International Journal on Advanced Science Engineering Information Technology

Vol.15 (2025) No. 1
ISSN: 2088-5334

Cocoa Bean Shells: A Potential Chocolate Replacement in Food Production

Fetriyuna Fetriyuna [a,b,*], Mohamad Djali [a], Afif Ziyadi Rafi [a], Delfina Awalia Nurunnisa [a], Ratna Chrismiari Purwestri [c]

[a] *Department of Food Technology, Faculty of Agro-Industrial Technology, Padjadjaran University, Jatinangor, Sumedang, Indonesia*
[b] *Study Center for the Sustainable Development of Agroindustry, Faculty of Agro-Industrial Technology, Universitas Padjadjaran, Jatinangor Sumedang, Indonesia*
[c] *Faculty and Forestry and Wood Sciences, Czech University of Life Sciences Prague, Kamycka 129, Praha-Suchdol, Czechia*
Corresponding author: fetriyuna@unpad.ac.id

Abstract **—The cocoa bean shells (CBS), a by-product of the cocoa processing industry, are gaining attention for their rich polyphenolic composition, high fiber content, and promising nutraceutical qualities, making them an excellent clean-label ingredient for a variety of food applications. CBS offers a unique scent of cocoa and chocolate, providing a novel and affordable way to flavor or even replace cocoa in a variety of products. This paper's objective is to present a thorough analysis of CBS's potential in food production, with an emphasis on how it can affect the nutritional and sensory qualities of food items. A systematic literature review reveals that CBS improves food attributes like taste, texture, nutritional profile, mineral content, and phytochemicals. CBS is a useful addition to functional food products, with recent trends showing an increase in demand for sustainable, health-promoting ingredients. By adding bioactive compounds, CBS improves the nutritional value and functional qualities of food and beverages. It also adds antioxidant benefits, increases consumer appeal, and supports sustainability initiatives by repurposing a by-product of the cocoa industry. Using CBS in food products offers a cost-effective solution from an economic standpoint by lowering raw material costs and waste disposal costs while also creating new market opportunities for creative food products. To meet the changing consumer demand for clean, functional foods, this review highlights the many benefits of CBS and highlights its potential as a highly valuable ingredient for the creation of wholesome, sustainable, and profitable food products.**

Keywords **—Cocoa by-product; cocoa bean shell; chocolate; antioxidant; dietary fiber.**

Manuscript received 21 Jul. 2024; revised 18 Dec. 2024; accepted 12 Jan. 2025. Date of publication 28 Feb. 2025.

I. INTRODUCTION

Cocoa (Theobroma cocoa L.,) has a numerous variety in nature, but only the three cultivars Criollo, Forastero, and Trinitario are commonly grown. The Forastero variety is the one that is planted the most widely worldwide [1]. The part of cocoa that is generally used as a raw material for food processing is cocoa bean. Cocoa bean is a popular ingredient in chocolate, which consists of nibs and husk (shell). Cocoa nibs are used as a component to make chocolate, while the cocoa bean shell—which makes up about 15% of the entire cocoa bean—is thrown away as a by-product [2].

The cocoa bean shell (CBS) is the term used to describe the outer layer of the cocoa bean, and it is also referred to as the bean husk, hull, or skin. It is removed during the de-hulling process in order to obtain cocoa nibs. As the primary by-product of cocoa, CBS is the outer layer surrounding the bean and is separated from the cotyledons either during or after roasting [1]. This by-product includes vitamins, antioxidants, phenolic compounds, fats, carbohydrates, and dietary fiber. CBS is frequently regarded as a residue and is thrown away or used in low-value applications like fertilizer and animal feed [3]. CBS, which make up between 17 and 20 percent of the weight of the entire cocoa bean, are regarded as one of the cocoa by-products that are frequently discarded. By-products of cocoa are thrown out as waste, which has a negative impact on the environment and the financial worth of cocoa beans [4]. While the cocoa bean accounts for approximately 33% of the cocoa plant, the remaining 67% is considered waste [5].

Global food waste surpasses 1.3 billion tons, with projections indicating it could reach an average of 2.6 billion tons by 2025. This staggering amount translates to an estimated economic loss of 400 billion US dollars. Such alarming figures underscore the critical importance of developing sustainable and eco-friendly approaches to repurpose industrial by-products, ensuring their optimal utilization [6].

