil-based oleogels to replace CB at levels up to 50% while preserving quality (Espert et al., 2021).

Alongside functional fats, local and underutilized plant sources are emerging as valuable inclusions. Although not a direct fat replacer, Coffee Husk Flour (CHF) improved chocolate hardness and rheological behavior while remaining acceptable to consumers (Borges et al., 2024). Meanwhile, coconut oil, used at 5% inclusion, enhanced oxidative stability and retained favorable sensory properties (Sarpong et al., 2024). In CBS-based chocolates, hydrogenated palm kernel oil stearin combined with specific milk powder types significantly influenced textural and sensory properties, emphasizing the role of ingredient interactions (Konar et al., 2023).

Recent technological advances, such as oleogelation and emulsification, are expanding possibilities for CB replacement. Oleogels developed using emulsion-template strategies offer controlled melting behavior and support desirable fat crystallization without reducing acceptability (Espert et al., 2021). Water-in-oil emulsions enhanced with citric acid and monoglycerides were reported to maintain polymorphic stability and surfactant performance even with reduced CB levels (Caballero-Tovar et al., 2024). Furthermore, emulsifier selection proved essential in ensuring flocculation control and emulsion stability (Schmid et al., 2025), highlighting the need for fine-tuned structural management during formulation.

Optimization methods, including ingredient reconstitution and predictive modeling, also play a crucial role. Reconstituted cocoa liquor made from cocoa cake and CB demonstrated comparable flavor and color to traditional liquor, reducing reliance on conventional raw materials (Puchol-Miquel et al., 2021). D-optimal mixture design enabled cost-effective CBS-based milk chocolate formulations, with milk powder type significantly influencing sensory and economic performance (Konar et al., 2023). Modeling studies on coconut oil also indicated that 5% inclusion provided an optimal balance of antioxidant retention and mouthfeel (Sarpong et al., 2024).

Despite these promising developments, key challenges remain. Many studies omit long-term evaluations of storage stability and fat bloom. While mahua oil-based chocolates exhibited no bloom under testing (Thilakarathna et al., 2025), similar evaluations were missing in studies involving CHF and oleogels (Borges et al., 2024; Espert et al., 2021). Additionally, sensory testing often lacks depth, relying mainly on basic hedonic scoring without advanced profiling or consumer input. To assess commercial potential, future work must incorporate analyses of storage behavior, polymorphic transitions, and detailed sensory perception.

Alternative lipid structuring approaches are gaining traction. Spreadable chocolates formulated with pistachio oil, xanthan gum, and monoglycerides demonstrated sensory characteristics comparable to commercial spreads when 15% pistachio oil was used (Mousazadeh et al., 2023). Hybrid gels combining beeswax-based oleogels with sodium alginate hydrogels replaced up to 15% of traditional CBAs, offering thermal and textural properties close to those of control samples (Ghorghi et al., 2023). Meanwhile, commercial Milk Fat Alternatives (MFAs) such as MF2 closely replicated CB polymorphism and were reported to be suitable for couverture applications (Fiore et al., 2025).

Chocolate is also being reimagined as a carrier for functional ingredients. Fortification with spray-dried blueberry and red wine powders significantly boosted phenolic content in white chocolate without compromising taste (Alvarez et al., 2024). Moreover, pistachio oil further contributed to oxidative stability and spreadability in chocolate spreads (Mousazadeh et al., 2023). In a pharmaceutical application, tadalafil incorporated into β-cyclodextrin-containing chocolate improved solubility and taste masking, highlighting chocolate's potential as a health-oriented matrix (Modi et al., 2024). However, the stability and sensory performance of such bioactive systems require further exploration.

Innovation in processing methods is also shaping the future of chocolate. The success of 3D printed chocolate was discovered to depend heavily on the fat's yield stress and thermal setting properties (Rando & Ramaioli, 2021). Hybrid gels effectively adjusted flow behavior for 3D printing applications (Ghorghi et al., 2023), while stable polymorphism and thermal behavior remained critical in new manufacturing contexts (Fiore et al., 2025). Nevertheless, high substitution rates and extended storage studies are underexplored, and understanding the matrix interactions remains crucial (Alvarez et al., 2024).

Looking ahead, future strategies must balance nutritional, sensory, and economic performance while ensuring processing compatibility. Predictive modeling of rheological and crystallization behavior offers pathways for more efficient formulation (Bölük et al., 2024) (Rando & Ramaioli, 2021). Additionally, optimizing the interaction of CBAs with emulsifiers, hydrocolloids, and bioactives can enhance product stability and appeal.

Socio-economic and environmental factors are increasingly influential in CBA adoption. For instance, shea butter's rise from a subsistence commodity to a global CBE has economically empowered women's cooperatives but also introduced ecological trade-offs (Wardell et al., 2022). Conversely, engineered lipids like oleogels and emulsions offer technical advantages but often lack integration with local economies (Alvarez et al., 2021; You et al., 2023). Notably, combining traditional fats with modern structuring techniques may yield sustainable, culturally aligned solutions.

In conclusion, CBAs offer significant promise for couverture chocolate when fat composition, structuring methods, and bioactive incorporation are carefully managed. Integrated approaches using oleogelation, emulsification, and sensory validation paired with economic and sustainability assessments will be central to developing the next generation of functional and environmentally conscious chocolate products.

