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Towards a Circular Bioeconomy in Cacao Bean Shells: Recent Valorization Pathways and Potential Applications in Food Powder Formulations–A Review

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Abstract

Cacao bean shells (CBS), a by-product of chocolate production known for their rich content of bioactive, nutritional, and functional compounds, have gained increasing attention in recent years as part of circular bioeconomy strategies. In the framework of valorization, CBS has been widely explored for diverse applications, including as a fuel, feed, fiber, and nutraceuticals. However, despite its industrial potential, no comprehensive review has yet addressed its valorization pathways, particularly its viability as an ingredient in food powder formulations. Therefore, this review examines the potential of CBS as a food powder resource and evaluates its feasibility as functional ingredient in food systems, focusing on formulation techniques, processing technologies, and the assessment of techno-functional properties. This comprehensive review further examines the potential utilization of CBS powder in food formulations and its corresponding feasibility as an admixture for premix powder formulations. The findings indicate that the valorization of CBS powder in food formulations remains largely unexplored, with only a limited number of studies investigating its application in baked systems. Overall, this review highlights significant opportunities for further exploration of CBS valorization, particularly its potential as an admixture in instant premix powder formulations, as current applications primarily rely on direct incorporation. This review serves as foundational knowledge for food processors and researchers committed to circular economy principles, with a strong interest in the development of innovative food products derived from CBS powder.

Keywords: baked systems; bioactive compounds; cacao byproduct; functional ingredient; premix formulation

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INTRODUCTION

Cacao bean shells (CBS), a major by-product of cacao (*Theobroma cacao*) bean processing, have gained increasing attention in recent years due to their high content of nutritional and bioactive compounds (Belwal et al., 2022). CBS, generated during the shelling process, accounts for approximately 12 to 20% of the total bean weight, representing more than 800,000 tons of

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waste that is often discarded and remains underutilized (Okiyama et al., 2017; ICCO, 2023). This substantial amount of waste generated varies depending on the processing methods applied to the beans prior to roasting, such as harvesting, fermentation, and drying (Rojo-Poveda et al., 2020a). However, despite being a by-product, CBS contains valuable compounds with a chemical profile that closely resembles that of the beans. They are rich in soluble and insoluble fiber, fats, and polyphenols, which are vital for formulating health-promoting food products (Indiarto et al., 2021; Younes et al., 2023). Thus, several bioconversion and valorization strategies have been applied to CBS in order to repurpose this by-product into a more beneficial and functional bioresource (Sanchez et al., 2025a).

The valorization of agricultural by-products, including CBS (Figure 1), represents an integrated strategy to maximize nutritional and functional properties for food and industrial applications. This approach simultaneously minimizes waste generation and promotes a green and sustainable environment (Sindol et al., 2022; Sanchez et al., 2025a). This strategy is closely aligned with the concept of circular bioeconomy, which seeks to transform by-products into valuable resources by extending their utility through upcycling or repurposing (Marshall et al., 2023; Valencia et al., 2024). According to Mallick et al. (2024), a circular bioeconomy is an economic system that utilizes renewable biological resources, such as crops, forests, and microorganisms, to generate a diverse range of products and services. Key benefits of the circular bioeconomy include food waste reduction, value addition to by-products, enhanced nutrition, and a diminished environmental footprint for agriculture and food processing sectors (Holden et al., 2023; Khanna et al., 2024). Hence, employing a bioeconomy approach offers a promising pathway toward a more sustainable and circular economy, where waste is minimized and resources are utilized more efficiently.

In the case of CBS, several authors have reviewed the valorization of CBS into valuable resources across various applications, including human food, animal feed, fertilizer, bioadsorbents, and biofuels (Panak Balentić et al., 2018; Cinar et al., 2021; Afedzi et al., 2023). Other studies have provided comprehensive profiling of the nutritional and bioactive composition of CBS and its derivatives for functional and nutraceutical use (Okiyama et al., 2017; Rojo-Poveda et al., 2020a; Younes et al., 2023). Yuneri and Syarifuddin (2024) critically discussed the potential of CBS powder as a functional ingredient in food and beverages, emphasizing the interaction between physicochemical properties and the valorized product. Recently, Sanchez et al. (2025a) reported various green and emerging bioconversion

Figure 1. Circular bioeconomy pathways of CBS
Note: Adapted with modifications from Sanchez et al. (2025b)

techniques for extracting valuable compounds present in CBS for diverse applications.