The push towards sustainable food processing has further emphasized the importance of utilizing by-products like CBS, supporting the circular economy by transforming waste into valuable ingredients. Additionally, the economic viability of adopting CBS in food production is significant, as it reduces waste and lowers raw material costs, while creating new market opportunities for functional foods. The growing consumer demand for sustainable and health-promoting products presents new market opportunities for CBS-based foods. Products enriched with CBS can be marketed as high-fiber, antioxidant-rich, and environmentally friendly, appealing to health-conscious and eco-aware consumers. This can lead to increased sales and customer loyalty, further enhancing the economic viability of CBS.

According to [7], CBS is a portion of the cocoa bean that is separated from the cotyledon along with the nib before or after roasting. Per 100 g of weight, CBS contains proteins (20.9 g), carbohydrates (7.85 g), fats (2.3 g), dietary fiber (55.1 g), some minerals, such as potassium (0.21− 1.82 g), magnesium (0.20− 1.29g), calcium (0.09−0.51g), phosphorus (0.15−1.00 g), copper (12.1− 66.2 g), zinc (17.3− 75.3 g) [8]. During various production stages like fermentation, roasting, and alkalization, specific phenolic compounds migrate from cocoa beans into CBS, lowering the polyphenol content in cocoa beans and raising the content in CBS. As a result, this by-product is rich in these compounds [9]. The total flavonoid content of CBS is 1.6–43.9 mg CE/g, and the total phenolic content ranges from 22–100 mg GAE/g [3]. Moreover, the abundance of different cell-wall polysaccharides (CWP) including cellulose, pectin, 1,3 and 1,4 β-glucans, and arabinoxylans makes CBS a rich source of dietary fiber [4]. Dietary fiber content in CBS ranges from 13.8 to 65.6 g/100g [3].

Despite having a high nutritional value, CBS is still discarded as a by-product of the cocoa industry. Due to its high phenolic content, it is not only a source of fiber but also a potential source of antioxidants, making it an excellent raw material for other uses. It is necessary to further investigate and identify appropriate applications for CBS in the food industry.

Several studies have been conducted on this by-product, cocoa shell showing significant promise as a food additive. The characterization, assessment, and evaluation of cocoa shell and its bio compounds, as well as the health consequences and application of this by-product as a food ingredient have been reviewed. Despite not being utilized in the making of chocolate, CBS shares many characteristics with cocoa powder, such as comparable volatile and polyphenolic profiles. As a result, they share many of the same organoleptic qualities as chocolate and offer a number of advantages thanks to the polyphenolic compounds in CBS, including procyanidins, catechin and epicatechin. Compared to cocoa beans, CBS are lower in fat content, but they are more significant amount of nutritional fiber.

To utilize this by-product, CBS has been extensively advocated for the production of various foods, typically baked goods, with the aim of lowering production costs, imparting specific structural properties to the resulting product, and, most notably, to add value to the product. Various foods have been tried using CBS as a substitute for chocolate, which is then investigated the characteristics of the resulting product.

The aim of this paper is to provide a comprehensive analysis of CBS's potential in food production, with a focus on how it can impact food items' sensory and nutritional qualities. This paper reviews every detail about CBS which is applied to processed food as a substitute for chocolate. The description related to the product's psychochemical composition, texture and product's acceptability was discussed to review the opportunities for CBS as a substitute for chocolate. Any potential economic benefits of adopting CBS for food products in the context of a circular economic strategy were also covered.

II. Materials and Method

This study's methodology, known as the systematic literature review method, entails the identification, assessment, and synthesis of previous research findings and conclusions [10]. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) was used to conduct the systematic literature review [11]. Figure 1 describes the process for selecting and excluding studies.