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Research Question

Research questions play a vital role in a Systematic Literature Review (SLR) since they lay the groundwork and shape the direction of the entire review process. They help narrow the scope and focus, guiding decisions on which studies to include or exclude. This focus ensures that the review stays relevant and specific to its topic. In particular, clearly defined research questions lead to a comprehensive and methodical literature search, encompassing all relevant studies that highlight essential aspects, which minimizes bias and provides a thorough overview of existing evidence.

Moreover, research questions aid in categorizing and organizing data from the included studies, offering a framework for analyzing findings and synthesizing results into meaningful conclusions. They enhance clarity and focus, avoiding ambiguity and keeping the review anchored to specific issues, ultimately making the findings more actionable and applicable.

Additionally, well-formulated research questions improve the transparency and reproducibility of the review process. This allows other researchers to follow the same methodology to verify findings or expand the review into related areas. Ultimately, research questions ensure that the review aligns with the study's overall goals, whether that involves identifying gaps in the literature, assessing the effectiveness of interventions, or examining trends within a particular field. In essence, they are the backbone of a rigorous and relevant SLR.

Using the PICo framework helps structure research questions clearly and systematically by breaking down key study components into three elements. This approach ensures research is targeted and questions are well-defined, simplifying the search for relevant literature or the design of a study. As a result, this study formulated three research questions, outlined below;

1. How do CBAs and fat modification strategies influence the physicochemical and sensory properties of chocolate couverture formulations?
2. What is the impact of incorporating functional and nutritional ingredients into chocolate couverture on its health benefits and consumer acceptability?
3. In what ways do processing conditions and crystallization behavior, analyzed through advanced techniques, affect the texture, stability, and shelf life of chocolate couverture?

Materials and Methods

Conducting an SLR demands a clear and structured methodology, and one of the most widely accepted frameworks for this purpose is the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach. This framework promotes transparency, thoroughness, and consistency across the review process, as outlined in the work (Page et al., 2021). By adhering to PRISMA guidelines, researchers are able to strengthen the credibility and rigor of their analysis. In addition, the framework provides detailed direction on systematically identifying, selecting, and including relevant studies, with particular emphasis on randomized studies due to their ability to reduce bias and enhance the strength of evidence. This review utilizes two prominent databases, ScienceDirect and Scopus, which were selected for their broad coverage and established credibility within the academic research community.
The PRISMA method is divided into four critical stages: identification, screening, eligibility, and data abstraction. In the identification stage, comprehensive searches are conducted across the databases to capture all potentially relevant studies. Meanwhile, the screening stage involves

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applying inclusion and exclusion criteria to eliminate irrelevant or insufficient studies. Next, during the eligibility stage, the remaining studies undergo a more in-depth assessment to ensure they fully meet the criteria established for inclusion. The final stage, data abstraction, involves systematically extracting and synthesizing data from the selected studies, which provides the foundation for drawing meaningful conclusions.

Following this structured approach enables researchers to conduct systematic reviews that are methodologically robust and capable of yielding insights that can inform academic research and practical decision-making.

Identification

Identification is the first and foundational step in the SLR process. In this stage, relevant studies are located through comprehensive database searches using predefined keywords. For this review, searches were conducted using two leading academic databases, Scopus and ScienceDirect, due to their broad coverage and reliability. A keyword strategy was applied that included terms such as development, formulation, composition, chocolate, CBA, CBE, CBR, CBS, and CB. This search yielded 435 records, with 336 records identified through Scopus and 99 through ScienceDirect (as outlined in Table 1).

Table 1: The Search String

Scopus	TITLE-ABS-KEY-AUTH ((development OR formulation OR composition) AND chocolate AND ("cocoa butter alternative" OR cbe OR cbr OR cbs OR "cocoa butter")) AND (LIMIT-TO (SRCTYPE, "j")) AND (LIMIT-TO (PUBSTAGE, "final")) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (SUBJAREA, "AGRI")) AND (LIMIT-TO (PUBYEAR, 2022) OR LIMIT-TO (PUBYEAR, 2023) OR LIMIT-TO (PUBYEAR, 2024) OR LIMIT-TO (PUBYEAR, 2025)) AND (LIMIT-TO (LANGUAGE, "English")) **Date of Access: May 2025**
ScienceDirect	(development OR formulation OR composition) AND chocolate AND ("cocoa butter alternative" OR cbe OR cbr OR cbs OR "cocoa butter") **Date of Access: May 2025**

Screening

As the second stage of the SLR, the screening process involved a structured application of exclusion criteria to refine the initially identified records and ensure the relevance and quality of the literature included. A total of 309 records were excluded based on several key parameters: non-English language publications were excluded to maintain clarity and consistency. Studies published before 2022 were excluded to focus on recent advancements, and document types such as conference papers, book chapters, reviews, and in-press articles were omitted to prioritize peer-reviewed original research (refer to Table 2). Additionally, subject areas unrelated to the core topic, such as Chemistry, Chemical Engineering,

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Engineering, Health Professions, and Immunology and Microbiology, were filtered out to narrow the scope to food science and technology, specifically concerning CBAs in chocolate couverture. Following this rigorous screening, 63 relevant articles remained for further review, comprising 44 from Scopus and 19 from ScienceDirect, ensuring a focused and high-quality dataset for subsequent analysis.