However, existing reviews are too comprehensive in detail and lack specific information regarding valorization pathways for food powder applications. Moreover, to the best of our knowledge, no review has critically analyzed the valorization pathways of CBS within a circular bioeconomy framework, focusing on 4 major processes of valorization: characterization, extraction, optimization, and value addition, particularly in relation to food applications. In particular, the potential of CBS as a primary ingredient in instant premix powder formulations remains unaddressed. Therefore, this review highlights key characteristics of CBS by-products as food powder resources and assesses their potential as functional ingredients in food systems, with emphasis on formulation strategies, processing technologies, and techno-functional properties. It also evaluates the valorization pathways and feasibility of incorporating CBS powder as an admixture in premix powder formulations. The insights gained in this review will provide up-to-date information on the processes involved in utilizing CBS as potential powder material for functional food composition, which is vital for food processors, researchers, and especially in the cacao industry.

MATERIALS AND METHOD

This review paper was conceptualized through a systematic examination of available and published literature pertaining to the utilization of CBS powder as an ingredient in food formulations. The review encompasses discussions on bioactive compounds, valorization pathways, and applications ranging from general uses to food applications, with a particular emphasis on bakery products. While various articles reporting the industrial use of CBS as a raw or processed material were included, the primary focus is to critically analyze and synthesize its potential as a food powder resource for premix powder formulations. Consequently, emphasis is placed on existing literature examining similar applications and their adaptability for premix powder formulations. The review sources include peer-reviewed and internationally indexed journal articles, conference proceedings, and books or book chapters. All references were critically reviewed and discussed in alignment with the main objective of the review.

RESULTS AND DISCUSSION

Valuable compounds of CBS for food formulations

Several authors have comprehensively reported the proximate, nutritional, and bioactive properties of CBS under various experimental conditions, including dried, undried, roasted, and untreated samples. The value ranges of these data are summarized and presented in Table 1. However, it should be noted that these data are critically compiled; thus, readers are encouraged to consult the original sources for detailed information on the specific measurement methodologies. As shown in Table 1, CBS contains substantial amounts of moisture (3.60 to 13.30 g 100 g^{-1}), ash (6.00 to 11.50 g 100 g^{-1}), and protein (10.30 to 27.40 g 100 g^{-1}). The variation in these proximate values is influenced by processing steps such as roasting, additional drying, or washing (Agus et al., 2018; Djali et al., 2023; Valencia et al., 2024). Agus et al. (2018) reported that roasting plays a major role in increasing the ash content of CBS, with levels potentially rising by up to 15%. Moreover, the moisture content of fresh CBS has been reported to be higher than that of roasted samples (Djali et al., 2023). Due to its hygroscopic nature, several authors have suggested that once powdered, CBS should be stored at elevated temperatures to prevent mycotoxin and fungal formations (Osundahunsi et al., 2007; Indiarto et al., 2021).

The carbohydrate and fat contents of CBS have been documented to range from 7.00 to 70.00 and 1.50 to 10.00 g 100 g^{-1}, respectively, depending on the processing methods applied. From a nutritional perspective, these carbohydrates in food products enhance the value of CBS-enriched materials, by serving as an energy source, supporting cellular activities, and playing a vital role in overall metabolism (Sanchez et al., 2025b). This broad range in reported values is often attributed to whether dietary fiber is included in the calculation, as carbohydrate content is typically estimated by difference method, which can introduce variability (Martínez et al., 2012). Similarly, the roasting process may also influence variation in the fat content of CBS samples. The predominant fatty acids identified in CBS are oleic, palmitic, capric, and stearic acids (González-Alejo et al., 2019). Notably, while CBS contains significantly less fat than the beans, this lower lipid content is offset by a substantial increase in dietary fiber content (Yuneri and Syarifuddin, 2024).

Furthermore, several researchers have previously characterized the nutritional and bioactive compounds in CBS. As shown in Table 1, significant amounts of dietary fiber, polyphenols, and methylxanthines can be extracted from CBS as a cacao by-product. These 3 major bioactive compounds have gained increasing popularity in the valorization of agricultural by-products due to their reported health-promoting properties, including antioxidant, anti-inflammatory, and metabolic benefits when incorporated into food products (Okiyama et al., 2017; Panak Balentić et al., 2018; Yuneri and Syarifuddin, 2024). Dietary fiber is the edible part of plants or analogous carbohydrate resistant to digestion and absorption in the small intestine. In CBS, the dietary fiber content ranges from 7.00 to 50.00 g 100 g^{-1}, and varies depending on the applications of roasting and drying (Agus et al., 2018; Younes et al., 2023). Dietary fiber is categorized into soluble and insoluble fractions; variations in these values are often attributed to the analytical methods employed (Rojo-Poveda et al., 2020a).