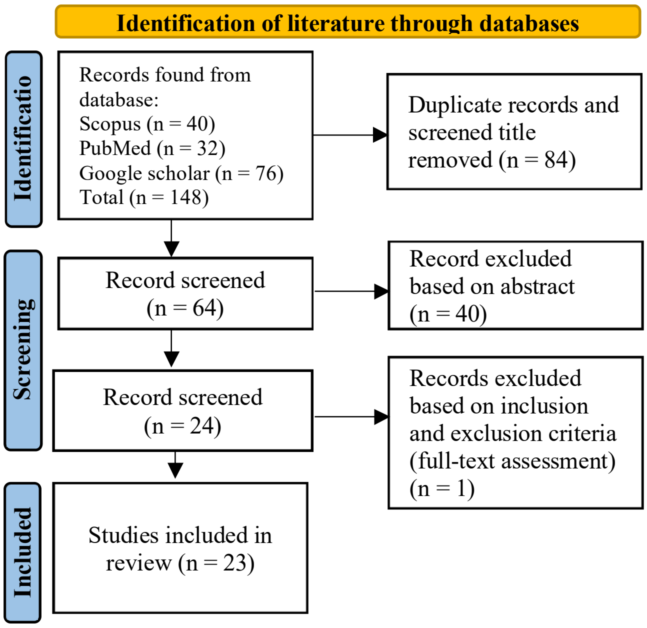

Fig. 1 The process for selecting and excluding previous studies

This review was elaborated upon using peer-reviewed literature and books released between 2000 and 2024; however, some earlier works were eventually included because they were deemed important in the field or because they were the most recent studies for a certain area of the research field. The following databases and search engines were used to look up literature: Scopus, Google Scholar, and PubMed. By looking through the bibliographies of all the collected articles, scientific papers and other sources were also carefully chosen and located. The primary source for downloading the literature, among others, was Google Scholar. Various search phrases, such "cocoa shell", "cocoa bean shell", "biscuit", "cookie", "bread", "bakery"," chocolate cake", "effect", "application", "replacer", or "substitute" were used singly and in combination. Also, different synonyms for the cocoa bean shell term were employed in order to complete the research, such as husk, hull, testa, or tegument.

III. Results and Discussion

A. Applications for Cocoa Bean Shell in the Food Industry

Due to their fiber, polyphenol, and nutraceutical properties, CBSs have been recommended as additives or clean label ingredients in food applications. Furthermore, studies have indicated that CBS comprise 10 to 20% of the total volatile organic compounds present in roasted cocoa beans; many of these compounds are crucial to the aroma of cocoa and chocolate [12]. This makes CBS a very unique and affordable ingredient for cocoa flavoring or as a cocoa substitute. Based from these factors, the food industry find CBS useful in the production of confectionery and bakery goods, or in the creation of low-calorie dietetic and fiber-rich foods, among other uses [1]. It is possible to use cocoa shells as food additives both after being alkalized and after being milled without any modifications [13].

The use of CBS in the food industry varies, according to a selection of the systematic review's literature. The CBS served as a chocolate substitute, fat substitute, fiber-adding alternative flour, emulsifier, antioxidant and antidiabetic agent, bioactive compound, and enrichment of essential elements, in addition to enhancing the product's sensory and physical qualities. Numerous food items, including cookies, cakes, bread, drinks, sausage, burgers, jam, butter, and more, have been made with it. As shown in Table 1, the observed characteristics are positively impacted by the use of CBS.

TABLE I
APPLICATIONS OF COCOA BEAN SHELL IN FOOD INDUSTRY

Food Product	Application	Concentration	Main Result	Reference
Cookies	Alternative flour with added fiber	10, 20, and 30% of CBS	By replacing 20% of the wheat flour with CBS flour, the texture, flavor, crunchiness, hardness, and aftertaste were all highly acceptable.	[14]
Pound cake	Fat replacer	30, 40, and 50% of RCBH and LCBH as a substitute for sunflower oil	The chemical, physical, and sensory properties of pound cake were improved when 50% of the vegetable oil was replaced with leached or raw CBS as opposed to the control.	[15]
Pork sausage	Emulsion stability	0.75 and 1% of cocoa bean husk powder	The treatment groups at 0.75 and 1% showed significantly greater overall acceptability. Additionally, there was a decrease in cooking loss and an increase in emulsion stability.	[2]
Functional beverage	Antioxidant and anti-diabetic agents	2-32 g of CBS powder being added to the beverages	The strong antioxidant activity was facilitated by CBS polyphenol extracts.	[16]
Gluten-free bread	Improving physical attributes	4% of CBS with different kinds of dimensional fractions (F1, 1.00-1.99 mm; F2, 0.50-0.99 mm; F3, 0.355-0.49 mm)	CBS led to a pleasant darker and had lower volume. Crumb grain had coarser structure, also there were no significant differences in textural characteristics.	[17]
Extra virgin olive oil jam	Antioxidant enrichment	0.25% of cocoa bean husk extract	Total phenols, epicatechin, and theobromine were higher jam with non-encapsulated CBHE extract.	[18]
Dark and milk chocolate	Essential elements enrichment	0-15% of cacao shell powder	There was an increase in some essential elements.	[19]
Chocolate cake	Substitute for wheat flour	0, 25, 50, 75, and 100% of CSp	CSp had an impact on the cakes' technological properties and antioxidant activity. Also, 75% of CSp demonstrated adequate sensory acceptance.	[20]
Cocoa tea	Antioxidant enrichment and sensory evaluation's purpose	2.25 g of cocoa bean hull	Cocoa tea showed a much higher TPC as compared to raw and traditional chocolate.	[21]
Iced tea	Antioxidant enrichment	20, 30, and 40 g of CBS powder being added to the iced tea	The most favored/accepted formulation was made with 30 g of powder and 1 liter of water, and the iced tea retained 85.3% of the phenolics from CBS.	[22]
Chocolate cookies	Sensory evaluation's purpose	5, 7.5, and 10% of cocoa bean husk powder	The addition of 5% powder had the most preferred taste and texture by the panelist.	[23]
Corn snack	Antioxidant enrichment and physical property's purpose	HVED extraction under different cocoa shell: water ratio (1:30 and 1:50)	Addition of CBS extracts led to changes in the physical properties of extrudates and significantly improved their antioxidant activity.	[24]
Bread	Soluble fiber enrichment	0, 2, 4, 6, 8% of soluble dietary fiber from CBS	The addition of fiber from cocoa shell significantly impacted the visual properties,	[25]