Table 2: The Selection Criterion Is Searching

Criterion	Inclusion	Exclusion
Language	English	Non-English
Time line	2022 – 2025	< 2022
Literature type	Journal (Article)	Conference, Book, Review
Publication Stage	Final	In Press
Subject Area	Agricultural and Biological Sciences, Material Science	Chemistry, Chemical Engineering, Engineering, Health Professions, Immunology, and Microbiology

Eligibility
In the eligibility stage of the SLR, a total of 46 articles were closely examined to determine their suitability for inclusion in the final qualitative analysis. This stage involved thoroughly assessing each article's title, abstract, and availability of full-text content. Several articles were excluded at this point due to specific reasons that rendered them incompatible with the research scope. First, some studies were discovered to be out of the intended field, diverging from the focus on chocolate couverture and CBAs. Others had titles that were not sufficiently indicative of relevance or abstracts that did not align with the research objectives, suggesting a lack of direct contribution to the topic. Additionally, a number of articles were removed due to restricted access to full-text content, which impeded detailed evaluation.

As a result of this critical filtering process, 19 articles were excluded, retaining a final total of 27 studies deemed eligible for inclusion in the qualitative synthesis. These selected articles represent a refined, thematically focused body of literature, offering valuable insights into formulation strategies, functional properties, and the technological implications of CBAs in couverture chocolate. By narrowing down the dataset through meticulous evaluation, this stage ensured that only the most relevant, accessible, and substantive studies were retained, strengthening the overall review's credibility and depth.

Data Abstraction and Analysis
This study employed an integrative analysis as a key assessment strategy to review and synthesize various quantitative research designs. The main aim was to identify relevant topics and subtopics within the field. The first step in developing the themes involved data collection.

As illustrated in Table 3, the authors carefully analyzed a collection of 27 publications to extract assertions or information pertinent to the study's topics.

Following this, the authors evaluated significant studies related to formulation strategies for chocolate couverture utilizing CBAs, examining both the methodologies used in these studies and their findings. They collaborated with co-authors to develop themes that reflected the evidence gathered in the context of this research. A log was maintained throughout the data analysis process to document any analyses, perspectives, challenges, or insights related to interpreting the data.

Finally, the authors compared their results to identify any inconsistencies in the theme development process. If any disagreements arose regarding the concepts, the authors engaged in discussions to clarify and resolve them.

Quality of Appraisal

According to the guidelines proposed by (Kitchenham, 2007), once we have selected primary, we have to assess the quality of the research they present and quantitatively compare them. In this study, we apply QA from (Abouzahra et al., 2020), comprising six QAs for our SLR. The scoring procedure for evaluating each criterion involves three possible ratings: "Yes" (Y) with a score of 1 if the criterion is fully met, "Partly" (P) with a score of 0.5 if the criterion is somewhat met but contains some gaps or shortcomings, and "No" (N) with a score of 0 if the criterion is not met at all.

• QA1. Is the purpose of the study clearly stated?
• QA2. Is the interest and the usefulness of the work clearly presented?
• QA3. Is the study methodology clearly established?
• QA4. Are the concepts of the approach clearly defined?
• QA5. Is the work compared and measured with other similar work?
• QA6. Are the limitations of the work clearly mentioned?

The table outlines a QA process used to evaluate a study based on specific criteria. Three experts assess the study using the criteria listed, and each criterion is scored as "Yes" (Y), "Partly" (P), or "No" (N).

Each expert independently assesses the study according to these criteria, and the scores are then totaled across all experts to determine the overall mark. For a study to be accepted for the following process, the total mark, derived from summing the scores from all three experts, must exceed 3.0. This threshold ensures that only studies meeting a certain quality standard proceed further.

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Table 3: Number and Details of Primary Studies Database

No.	Authors	Title	Year	Journal	Scopus	ScienceDirect
1	Borges et al.	Technological and nutritional aspects of dark chocolate with added coffee husk flour; [Aspectos tecnológicos e nutricionais de chocolate amargo com adição de farinha de casca de café]	2024	Pesquisa Agropecuaria Brasileira	/	
2	Kamali et al.	Effect of transesterified amaranth oil oleogel as a cocoa butter replacer on the physicochemical properties of dark chocolate	2025	Food Chemistry: X	/	/
3	Fetriyuna et al	Cocoa Bean Shells: A Potential Chocolate Replacement in Food Production	2025	International Journal on Advanced Science, Engineering and Information Technology	/	
4	Adaptar et al.	Chemical composition and thermal characterization of selected Philippine cacao (Theobroma cacao L.) and tablea	2024	SciEnggJ	/	
5	Simone et al.	A synchrotron X-ray scattering study of the crystallization behavior of mixtures of confectionary triacylglycerides: Effect of chemical composition and shear on polymorphism and kinetics	2024	Food Research International	/	/
6	Iacumin et al.	Microbial Characterization of Retail Cocoa Powders and Chocolate Bars of Five Brands Sold in Italian Supermarkets	2022	Foods	/	
7	Rostami et al.	Modelling thermal characteristics of cocoa butter using a feed-forward artificial neural network based on multilayer perceptron	2024	International Journal of Food Science and Technology	/	
8	Konar et al.	Effects of various milk powders on main quality parameters of cocoa butter substitute-based chocolate	2023	International Dairy Journal	/	/
9	Shuai et al.	Effect of different oleogelation mechanisms on physical properties and oxidative stability of macadamia oil-based oleogels and its application	2024	LWT	/	/
10	Torregrossa et al.	Vegan and sugar-substituted chocolates: assessing physicochemical characteristics by NMR relaxometry, rheology, and DSC	2024	European Food Research and Technology	/	