Polyphenols, which range from 3.00 to 95.00 g 100 g^{-1}, are among the most extensively studied compounds in CBS and are primarily responsible for its biofunctional properties (Sanchez et al., 2025b). Polyphenols are categorized into different groups according to the number of phenolic units and structural configurations. However, most studies report total phenolic content during extraction and characterization, representing the combined amount of all phenolic compounds in a sample, due to their strong antioxidant capacity and ability to neutralize reactive species such as oxygen, nitrogen, and chlorine radicals (Hernández-Hernández et al., 2019; Cinar et al., 2021).

CBS primarily contains the methylxanthines caffeine, theobromine, and theophylline, with theobromine being the most prevalent, while theophylline occurs only in trace amounts. Both caffeine and theobromine exert stimulatory effects on the central nervous system, contributing to the appeal of cocoa. However, the impact of theobromine is milder effect compared to caffeine (Okiyama et al., 2017; Cinar et al., 2021; Sanchez et al., 2025a). Yuneri and Syarifuddin (2024) reported that fermentation, roasting, and winnowing may influence the degradation of these bioactive compounds as they are the primary by-products of the beans during these processes. Given its moderate caffeine content and presence of other methylxanthines, CBS may provide valuable bioactive properties that support human health, enhancing its potential as a biofunctional ingredient in food and beverages. However, Olalekan-Adeniran et al. (2022) highlighted that despite its rich nutritional profile and exhibiting promising functional properties, evaluating the microbial load and potential toxic components is essential to ensure its safety for consumption.

Furthermore, CBS also contains various vitamins and minerals that enhance its potential as a functional food ingredient. While present in lower concentrations than proximate and bioactive compounds, these vitamins and minerals fulfill essential biological functions. CBS has been identified as a source of vitamins B1, B2, D, and E, with concentrations reaching up to 3.00 µg g^{-1} (Table 1). As early as the 1990s, the vitamin content of CBS powder was reported to include notable levels of vitamins B1 and B2, contributing to nearly 15% of the recommended dietary allowance. In contrast, only trace amounts of vitamins B6 and D were detected, while vitamin C was absent (Bonvehi and Jorda 1998; Rojo-Poveda et al., 2020a; Sanchez et al., 2025a). Moreover, it can be gleaned from Table 1 that this by-product is richest in potassium, magnesium, calcium, and phosphorus, with lesser amounts of sodium, iron, and other trace minerals. Variations in the physicochemical and nutritional composition of CBS may be influenced by several factors, including processing methods, drying and fermentation, cultivar, climate, and its origin (Okiyama et al., 2017; Rojo-Poveda et al., 2020a; Sanchez et al., 2025b).

In the context of valorization, maximizing the use of valuable compounds derived from bioresource materials is important. However, not all extractable components are fully optimized, as food safety and nutritional requirements must be met. In the case of CBS, despite its reported richness in macro- and micronutrients, concerns regarding its quality, integrity, and safety for direct utilization are emphasized (Alvarado et al., 2023; Sanchez et al., 2025b). This is because they may contain considerable amounts of phytotoxic compounds resulting from the bean-processing methods applied (Socas-Rodríguez et al., 2021; Yuneri and Syarifuddin, 2024). Consequently, the European Union has established permitted levels for CBS incorporation in food products, and any amount exceeding this may negatively affect overall quality (European Union, 2000; Okiyama

Table 1. Summary of the reviewed valuable chemical and nutritional profile of CBS

Proximate compound	Value range/Unit (g 100 g^{-1})	Reference
Moisture content	3.60-13.30	Arlorio et al. (2001); Lecumberri et al. (2007); Martínez et al. (2012); Okiyama et al. (2018); Rojo Poveda et al. (2020a); Djali et al. (2023); Dos Anjos Lopes et al. (2023); Duque et al. (2024)
Ash content	6.00-11.50	
Crude protein	10.30-27.40	
Crude fiber	39.00-66.50	
Crude fat	1.50-10.00	
Carbohydrate	7.00-70.00	
Bioactive compound		
Pectin	4.70-16.00	Panak Balentić et al. (2018); Vasquez et al. (2019); Rojo-Poveda et al. (2020a); Sánchez et al. (2023)
Dietary fiber (soluble/insoluble)	7.00-50.00	
Polyphenol	3.00-95.00	
Thebromine	0.40-2.30	
Caffeine	0.05-0.65	
Nutritional compound		
Vitamins (B1, B2, D, and E)	0.70-3.00*	Bonvehí and Jordà (1998); Iiyama et al. (2003); Vītola and Ciproviča (2016); Rojo-Poveda et al. (2020a); Younes et al. (2023)
Calcium	0.20-0.50	
Magnesium	0.50-1.30	
Phosphorus	0.60-1.00	
Potassium	1.25-1.80	
Sodium	0.16-0.18	
Iron	0.20-0.80	
Zinc	0.20-2.00	

Note: Data are referred to a CBS dry weight basis (%, g 100 g^{-1}) except for *vitamins (μg g^{-1})

et al., 2017). Nevertheless, the use of CBS as a functional ingredient in food formulations remains subject to national and local regulations, provided that proper profiling and evaluation are conducted (Hug et al., 2006).