Food Product	Application	Concentration	Main Result	Reference
			specific volume, sensory perception, and staling kinetics of the breads.	
Cookies	Nutritional, minerals, and phytochemical enrichment and microbiological and sensory evaluation's purpose	0, 2, 4, 6, 8, 10 g of CBS	By adding CBS in the production of cookies, it had shown improvement in the nutritional compositions, minerals values, and the phytochemical constituents of the enriched cookies. The sensory analysis showed positive ratings overall.	[26]
Chocolate	Bioactive compound's purpose	2.5, 5, 10, 15% untreated and treated cocoa shell	Addition of cocoa shell to chocolate resulted in reduced contents of TPC, TFC, and individual compounds.	[27]
Capsule and tea bag	Functional ingredient in the hot beverage	77, 87, 91, 92, 93.8, 94, 95.4, 95.5, 96.1, 96.6, 97% of CBS	In both capsule and tea bag beverages, the bio accessibility of methylxanthines was 100%, while that of total polyphenols exceeded 50%.	[28]
Cocoa butter	Pickering emulsion	Nanocellulose: 0.7 and 1 wt%	Nanocellulose from cocoa shell could be a promising stabilizer for Pickering emulsions, offering a potential solution for reducing the content of cocoa butter in food and cosmetic formulations while maintaining stability and rheological properties.	[29]
Beef burgers	Fat replacer	Beef burger where the 50 and 100% of fat content was replaced with gelled emulsion with walnut oil and CBS flour	A good source of bioactive compounds that remained stable after in vitro gastrointestinal digestion were the reformulated beef burgers made with walnut oil and CBS flour.	[30]
Biscuits	Functional biscuits	0, 10, and 20% of CBS	CBS in biscuits could enhance the bio accessibility and health-promoting properties of antioxidants present in the product.	[31]
Beverages	Functional properties and bioactive compound enhancement	Cacao shell was ground in an impact mill and passed through two sieves to obtain three particle sizes: (CS-A, >710 μm); CS-B, >425 μm and <710 μm; CS-C, <425 μm)	Cocoa shell infusion was a safe beverage for consumers. It provided macro- and micronutrients, as well as water-soluble pigments derived from the cocoa production processes.	[32]
Chocolate	Improving physical attributes	0, 2.5, 5, 10, 15% of treated and untreated cocoa shells	The treatment of CBS with HVED had varying effects on the physical properties of chocolate.	[33]
Biscuits	Functionalized biscuits for diabetic consumers	0, 10, and 20% of CBS powder	The incorporation of CBS in biscuits could lead to changes in fiber content, weight loss, and texture parameters, which could affect the overall physical properties of the biscuits.	[34]
Cookies	Wheat flour partial replacement	10, 20, 30, and 40% of CBS flour	Enriching cookies with bioactive compounds from CBS not only enhanced their nutritional value and functional properties but also provided antioxidant benefits, increased consumer appeal, and contributed to sustainability efforts by utilizing by-products of the cocoa industry.	[35]

Data from multiple studies on the impact of applying CBS to food products have been gathered for this review and are shown in Table 1. [14] conducted texture profile analysis, powder size analysis, and acceptance test on cookies made with alkalized CBS. Results showed that the alkalized CBS powder can be used as a substitute or mixing flour as there is no significant difference observed among them. Cookies made with alkalized CBS powder showed higher resistance than cookies made with wheat or oats, according to the texture profile analysis, but at the same mixing ratio. Additionally, no discernible differences were found between cocoa CBS and other fiber powders in an organoleptic test.