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No.	Authors	Title	Year	Journal	Scopus	ScienceDirect
11	Koh et al.	The Effects of Gamma-Aminobuytric Acid (GABA) Enrichment on Nutritional, Physical, Shelf-Life, and Sensorial Properties of Dark Chocolate	2023	Foods	/	
12	Mokbul et al.	Characterization of Cocoa Butter Replacer Developed from Agricultural Waste of Mango Kernel and Rice Bran	2023	Journal of Food Processing and Preservation	/	
13	Šeremet et al.,	Development of new chocolate formulations by incorporating spray-dried and liposomal encapsulates of ground ivy (Glechoma hederacea L.) polyphenolic extract	2025	Food Chemistry	/	/
14	Sarpong et al.	Oxidative Stability Mechanism of Coconut Oil as Substitute to Cocoa Butter in Chocolate	2024	Journal of Culinary Science and Technology	/	
15	Guckenbiehl et al.	Distribution and transition of aroma-active compounds in dark chocolate model systems under conching conditions	2024	Food Chemistry	/	/
16	Figueira & Luccas	Physicochemical characterization of national and commercial cocoa butter used in Brazil to make chocolate; [Caracterização físico-química de manteigas de cacau nacional e comercial utilizadas no Brasil para fabricação de chocolate]	2022	Brazilian Journal of Food Technology	/	
17	Thilakarathna et al.	Mahua oil fraction: A sustainable and functional 1,3-dipalmitoyl-2-oleoylglycerol (POS)-enriched cocoa butter equivalent for chocolate production	2025	Food Chemistry	/	/
18	Jasel Alvarez Gaona et al.	Phenolic composition and sensory dynamic profile of chocolate samples enriched with red wine and blueberry powders	2024	Food Research International	/	/
19	Avami et al.	Optimization of sugar free dark chocolate product compatible for ketogenic diet and investigating its physicochemical, textural, thermal and sensory properties	2023	Iranian Food Science and Technology Research Journal	/	
20	Younes et al.	Pilot plant extraction of oligo/polysaccharides from cocoa bean shells and their incorporation into chocolate-based formulations	2024	Food Chemistry	/	/

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21	Budiyanto & Sari	Product development of sweets chocolate cube using value engineering method	2024	Food Research	/	
22	Ghorghi et al.	Fabrication of novel hybrid gel based on beeswax oleogel: Application in the compound chocolate formulation	2023	Food Hydrocolloids	/	/
23	Bölük et al.	Determination of the process effect on cocoa butter crystallization by rheometer: Kinetic modeling by Gompertz equation	2024	Journal of Food Science	/	
24	Liu et al.	Effect of tempered procedures on the crystallization behavior of different positions of cocoa butter products	2022	Food Chemistry	/	/
25	You et al.	Development of fat-reduced 3D printed chocolate by substituting cocoa butter with water-in-oil emulsions	2023	Food Hydrocolloids	/	/
26	Laughter et al	Effect of curing conditions on heat resistance in white chocolate	2024	Food Science and Nutrition	/	
27	Yucel et al.	A rheometer-based method to determine the crystal types of cocoa butter in white chocolate	2022	European Food Research and Technology	/	