Valorization pathways of CBS

Valorization pathways refer to the methods or processes involved in repurposing or adding value to a bioresource, such as in the case of CBS (Sanchez et al., 2025c). From a circular bioeconomy perspective, the chocolate industry stands to gain significantly from valorizing cacao bean by-products, as this approach can lower production, manufacturing, and transportation expenses. CBS offers a cost-effective, clean-label functional ingredient that can partially replace cocoa and act as a cocoa flavoring agent (Rojo-Poveda et al., 2020a; Younes et al., 2023). In general, the valorization of CBS into value-added products involves the use of diverse technologies, including biochemical, physical, physicochemical, and thermochemical methods (Afedzi et al., 2023). These existing technologies range from conventional or traditional methods (such as Soxhlet extraction, cold pressing, reflux, etc.) to advanced emerging techniques. The selection of an extraction method is contingent upon the processor, considering factors such as cost, impact on yield, and availability. Therefore, the strong interest in valorizing CBS using these bioconversion techniques depends largely on researchers' accessibility to them. Nonetheless, the comparative applications of advanced and green extraction methods have been critically reviewed by Afedzi et al. (2023) for all cocoa by-products, and by Sanchez et al. (2025a) specifically for CBS.

A promising valorization pathway of CBS involves utilizing its bioactive and nutritional compounds, present in the raw powder, as ingredients in the formulation of various innovative products across diverse applications. However, according to Çopur et al. (2019), appropriate processing methods should be carefully selected to preserve the desired nutritional and functional characteristics of the powder before use. Basically, the valorization process involves collecting the shells immediately after roasting and winnowing, followed by drying and powdering, as shown in Figure 2. Powdering plays a crucial step in the valorization process as this significantly influences the quality of the powdered product during subsequent operations, such as mixing and dissolution. The particle size, distribution, shape, surface characteristics, and density of the powders are highly variable and depend on both the properties of the raw materials and the processing conditions during their formation (Bhandari et al., 2023; Apatan et al., 2024). These parameters contribute to the functional properties of powders, including flowability, compressibility, and other reconstitution properties. Understanding these properties is paramount, as they determine how the powder performs when used as a product or ingredient, and these are directly affected by the interplay of its fundamental properties (Bhandari et al., 2023; Apatan et al., 2024).

Another major consideration in valorizing CBS into raw powder is the selection of an appropriate powdering technique. In many cases, the selection of a specific drying method for powder production depends on factors such as raw material characteristics, target particle size, the preservation of nutritional and functional qualities, as well as cost and energy efficiency. As a result, various parameters, including drying time, temperature, speed, and the use of carrier agents, must be carefully managed, as they significantly influence the final quality of the powdered product (Apatan et al., 2024; Mazhar et al., 2024). Thus, the chosen drying and powdering technique is crucial for producing a nutritionally sustained CBS powder. For more detailed and comprehensive information on various emerging drying technologies applicable to foods, researchers highly recommend that readers refer to the article by Çopur et al. (2019) to gain a comparison of these techniques, including their applications and limitations.

Consequently, as the application of powders expands within the food industry, gaining a thorough understanding of their properties has become essential for maintaining quality control and improving processing efficiency. As a result, CBS powder production has emerged as a key area of research, particularly because many newly developed food products, such as juice powders, instant premixes, etc. (Figure 2), are challenging to convert into powder form due to their composition and tendency toward stickiness (Çopur et al., 2019; Bhandari et al., 2023; Apatan et al., 2024). Therefore, beyond just selecting the raw materials, it is vital for food engineers and processors to evaluate the physicochemical and techno-functional characteristics of CBS powders before using them as replacements or supplementary components in food formulations. Overall, the choice of which value-added product to develop using CBS powder is of particular interest, as various factors must be considered, such as the specific application, marketability, and comparable nutritional quality it can offer. Nevertheless, in the context of research and development, any innovative idea requires subsequent and repeated trials, with ample room for improvement.