Öztürk [15] analyzed the effect of cocoa bean husk in addition to pound cake. The result showed that the substitution of 30, 40, and 50% RCBH and LCBH powders were appropriate levels by replacing equivalent amount of sunflower oil in the cake mixture. There is a significant decrease of fat content, yet there are a significant increase of crude fiber content, total phenolic compounds, and total antioxidant activity.

Physicochemical properties and sensory traits of emulsion-type pork sausages with various levels of cacao bean husk powder (0.25, 0.5, 0.75, 1, and 2%) have been analyzed by [2]. As the level of cacao bean husk power increased, the moisture content increased in cooked sausages, while the protein content decreased. Regarding color, lightness and yellowness decreased, while redness significantly increased as the amount of cacao bean husk power increased. The stability of the emulsion and apparent viscosity were both positively impacted by cacao bean husk powder; there was an increase in emulsion stability and reduced cooking loss. Also, increased cacao bean husk content in the sensory evaluation led to higher flavor acceptability; the 0.75 and 1% treatment groups demonstrated noticeably higher overall acceptability.

A study by [16] investigated how the extraction techniques and CBS particle size affected the functional beverage's chemical composition and acceptability among consumers. The beverage made with the Capsule technique showed the poorest extraction, while it was shown that the Moka and Neapolitan techniques may be the most effective for extracting polyphenols, providing the highest capacity for α-glucosidase inhibition and radical scavenging activity. The most active beverages containing higher polyphenols were the least favored as far as taste and flavor were concerned, due to the greater presence of polyphenols and methylxanthines.

Effects of CBS on gluten-free bread were investigated in terms of volume, moisture content, crumb grain, texture and color. The presence of CBS caused the color of the bread to become darker, which is more of a pleasant darker color. Besides that, the crumb stalling process was greatly accelerated by the presence of CBS when compared to the control. Also, the crumb grain, which had a coarser structure, as well as the specific volume and moisture content, which had much lower values, were all likely negatively affected by the fiber derived from CBS fractions. The textural characteristics (hardness) supported the addition of CBS with minimal effect on product quality during storage. Furthermore, in terms of water absorption indexes, the F2 fractions (0.50-0.99 mm) demonstrated the highest water binding and holding capacities (WBC and WHC), while the water solubility index (WSI) was the lowest among the fractions, indicating a good retention of the fiber structure [17].

The freeze-dried or encapsulated cocoa bean husk extract (CBHE) was added to a virgin olive oil jam. Higher levels of epicatechin, theobromine, and total phenols were found in the jam's water fraction containing non-encapsulated CBHE extract. Additionally, jam containing the non-encapsulated CBHE extract had the best Rancimat induction time, showing a 32% increase over the control and retaining its oil content for a longer period of time without going rancid. In terms of sensory properties, the best results were obtained for flavor, color, and aroma in jam that contained 0.25% CBHE. Also, the panel scored texture and consistency lowest in the control sample, indicating that they are more highly regarded in the jams that contain cocoa bean husk extracts [18].

The researchers also analyzed dark and milk chocolates produced with untreated and HVED (high voltage electrical discharge)-treated cocoa shells, focusing on changes in elemental contents. They found that HVED treatment led to a decrease in the content of certain elements such as potassium, cadmium, uranium, cobalt, nickel, iron, molybdenum, chromium, manganese, and copper in cocoa shell. However, the treatment also caused an increase in the content of certain elements, with the largest increase observed for calcium. The utilization of cocoa shell in the manufacturing of chocolate can be inferred to have an impact on the following essential elements: iron, copper, manganese, zinc, molybdenum, cobalt, and selenium; calcium, magnesium, potassium, and copper. The addition of cocoa shell to chocolate raises the contents of toxic elements such as nickel, chromium, cadmium, lead, and uranium. But, chocolates with added cocoa shell were found to be safe for human consumption, with the content of toxic elements falling within reported safe ranges [19].