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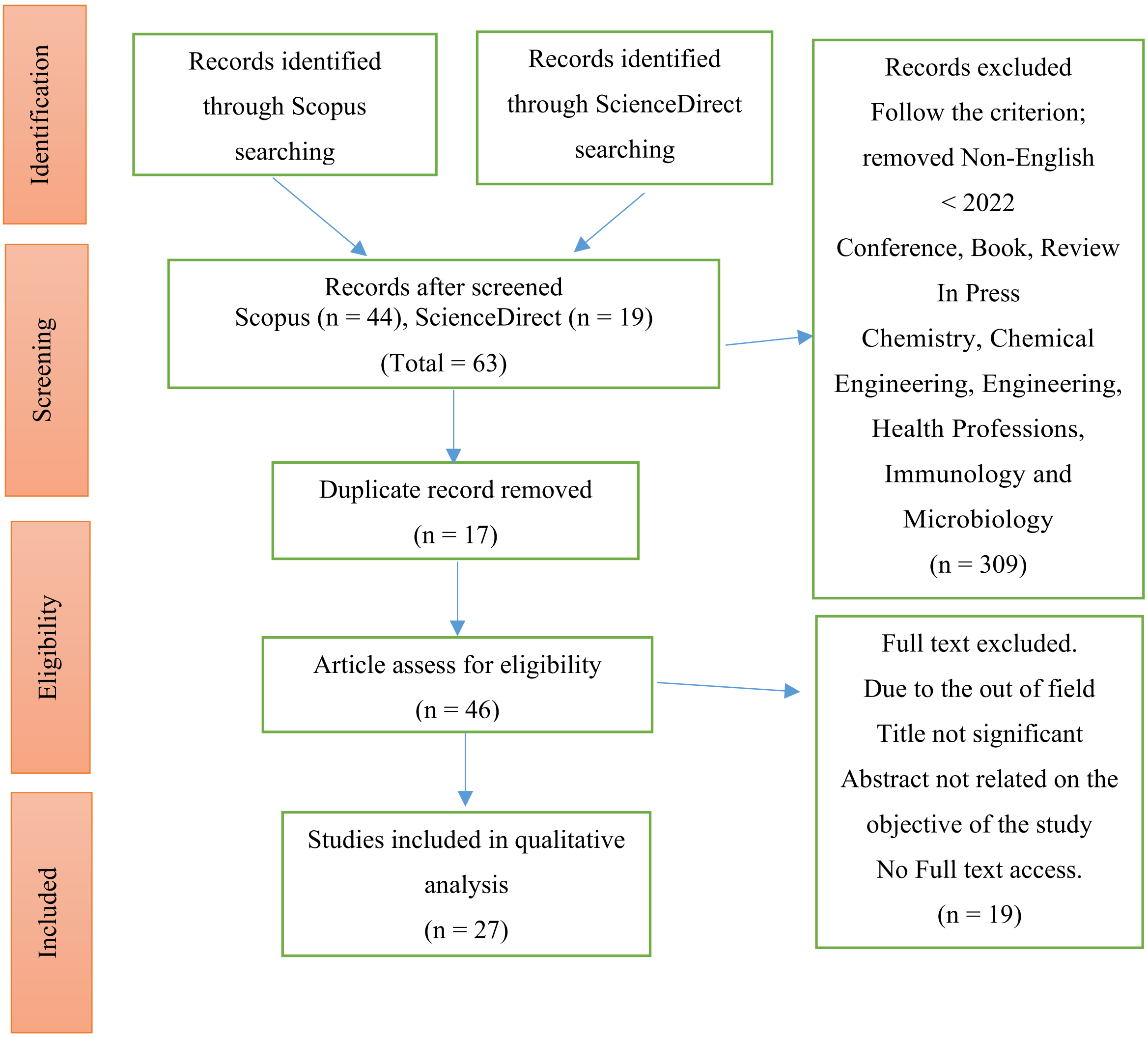

Figure 1: Flow Diagram of The Proposed Searching Study

Result and Findings

The QA of the 27 primary studies included in the qualitative analysis demonstrated commendably high methodological rigor and reporting standards. Evaluated against six criteria (QA1–QA6), the assessment focused on clarity of purpose, usefulness, methodological transparency, conceptual definition, comparative evaluation, and discussion of limitations. Remarkably, most studies (100%) successfully met the first four criteria, indicating they clearly articulated their objectives (QA1), relevance (QA2), methodological design (QA3), and core concepts (QA4). This strong compliance reflects a solid foundation of quality and relevance to the SLR aimed at exploring formulation strategies for chocolate couverture using CBAs.

However, there was notable variation in responses to QA5 (comparison with other similar works) and QA6 (discussion of limitations). Only 18 of the 27 studies (66.7%) fully addressed QA5, indicating that while many papers contextualized their findings within the existing literature, a substantial number did not explicitly benchmark against prior research. The lowest compliance was observed in QA6, with only nine studies (33.3%) discussing limitations, revealing a significant gap in critical reflection that affects the interpretability and generalizability of their findings. Overall, 18 studies scored 5.5 out of 6 (91.7%), while the

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remaining nine received scores of 4.5 (75%). These results highlight the need for improvement in presenting limitations and comparative analyses, which will be essential for guiding future research and informing the synthesis and recommendations from this SLR.

Table 4: Performance Quality Assessment Table for The Primary Selected Papers

Primary Study	QA1	QA2	QA3	QA4	QA5	QA6	Total Mark	Percentage (%)
PS 1 (Borges et al., 2024)	Y	Y	Y	Y	P	N	4.5	75
PS 2 (Kamali et al., 2025)	Y	Y	Y	Y	Y	P	5.5	91.7
PS 3 (Fetriyuna et al., 2025)	Y	Y	Y	Y	Y	P	5.5	91.7
PS 4 (Adaptar et al., 2024)	Y	Y	Y	Y	P	N	4.5	75
PS 5 (Simone et al., 2024)	Y	Y	Y	Y	Y	P	5.5	91.7
PS 6 (Iacumin et al., 2022)	Y	Y	Y	Y	P	N	4.5	75
PS 7 (Rostami et al., 2024)	Y	Y	Y	Y	Y	P	5.5	91.7
PS 8 (Konar et al., 2023)	Y	Y	Y	Y	Y	P	5.5	91.7
PS 9 (Shuai et al., 2024)	Y	Y	Y	Y	Y	P	5.5	91.7
PS 10 (Torregrossa et al., 2024)	Y	Y	Y	Y	Y	P	5.5	91.7
PS 11 (Koh et al., 2023)	Y	Y	Y	Y	Y	P	5.5	91.7
PS 12 (Mokbul et al., 2023)	Y	Y	Y	Y	Y	P	5.5	91.7