Recent applications of valorized CBS powder

General applications

Generally, the use of CBS has been explored in various industrial settings. As graphically

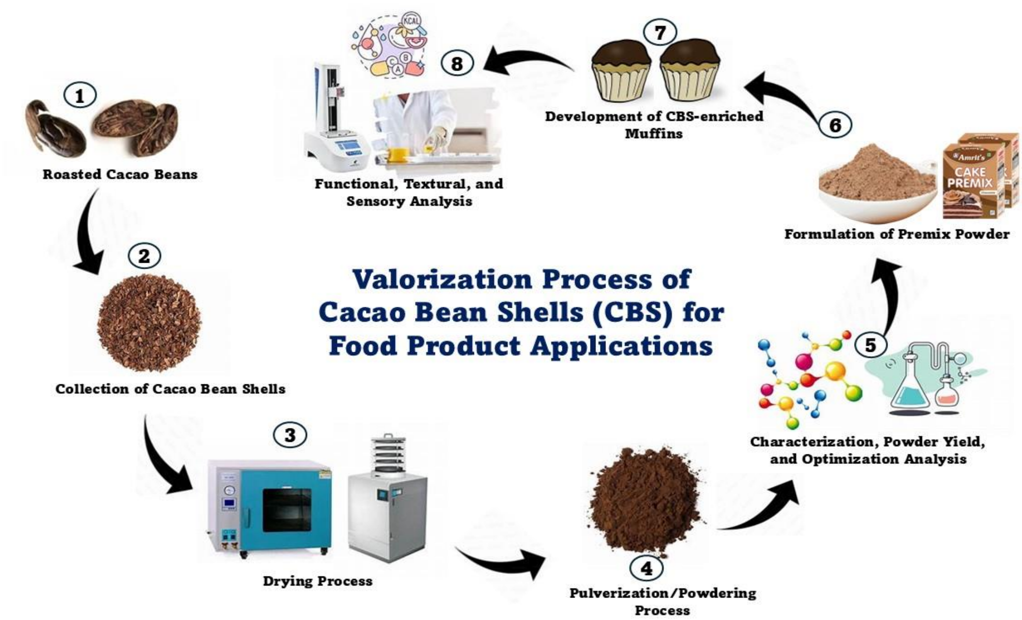

Figure 2. Schematic valorization process of CBS into powder for food and value-added product applications

Source: Sanchez et al. (2025a)

presented in Figure 3, the feasibility of CBS has been applied to several utilization methods such as a secondary source of antioxidants in drinks and beverages (Siow et al., 2022; Dos Anjos Lopes et al., 2023; Sánchez et al., 2024); supplements of carbohydrates, protein, and phenolics in foods (Rossin et al., 2021; Souza et al., 2022; Valencia et al., 2024); development of biocomposites, absorbents, and other biomaterials (Puglia et al., 2016; Rodríguez-Arellano et al., 2021); repurposed for biogas and biofuel (Awolu and Oyeyemi, 2015; Mancini et al., 2016), and admixtures to animal feed formulations (Andrade et al., 2010; Ayinde et al., 2010; Carvalho Junior et al., 2010; Emiola et al., 2011). Besides that, a few authors have comprehensively reviewed the use of CBS as a source of fiber (Okiyama et al., 2017); as extractives for value-added functional foods and animal feed additives (Afedzi et al., 2023); for food and beverage applications (Yuneri and Syarifuddin, 2024); in biotechnological uses (Sánchez et al., 2023); as well as critical discussions on its valuable nutritional, chemical (proximate), bioactive, and techno-functional properties (Panak Balentić et al., 2018; Rojo-Poveda et al., 2020a; Younes et al., 2023).

More recently, Sanchez et al. (2025a) provided an in-depth review of the latest applications and emerging green extraction methods for recovering valuable compounds from CBS for various purposes. However, the lack of critical discussion on the specific use of CBS powder as an ingredient in formulated food products inspired the authors to present this paper in order to contribute additional knowledge on its utilization. Therefore, the succeeding part of this paper will focus more on recent valorization strategies for CBS, with particular emphasis on powder production for value-added food products.

CBS powder applications in food products

As established in the preceding sections, CBS is a significant source of dietary fiber, carbohydrates, proteins, and notable amounts of bioactive compounds. Consequently, several authors have evaluated the feasibility of using powder derived from this by-product as a substitute or supplement in raw materials for preparing dough- and batter-based products such as breads, cakes, cookies, muffins, and others. These valorized and value-added food products, as presented and summarized in Table 2, have served as fundamental results in maximizing the potential of CBS as demonstrated by the variation in the formulations applied.