The potential of using CBS powder (CSp) as a substitute for wheat flour in chocolate cake has been investigated [20]. The study evaluates the technological characteristics, antioxidant profile, and sensory properties of the cakes. Substituting wheat flour with CSp affects the technological characteristics and antioxidant activity of chocolate cakes. As CSp has demonstrated the presence of phenolics and anthocyanins, the content of these compounds rises as CSp percentage increases. Sensory analysis shows that cakes with up to 75% CSp concentration are still acceptable in terms of taste and overall acceptance. The use of CSp as a substitute for wheat flour can help reduce environmental impacts caused by cocoa processing residues.

The antioxidant properties and sensory characteristics of cocoa tea made from cocoa bean hulls of different origins were investigated by [21]. The study finds that cocoa tea made from Venezuelan cocoa bean hulls has the highest antioxidant properties compared to other origins. The antioxidant properties of cocoa tea can tolerate roasting temperatures up to 100°C. The study also reveals that cocoa tea made from Malaysian and Venezuelan origins has a higher theobromine content and a lower caffeine content compared to green tea. Sensory evaluation shows that cocoa tea is well-accepted in terms of taste and overall preference. The study confirms that cocoa bean hulls do not contain pesticide residues and have unique flavor profiles based on regional differences. It concludes that cocoa tea made from cocoa bean hulls is a desirable beverage with antioxidant properties comparable to coffee and slightly lower than black tea.

The composition of CBS and produced an iced tea was analyzed in [22]. According to this study, the powder's primary constituents were proteins (14.6%), lipids (19.7%), dietary fiber (37.5%), and 25.7 mg of gallic acid equivalents/g. The most favored mixture was made with 30 g of powder and 1 liter of water, and the iced tea kept 85.3% of the phenolics from CBS.

The CBS presented high levels of fibers and phenolic compounds, indicating that this material has potential to be applied in the production of various foods and thus aggregating value to this waste from the cocoa industry. The iced tea produced in this study proved to be a low-cost and eco-friendly alternative to increase consumers' ingestion of antioxidants.

Sensory evaluation of chocolate cookies with various levels of cacao bean husk powder (5, 7.5, and 10%) have been analyzed by [23]. The color and odor that were preferred by the panelists were treated with 0% powder, whereas the taste and texture was treated with addition of 5% powder. Another study by [24] analyzed the antioxidant and physical properties of a corn snack that made using extract from cocoa shell. According to this study, adding cocoa shell extracts greatly increases the antioxidant activity of extrudates while also changing their physical characteristics, which may have an impact on how well-liked those products are by consumers. There is a reduction in the expansion ratio and increase in bulk density, as well as increased hardness and reduced fracturability of tested extrudates with the addition of extracts from cocoa shell. Also, samples with the addition of extracts were darker.

The effect of adding soluble dietary fiber from cocoa shell samples on wheat bread performance was investigated by [25]. The addition of fiber from cocoa shell significantly impacted the visual properties, specific volume, sensory perception, and staling kinetics of the breads. At 6% of addition, bread with natural cocoa-soluble fiber (ACSF) showed an increase in specific volume compared to control samples, with a positive change of 5%. In contrast, bread containing alkalinized cocoa-soluble fiber (BCSF) exhibited a reduction in specific volume, with a negative change of 5%. This indicates that the type and amount of added fiber influenced the specific volume of the bread loaves. In terms of sensory perception, ACSF and BCSF showed differences in acceptability and taste. ACSF-supplemented breads were as acceptable as control breads in terms of appearance and aroma when added up to 4%, had acceptable taste and overall acceptability up to 2%, and acceptable texture up to 8%. On the other hand, BCSF-enriched breads received similar scores to ACSF at the same or lower percentage of incorporation into the dough. However, at higher dosages, particularly at 8% of addition, the sensory acceptability and taste of breads with BCSF were reduced compared to ACSF-supplemented breads.

Cookies that were enriched with CBS. This study evaluates nutritional, phytochemical, microbiological, and sensory properties was analyzed in [26]. Enriched cookies showed a balance of macronutrients with increased protein, fat, fiber, and ash content compared to traditional cookies, while moisture and carbohydrate content decreased. The cookies enriched with CBS also increased mineral content, including iron, potassium, sodium, copper, and phosphorus. The enriched cookies contained a variety of phytochemicals, such as tannins, total phenolics, flavonoids, and caffeine. The bacteria count of the enriched cookies in this study indicated low total bacteria, ranging from 1.7×10^2 to 3.1×10^3. No enteric bacteria were detected, and the presence of yeasts and molds in the cookies was within acceptable limits. The sensory analysis of the enriched cookies with CBS showed positive ratings overall. However, the sample with the highest addition of CBS had a darker color and aftertaste due to the deep brown color of CBS. The sensory attributes evaluated included color, crunchiness, taste, flavor, aftertaste, texture, and overall acceptability.