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Primary Study	QA1	QA2	QA3	QA4	QA5	QA6	Total Mark	Percentage (%)
PS 13 (Šeremet et al., 2025)	Y	Y	Y	Y	Y	P	5.5	91.7
PS 14 (Sarpong et al., 2024)	Y	Y	Y	Y	P	N	4.5	75
PS 15 (Guckenbiehl et al., 2024)	Y	Y	Y	Y	Y	P	5.5	91.7
PS 16 (Figueira & Luccas, 2022)	Y	Y	Y	Y	P	N	4.5	75
PS 17 (Thilakarathna et al., 2025)	Y	Y	Y	Y	Y	P	5.5	91.7
PS 18 (Jasel Alvarez Gaona et al., 2024)	Y	Y	Y	Y	Y	P	5.5	91.7
PS 19 (Avami et al., 2023)	Y	Y	Y	Y	P	N	4.5	75
PS 20 (Younes et al., 2024)	Y	Y	Y	Y	Y	P	5.5	91.7
PS 21 (Budiyanto & Sari, 2024)	Y	Y	Y	Y	P	N	4.5	75
PS 22 (Ghorghi et al., 2023)	Y	Y	Y	Y	Y	P	5.5	91.7
PS 23 (Bölük et al., 2024)	Y	Y	Y	Y	Y	P	5.5	91.7
PS 24 (Liu et al., 2022)	Y	Y	Y	Y	Y	P	5.5	91.7
PS 25 (You et al., 2023)	Y	Y	Y	Y	Y	P	5.5	91.7

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Primary Study	QA1	QA2	QA3	QA4	QA5	QA6	Total Mark	Percentage (%)
PS 26 (Laughter et al., 2024)	Y	Y	Y	Y	P	N	4.5	75
PS 27 (Yucel et al., 2022)	Y	Y	Y	Y	Y	P	5.5	91.7

Cocoa Butter Alternatives and Fat Modification

Researchers have extensively explored CBAs and fat modification strategies to tackle the high cost, limited availability, and health concerns related to saturated fats in chocolate. Effective methods include enzymatic interesterification, oleogelation, and blending of natural fats. (Kamali et al., 2025) demonstrated that enzymatically modified amaranth oil oleogels could replace up to 15% CB without significantly altering crystallization or thermal properties. Similarly, blends of mango kernel and rice bran oils, modified enzymatically, maintained desirable melting behavior and fat polymorphism at 20% substitution levels (Mokbul et al., 2023). POS-rich fractions from mahua oil were also successfully used up to 20% without compromising rheological or textural characteristics in chocolate (Thilakarathna et al., 2025), highlighting the significance of enzymatic precision and fat composition in effective substitution.

Oleogelation, using plant-based oils, has gained traction for its ability to enhance the oxidative and thermal stability of chocolates. For instance, oleogels made from macadamia oil structured with γ-oryzanol and β-sitosterol formed stable networks suitable for chocolate formulations (Shuai et al., 2024). A hybrid gel combination of beeswax oleogels and sodium alginate hydrogels demonstrated promising physical and sensory properties, particularly at a 5:95 hydrogel-to-oleogel ratio (Ghorghi et al., 2023). Moreover, incorporating monoglyceride oleogels based on modified amaranth oil supported the formation of stable β-type crystals and preserved favorable textures (Kamali et al., 2025), reinforcing oleogelation as a valuable structuring tool.

Fat substitution also includes emulsion systems, especially in novel applications such as 3D printed chocolates. (You et al., 2023) reported that reduced-fat chocolates made with water-in-oil emulsions stabilized by gum Arabic could replace up to 75% of CB while maintaining form V polymorphism and acceptable mouthfeel. Although viscosity increased and snap properties improved, critical structural and tempering characteristics remained intact. Similarly, structured emulsions and hybrid gels have effectively reduced CB and saturated fat content, aligning with consumer demand for healthier chocolate (Ghorghi et al., 2023).

Oxidative stability remains a key concern, particularly when using tropical oils. (Sarpong et al., 2024) observed that increasing coconut oil levels raised peroxide values, yet a 5% inclusion retained polyphenols and sensory quality. In contrast, oleogels from macadamia oil exhibited superior oxidative stability due to robust polymeric structures (Shuai et al., 2024). Mahua oil-based formulations also presented no fat bloom at 20% substitution, supporting their storage suitability (Thilakarathna et al., 2025).

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Blending strategies with milk powders and CBAs have produced cost-effective and sensory-acceptable outcomes. (Konar et al., 2023) asserted that CBS-based chocolate with various milk powders preserved texture and flavor while cutting costs. Likewise, 5% oleogel inclusion had minimal impact on hardness or bloom (Kamali et al., 2025), and mahua oil blends preserved mouthfeel and hardness at 20% replacement (Thilakarathna et al., 2025).

In conclusion, CBA strategies such as enzymatic modification, oleogelation, emulsification, and blending have demonstrated strong potential to replicate CB's functionality. Success depends on careful selection of fat sources, structuring techniques, and blend ratios to maintain chocolate products' sensory, chemical, and physical integrity.