In the case of breads, Rinaldi et al. (2020) examined the impact of CBS powder sizes on the quality attributes of gluten-free bread during

Figure 3. Graphical representation of some general applications of CBS

storage. In their study, gluten-free bread was supplemented with different CBS particle size fractions (Table 2) and evaluated over a three-day storage period for volume, moisture content, crumb structure, texture, and color. The results showed that CBS addition affected the crumb grain and reduced the specific volume, especially in the formulation 2 (F2) group. It also accelerated crumb staling, although bread with F1 remained softer than the control by the end of the storage period. Additionally, CBS darkened the bread, with F3 having the most significant impact on L* and a* values. These findings highlight the potential of CBS powder as a functional additive in stored bread formulations, particularly fiber-enriched or gluten-free varieties, demonstrating its value in improving overall bread quality.

In an earlier study, Collar et al. (2009) investigated the impact of varying levels of CBS powder (Table 2) on the dietary fiber content of CBS-supplemented breads. The evaluation revealed that the incorporation of dietary fibers from CBS, both natural and alkalinized, significantly influences the visual properties, specific volume, and sensory attributes of the breads. Moreover, it influences the texture and staling behavior of fiber-enriched breads throughout storage. The authors concluded that incorporating up to 6% dietary fiber from CBS can successfully be used to create innovative wheat bread formulations that are technologically feasible, sensory-appealing, and have improved shelf stability.

Conversely, as CBS powder is a rich source of nutrients and bioactive compounds, such as fiber, it may serve as a valuable ingredient or additive for innovative and functional foods like biscuits (Rojo-Poveda et al., 2020a; Sanchez et al., 2025b). Rojo-Poveda et al. (2020b) investigated the physical properties and consumer acceptance of CBS-enriched biscuits designed for diabetic patients by replacing sucrose with tagatose. In their study, roasted CBS (Forastero variety) was ground to a grain size of less than 500 µm and further micronized using a ball mill to obtain powder with a particle size of less than 20 µm.

Six biscuit formulations were produced using 3 levels of wheat flour substitution (Table 2) and 2 types of sugar (sucrose and tagatose). The formulations utilized butter instead of shortening and excluded nonfat dry milk and high-fructose corn syrup. The biscuits exhibited significant differences in both technological and sensory properties. The use of tagatose and higher CBS levels increased water retention, which affected the physical and structural characteristics of the biscuits. Sensory analysis showed that biscuits made with sucrose were preferred to those made with tagatose, indicating notable differences between the 2 sugars and limited consumer acceptance of the physical attributes imparted by tagatose. The study demonstrated the feasibility of producing CBS- and tagatose-based biscuits for diabetic consumers. However, the lack of pretreatment of CBS powder may have contributed to the less favorable results with tagatose biscuits. The authors recommended further research on the functional properties of CBS-based biscuits to develop a more comprehensive understanding.

Building on the promising results from their high-fiber functional biscuits for diabetic consumers, Rojo-Poveda et al. (2020c) further investigated the effects of the biscuit food matrix on the bioaccessibility and bioactivity of bioactive compounds (polyphenols and methylxanthines)

Table 2. Summary of the reviewed food product applications of valorized CBS

Food products	CBS formulation range	Authors
Bread	0-8.00%	Collar et al. (2009)
	1.00-1.99 (fractions)	Rinaldi et al. (2020)
Biscuits	0%, 10%, and 20%	Rojo-Poveda et al. (2020b)
	10% and 20%	Rojo-Poveda et al. (2020c)
Cakes	30%, 40%, and 50%	Öztürk and Ova (2018)
	25%, 50%, 75%, and 100%	Souza et al. (2022)
Cookies	10%, 20%, and 30%	Handojo et al. (2019)
	1%, 2%, 3%, and 5%	Kim et al. (2021)
	5.00%, 7.50%, and 10.00%	Mahendradatta et al. (2020)
	2, 4, 6, 8, and 10 g	Olalekan-Adeniran et al. (2022)
Cereals	33%, 50%, and 100%	De Barros et al. (2021)
Muffins	11.5, 23.00, and 34.50 g	Martínez-Cervera et al. (2011)
Snack foods	10%, 30%, and 50%	Kovač et al. (2021)
Sausages	0.25%, 0.5%, 0.75%, 1%, and 2%	Choi et al. (2019)

following simulated gastrointestinal digestion. Roasted CBS in its natural form was used. Two biscuit groups were developed, one containing sucrose and the other containing the low-glycemic sugar tagatose. For each group, a control biscuit without CBS was produced, along with 2 variants in which wheat flour was partially replaced with CBS flour (Table 2).