A previous study by [27] explored how adding cocoa shell as a source of fiber can enhance the nutritional properties of chocolates while maintaining their bioactive components. By incorporating cocoa shell, chocolate can offer a more balanced nutritional profile with added fiber content. Fiber intake is associated with various health benefits, such as improved digestion and a reduced risk of chronic disease. There was a reduction in total polyphenol content (TPC) and total flavonoid content (TFC) when cocoa shell was added to chocolate, but the impact on these bioactive compounds was not significant. This means that the addition of cocoa shells can still provide some of the beneficial polyphenols found in cocoa. Polyphenols have been associated with various health benefits, such as antioxidant properties and potential cardiovascular health effects. Adding cocoa shells to chocolates can not only improve their nutritional content by increasing fiber intake but also contribute to sustainability efforts by utilizing a by-product of cocoa processing.

In vitro bio accessibility and functional properties of phenolic compounds from enriched beverages based on CBS have been conducted by [28]. This study showed that CBS contains bioactive compounds with significant functional properties, such as polyphenols, methylxanthines (theobromine and caffeine), dietary fibers, and other nutrients (vitamins, minerals, and essential fatty acids). The bio accessibility of methylxanthines was 100%, while that of total polyphenol exceeded 50%. By incorporating CBS into beverages, such as flavored beverages for at-home consumption, it is possible to enhance the nutritional profile and functional properties of the final products. This study suggests that incorporating CBS into beverages and food can offer both nutritional and functional benefits while also supporting sustainability efforts in the food industry.

Research about nanocellulose from cocoa shell in Pickering emulsions of cocoa butter in water has been conducted [29]. This study finds that the isolation treatments of nanocellulose from cocoa shells significantly influenced its stability in Pickering emulsions. Different chemical treatments resulted in variations in the nanocellulose compositions, affecting its ability to stabilize the emulsions. Nanocellulose with a higher degree of polymerization (DP) and a stronger three-dimensional network exhibited improved stabilization of cocoa butter in water-based Pickering emulsions. This enhanced stability was attributed to the entangled network structure formed by the nanocellulose. The developed Pickering emulsions with nanocellulose formed from cocoa shell remained stable for more than 15 days, even in the presence of cocoa butter, which tends to solidify and form crystals that can destabilize the emulsions through arrested coalescence. The nanocellulose effectively prevented this destabilization mechanism. This study demonstrated that nanocellulose from cocoa shell can be a promising stabilizer for Pickering emulsions, offering a potential solution for reducing the content of cocoa butter in food and cosmetic formulations while maintaining stability and rheological properties.

The changes in bioactive compounds present in beef burgers formulated with CBS and walnut oil gelled emulsion as a fat substitute during in vitro gastrointestinal digestion were analyzed by [29], [30]. Reductions were observed in the bound fraction of the polyphenolic compound after digestion compared to the undigested samples. Reductions ranged from 47.57 to 53.12% for protocatechuic acid, 60.26 to 78.01% for catechin, and 38.73 to 60.95% for epicatechin. The methylxanthine content in the reformulated beef burgers decreased by approximately 48.41 to 68.61% for theobromine and 96.47 to 97.95% for caffeine during digestion. These results indicate that the reformulated beef burgers maintained a significant number of polyphenolic compounds even after the digestion process, while the methylxanthine content decreased. The reduction in methylxanthine content may have implications for bioavailability and potential health effects.

Bio accessibility of antioxidants in CBS functional biscuits have been analyzed [31]. The presence of a food matrix, such as in biscuits containing CBS, contributed to the release of polyphenols and methylxanthines during digestion, increasing their concentrations available at the intestinal level. The bioavailability of compounds was lowered by the presence of food matrix, but digestion improved their release from the matrix, enhancing their potential to promote antioxidants and antidiabetic activities. The stability of polyphenols throughout the digestion process was improved by the presence of the food matrix, indicating a protective effect on these bioactive compounds. Flavan-3-ol absorption appeared to have a maximum threshold and was independent of the sample, while procyanidins were not absorbed. Methylxanthine absorption was high and was enhanced by the food matrix. This study confirmed the bio functional potential of CBS-based biscuits, highlighting their ability to inhibit α-glucosidase and promote antioxidant activities.