Nutritional and Functional Enhancement of Chocolate

Recent advancements in chocolate couverture formulation have shifted towards enhancing nutritional and functional attributes, particularly through integrating CBAs and bioactive additives derived from agricultural by-products. One notable approach is the incorporation of CHF, which has been demonstrated to improve the texture and physicochemical properties of dark chocolate. Although higher CHF inclusion increases hardness, it still enriches the chocolate's overall quality (Borges et al., 2024).

Research also highlights the enrichment of chocolates with specific bioactive compounds to confer targeted health benefits. For example, gamma-aminobuytric acid (GABA)-enriched chocolates have demonstrated a significant improvement in Angiotensin-Converting Enzyme (ACE) inhibition, without compromising sensory quality or shelf life (Koh et al., 2023). Additionally, encapsulated polyphenolic extracts from ground ivy have been incorporated to enhance sensory characteristics and ensure stable release behaviors, maintaining favorable melting properties (Šeremet et al., 2025). Moreover, phenolic-rich powders derived from red wine and blueberry extracts have increased anthocyanin and flavanol content in chocolate, resulting in modified sensory attributes and health-oriented formulations (Alvarez et al., 2024). Nutritional enhancements have also included macronutrient reformulations to align with ketogenic diets. For instance, sugar-free dark chocolates developed with CBSs and sodium caseinate have achieved higher protein and fat contents while preserving desirable melting and textural properties. These formulations also exhibit extended oxidative stability (Avami et al., 2023). Evaluations of vegan and sugar-substituted chocolate variants demonstrate that eliminating milk and sucrose can alter rheological and thermal characteristics while still facilitating the formation of desirable CB crystals and maintaining acceptable sensory qualities (Torregrossa et al., 2024).

Consumer-driven product development has been pivotal in shaping these reformulation strategies. Innovations such as bite-sized milk chocolate cubes enhance convenience and cleanliness, catering to consumer preferences and market demands. These products leverage CB content in combination with nut inclusions to boost appeal, aligning with trends toward premium, functional chocolate formats (Budiyanto & Sari, 2024).

In summary, the literature reviewed reflects a multidisciplinary approach to chocolate couverture reformulation, integrating elements of food science, sensory analysis, and consumer insights. The use of CBAs, bioactive-rich ingredients, and diet-friendly formulations enhances the nutritional and functional value of chocolate while addressing health concerns and

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promoting sustainability through the utilization of underused by-products and clean-label ingredients.

Processing, Crystallization, and Analytical Techniques in Chocolate Formulation
The formulation of chocolate couverture with enhanced nutritional and functional properties requires a thorough understanding of CB's crystallization behavior, processing parameters, and compositional influences. Numerous studies have explored these elements using advanced analytical and modeling techniques. A key finding highlights the significant impact of CB's chemical composition, specifically its TAG profiles, on its polymorphic crystallization behavior. For instance, CBEs rich in SOS exhibit a greater variety of polymorphs and faster transformation kinetics, whereas those high in POP demonstrate slower polymorphic transitions (Simone et al., 2024). Additionally, the superior thermal stability of Brazilian CB has been linked to its higher content of saturated fatty acids, which influences its polymorphic transitions and crystallization kinetics (Figueira & Luccas, 2022). This correlation between TAG composition and crystallization behavior has also been validated through artificial neural networks, which modeled the thermal behavior of CB samples based on their compositional variables (Rostami et al., 2024).

Moreover, analytical and rheological methods have been critical in understanding how processing conditions, such as temperature and shear, affect crystallization. Research demonstrated that a crystallization temperature of 26°C and a shear strain of 1% promoted rapid crystal growth and the formation of the βV polymorph. This was explored using the Gompertz model along with rheometric analysis (Bölük et al., 2024). Temperature scanning rheometry was applied to differentiate crystal types in white chocolate, linking polymorphic transformations to thermal treatment and storage conditions (Yucel et al., 2022). It was reported that under-tempered CB resulted in heterogeneous crystallization, increasing the risk of fat bloom due to the migration of low-saturated TAGs (Liu et al., 2022). These studies collectively emphasize the significance of precise thermal and mechanical processing in achieving desirable polymorphic outcomes for enhanced stability and texture.

Thermal analysis has played an essential role in characterizing CB and its products, contributing to quality assurance and functional enhancement. For example, studies on Philippine cacao and tablea revealed consistent polymorphic behavior among samples, with form V polymorph ideal for couverture production (Adaptar et al., 2024). The research also indicated that rapid thermal cycling could lead to the formation of less stable polymorphs, which processing control can mitigate. The distribution of aroma-active compounds under conching conditions revealed that volatiles such as acetic acid are absorbed into the fat phase depending on their polarity and fat content, thereby underscoring the nutritional and sensory implications of chocolate processing (Guckenbiehl et al., 2024). Furthermore, curing chocolate under controlled humidity and temperature demonstrated functional enhancement through post-production thermal treatment. This results in increased hardness and an improved internal structure in heat-resistant white chocolate (Laughter et al., 2024).