Overall, no significant differences were associated with the type of sugar used. However, marked differences were observed when comparing CBS-enriched biscuits with samples containing an equivalent amount of CBS without a food matrix. Substituting sucrose with tagatose did not affect the bioavailability of CBS bioactive compounds. Notably, CBS incorporation increased the bioaccessibility of these compounds, leading to substantial α-glucosidase inhibition, and confirming their anti-diabetic potential. The 2 cited studies are the first to report the *in vitro* absorption of CBS methylxanthines. Overall, CBS powder has been shown to be an optimal revalorized ingredient for functional biscuits, with its biofunctional potential clearly demonstrated.

On the other hand, several researchers have explored the feasibility of incorporating CBS powder into cookie formulations. Cookies are a type of biscuit made from soft dough with a high fat content, which makes them relatively fragile. When cut lengthwise, they show a solid texture. According to Mahendradatta et al. (2020), cookie products have evolved through variations in ingredient combinations or substitutions with new materials aimed at improving nutritional value and offering more diverse varieties. Hence, they have investigated the quality of cookies enriched with CBS powder at 5 to 10% levels. Organoleptic tests, including color changes, texture, flavor, and aroma, were evaluated.

Based on the results, the optimal addition of CBS powder to the cookie formulation was 5%. Organoleptic test results also confirmed that the best treatment was the addition of 5% CBS powder. These findings are consistent with the earlier study by Olalekan-Adeniran et al. (2022), which reported that the highest addition of CBS (10 g) was poorly rated in terms of color and aftertaste. Thus, a lower level of powder incorporation produced a better taste, as smaller amounts enhanced the flavor without generating bitterness upon consumption (Kim et al., 2021). These observations were previously reported by Handojo et al. (2019). However, their work focused on pre-treating the samples by alkalizing them with a sodium phosphate solution prior to formulation, in order to adjust the pH and remove potential heavy metals. Similarly, they observed that the concentration of sodium phosphate and the temperature during the alkalization process played important roles in influencing the color of the cookie products.

Apart from breads, biscuits, and cookies, the utilization of CBS powder as a flavor enhancer has been extended to cake systems (Table 2). Cake is a complex baked system in which interactions between ingredients (flour, sugar, fat, eggs, and leavening agents) and the baking process create the final aerated tender structure. For instance, Öztürk and Ova (2018) examined the effects of raw and leached CBS as a fat replacer in pound cakes. This substitution was applied to raw (RCBS) and leached (LCBS) ground CBS/oil in the ratios of 30/70 (30%), 40/60 (40%), and 50/50 (50%). Accordingly, RCBS cakes showed higher bioactive components than LCBS, including higher levels of phenolic compounds and total antioxidant activity. The results also showed that replacing 50% of vegetable oil with RCBS in cake formulations significantly improved chemical, physical, and sensory properties of fat-substituted cakes.

In a related study, Souza et al. (2022) developed a chocolate cake by substituting wheat flour with CBS powder in formulations ranging from 25 to 100%, with 0% as the control. Technological characteristics such as volume, texture profile, firmness, color, and antioxidant activity were evaluated. The results showed that the varying concentrations of CBS powder influenced both the technological properties and antioxidant activity of the cakes compared to the control. Cakes containing up to 75% CBS demonstrated satisfactory sensory acceptance. In contrast to the favorable results observed in cookies with lower levels of CBS, this difference may be attributed to the distinct baking processes of cookies and cakes (Sanchez et al., 2025b). Nonetheless, CBS has been shown to be a promising alternative ingredient with potential applications in the food industry.

In summary, Table 2 shows that the incorporation of CBS powder in various baked systems has extended to other food products such as snack foods (Kovač et al., 2021), cereals (De Barros et al., 2021), sausages (Choi et al., 2019), and muffins (Martínez-Cervera et al., 2011). However, it can be gleaned from the reviewed references that the application of CBS powder in food formulations is largely concentrated on baked systems and typically follows a direct, trial-and-error substitution approach for wheat flour and other ingredients. The authors employed varied formulation ratios that do not fall within consistent ranges due to these trial-and-error approaches. As a result, determining a specific substitution range to follow in future replication studies becomes challenging, despite the commonly reported substitution levels of 10 to 30%.

Moreover, the potential of CBS as an ingredient or flour replacement in premix powder formulations remains less explored. Thus, it can be inferred that the typical substitution ranges require further investigation. Conversely, only a limited number of studies have explored the potential of CBS in muffins and other baked goods, such as pastries and pancakes. Moreover, the use of CBS as a premix formula has not yet been investigated (Sanchez et al., 2025c). Therefore, this area presents a promising opportunity for further research in valorizing the food applications of CBS powder.

Future directions and research tendencies

Based on the reviewed literature, CBS powder has primarily been investigated as a raw ingredient for direct incorporation into various food products, particularly baked and pastry goods. However, no study to date has examined its potential use as an admixture in ready-to-cook premix formulations for similar applications. A premix is a product consisting of a blend of 2 or more ingredients, formulated for immediate use (Capanoglu et al., 2022). In food applications, premixes are generally defined as blends of food additives or food-derived materials, often formulated to dissolve in water and frequently used as carriers. Developing premixes from agricultural by-products aims to valorize nutrient-rich food processing residues by converting them into nutrient-dense, shelf-stable, and easy-to-use ingredients with desirable technological properties (Marzlan et al., 2020; Negi et al., 2021). Instant premix powders provide a convenient and time-efficient solution for preparing ready-to-cook foods and ready-to-drink beverages, while serving as a practical approach to preserving perishable fruits and vegetables.

Moreover, instant premix powders are increasingly favored by consumers because of their convenience and extended shelf life (Singh et al., 2023). Advances in food engineering have enabled the production of ready-to-use premixes from various agricultural by-products, including formulations incorporating banana, apple pomace, mango, strawberry, pineapple, potato, surimi, moringa leaves, and dates, among others (Sanchez et al., 2025c). Nonetheless, to date, no study has explored the potential of CBS powder. Hence, this can be regarded as a timely and relevant research direction for this by-product. Investigating the feasibility of CBS as an instant premix product would not only offer an innovative valorization strategy but also pave the way for a more sustainable bioeconomy in the cacao industry. Figure 4 presents a graphical representation of the potential applications of instant premix powder derived from CBS

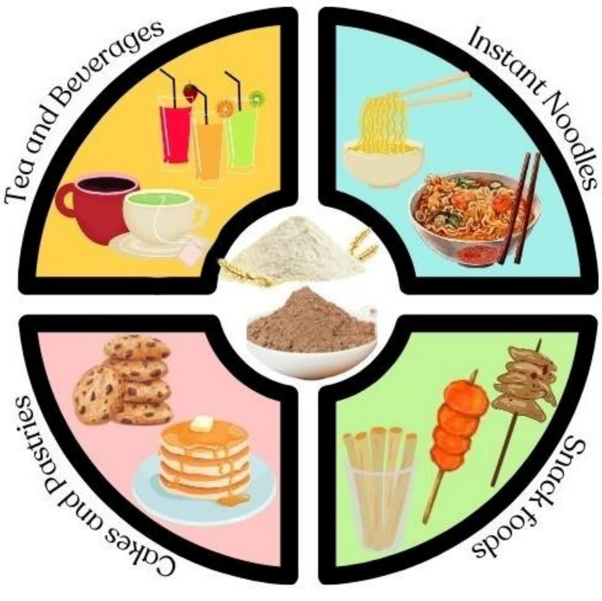

Figure 4. Some of the potential food applications of instant premix powder from CBS

valorization. Beyond baked and pastry products, revalorized CBS powder as a food additive can also be applied to beverages, noodles, and snack foods (Sanchez et al., 2025b).

In addition, optimizing the admixture application of CBS instant premix can provide a valuable reference for food processors. From a valorization perspective, direct utilization without determining optimal requirements still leaves room for improvement, as food processing and production aim for more precise and standardized mixture preparations. With this approach, errors and negative implications in the mass production of premix formulas can be minimized. Therefore, exploring the optimal admixtures of CBS premix powder for various food applications is a promising strategy and represents a vital area of research. Moreover, in designing premixes, it is important to ensure balanced formulations that are user-friendly and possess extended shelf life. This technological advancement offers several benefits, including cost reduction, improved quality and product standardization, labor optimization, simplified sanitation processes, and reduced raw material storage requirements. Therefore, formulating instant mixed powders with enhanced nutritional value and optimal physical characteristics remains a researchable task for CBS by-products that needs attention.

CONCLUSIONS

As synthesized in this review, the valorization pathways of CBS have predominantly focused on general applications, such as animal feed, biomaterials, and fertilizers, with limited exploration into human food systems. Existing studies on food applications primarily emphasize the direct incorporation of CBS powder into bakery and pastry products, often without adequate formulation or optimization considerations. Moreover, the use of CBS powder as a flour substitute in baked systems has generally relied on direct and trial-and-error approaches, without the application of pretreatment or alkalization processes that could enhance the nutritional and physicochemical properties of the powder. Hence, future valorization efforts involving CBS powder should consider appropriate treatments and comprehensive characterization prior to its incorporation into food formulations. Consequently, this review identifies a significant research gap: there is no published literature addressing the use of CBS powder as a functional ingredient in premix powder formulations for baked systems, indicating significant opportunities for further exploration.

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