The microbial and physicochemical stability of chocolate is also critical for its functional quality. While low water activity in retail cocoa powders and chocolate bars can inhibit microbial growth, some products exhibited mold contamination likely due to CB bloom and humidity during packaging (Iacumin et al., 2022). These findings underline the significance of maintaining structural integrity and ensuring hygienic processing to preserve product safety and quality. Additionally, employing rheometry and synchrotron X-ray scattering has enabled detailed investigations of polymorphic transitions, highlighting the value of advanced analytical tools in chocolate research and development (Bölük et al., 2024; Simone et al., 2024). In conclusion, the studies reviewed demonstrate that nutritional and functional improvements in chocolate are closely tied to the physicochemical properties of CB and its processing. Manufacturers can optimise chocolate formulations by integrating thermal analysis, rheological assessments, and compositional modeling for enhanced stability, sensory characteristics, and shelf life. Notably, these findings significantly contribute to the development of chocolate couverture using CBAs or modified fats.

Discussion

The systematic review of 27 studies on CBAs in chocolate couverture reveals significant advancements in formulation strategies, nutritional enhancement, and processing techniques. Three key themes emerged: (1) CBAs and Fat Modification, highlighting enzymatic interesterification, oleogelation, and hybrid gels as effective methods to mimic CB's properties; (2) Nutritional and Functional Enhancement, where bioactive compounds, agricultural by-products (e.g., Cocoa Bean Shells), and macronutrient reformulation (e.g., ketogenic, vegan chocolates) improved health benefits without compromising sensory quality; and (3) Processing and Crystallization, emphasizing the critical role of temperature, shear, and advanced analytical techniques (e.g., rheometry, synchrotron X-ray scattering) in optimizing polymorphic stability and shelf-life. Notably, 66.7% of studies scored highly (≥ 91.7%) in methodological rigor, though only 33.3% explicitly discussed limitations, indicating a need for greater transparency in future research.

The findings underscore the interdisciplinary nature of chocolate innovation, where food chemistry, material science, and consumer preferences intersect. For instance, oleogels (e.g., macadamia oil structured with γ-oryzanol/β-sitosterol) and enzymatic modifications (e.g., mango kernel-rice bran blends) successfully replicated CB's melting profile and texture at ≤ 20% substitution, addressing cost and sustainability challenges. Still, oxidative stability remains a hurdle for tropical oil-based CBAs (e.g., coconut oil), necessitating antioxidant strategies or lower inclusion levels (5%). Functional enhancements, such as GABA enrichment for hypertension management or polyphenol encapsulation for controlled release, demonstrate chocolate's potential as a health-oriented product. However, sensory trade-offs like altered mouthfeel in vegan formulations highlight the need for balanced reformulation. The consistent use of advanced analytical tools (e.g., Differential Scanning Calorimetry (DSC), X-ray Diffraction (XRD)) to monitor polymorphic behavior (βV form) and crystallization kinetics reflects the industry's shift toward precision in processing, ensuring quality in novel formats like 3D-printed chocolates.

The practical implications of these findings are profound for the confectionery industry. Manufacturers can adopt CBAs like POS-rich mahua oil or hybrid gels to reduce reliance on CB while meeting clean-label and sustainability demands. However, scaling these innovations requires addressing gaps in long-term storage stability (e.g., fat bloom resistance) and regulatory compliance, particularly in markets with strict CB standards (e.g., EU). Future research should prioritize: (1) holistic sensory and consumer studies to validate the acceptability of CBA-based chocolates across diverse demographics; (2) real-world storage trials to assess oxidative and polymorphic stability under commercial conditions; and (3) lifecycle assessments to evaluate the environmental impact of alternative fat sources.

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Accordingly, collaborative efforts between academia and industry will be essential to translate lab-scale successes into scalable solutions, ensuring that functional, sustainable chocolates meet both consumer expectations and industrial feasibility.

This review bridges theoretical insights with actionable strategies, offering a roadmap for next-generation chocolate couverture. The integration of socio-economic considerations, such as supporting smallholder farmers in CBA supply chains (e.g., shea butter cooperatives), could further enhance sustainability. Ultimately, the evolution of chocolate formulation lies in balancing innovation with tradition, ensuring that health-focused, environmentally friendly products retain the sensory magic that defines chocolate's universal appeal.

Conclusion

This systematic review explored formulation strategies for chocolate couverture using CBAs, focusing on three key research questions: the impact of CBAs on physicochemical and sensory properties, the role of functional ingredients in enhancing nutritional value, and the influence of processing techniques on product stability. Analyzing 27 studies, the review identified significant fat modification, nutritional enrichment, and crystallization control advancements, providing insights into current innovations and persisting challenges.

The findings highlight effective methods such as enzymatic interesterification, oleogelation, and hybrid gels that can replicate CB's functional properties, with certain alternatives like mahua oil and enzymatically modified blends achieving substitution levels of up to 20%. Nutritional enhancements, including the incorporation of cocoa bean shells or GABA, offered potential health benefits without compromising sensory quality. At the same time, advanced processing techniques helped maintain optimal polymorphic stability and shelf life. Nevertheless, gaps exist in long-term storage studies, comparative benchmarking, and regulatory alignment, especially concerning tropical oil-based alternatives.

Therefore, future research should prioritize scalable solutions, consumer acceptability, and sustainability assessments. This review emphasizes interdisciplinary collaboration for advancing formulations, balancing innovation with tradition to meet consumer and industry demands. It consolidates fragmented knowledge on CBAs and offers actionable insights for manufacturers and researchers.

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