Cocoa shell infusion for added-value beverages have been studied by [32]. This study showed that particle sizes did not significantly influence shell infusion at most wavelengths in the reflectance spectra of cocoa shell infusion, except for the largest particle sizes (>710 μm) at wavelengths 540–630 nm. Decreasing the particle size of cocoa shell increased the antioxidant capacity and polyphenol content, particularly enhancing the availability of biomolecules like epicatechin. This change also influenced the perception of bitter and astringent Flavors in the infusion. Cocoa shells were found to be contaminated with bacteria, yeast, and filamentous fungi after fermentation and drying. Lactic acid bacteria, mesophilic aerobic bacteria, and yeast were prevalent, but total coliforms and molds were present in low amounts. Additional processes may be necessary to ensure product safety without compromising functionality.

Another previous study by [33] conducted research about physical properties of chocolate enriched with untreated CBS and CBS treated with high-voltage electrical discharge (HVED). Cocoa shells treated with HVED were found to have larger particles compared to untreated cocoa shells, which can impact the overall texture and mouthfeel of the chocolate. Chocolate with HVED-treated cocoa shells may exhibit different hardness properties compared to chocolate with untreated shells, potentially influencing the overall sensory experience for consumers. The treatment of cocoa shells with HVED may also influence the color of the chocolate, with potential implications for visual appeal and consumer acceptance. The rheological behavior of chocolate with HVED-treated shells may differ from those with untreated shells, affecting factors such as viscosity and texture.

Study about physical properties and consumer evaluation of tagatose and CBS-functionalized biscuits adapted for diabetic consumer have been conducted by [34]. This study showed that biscuits containing 10 and 20% CBS increased total dietary fiber content with values of 5.66% and 8.70–8.71%, respectively. The weight loss after baking may vary depending on the CBS content and the type of sugar lost. For instance, an increase in weight loss was observed when increasing the CBS content for sucrose biscuits, while the opposite effect was seen for the tagatose biscuit group. The difference could be attributed to the lower solubility of tagatose during baking, which affects water retention capacities. Replacing sucrose with tagatose in diabetic-friendly biscuits offers advantages such as a low-glycemic index, prebiotic properties, and reduced sugar metabolism, making it a beneficial alternative to sucrose for individuals with diabetes.

Soares et al [35] also analyzed the production of cookies enriched with bioactive compounds by partially replacing flour with CBS. Enriching cookies with bioactive compounds from CBS not only enhance their nutritional value and functional properties but also provides antioxidant benefits, increases consumer appeal, and contributes to sustainability efforts by utilizing by-products of the cocoa industry.

B. Comparisons of cocoa bean shell and traditional chocolate ingredients

Adopting CBS in food production offers significant economic benefits for manufacturers. One of the primary advantages is the reduction in raw material costs. CBS, being a by-product of cocoa processing, is relatively inexpensive compared to traditional cocoa ingredients. By incorporating CBS into their products, manufacturers can lower their production costs while maintaining or even enhancing the nutritional and functional properties of their food items. This cost-effective approach not only improves profit margins but also allows companies to offer competitively priced products in the market.

TABLE II
NUTRITIONAL VALUE, COST, AND SUSTAINABILITY OF COCOA BEAN SHELL COMPARED TO TRADITIONAL CHOCOLATE INGREDIENTS

Aspects	CBS	Traditional chocolate ingredients
Nutritional value	High fiber (55g / 100g), polyphenols, and minerals [5]	Moderate fiber (23-29g / 100g), rich in polyphenols, and minerals [36]
Cost	Lower raw material cost, reduces waste disposal costs [12]	High raw material and labor cost, supply chain issues [37]
Sustainability	Reduces waste, supports circular economy, minimizes environmental footprint [38]	Linked to deforestation, habitat loss, and ethical concerns [37]

In addition, the use of CBS contributes to substantial waste reduction, aligning with the principles of sustainable food production. The cocoa industry generates a large amount of waste in the form of cocoa bean shells, which are often discarded. By upcycling these shells into valuable food ingredients, manufacturers can significantly reduce the volume of waste sent to landfills. This not only minimizes the environmental impact but also supports the circular economy by transforming waste into a resource. The reduction in waste disposal costs further enhances the economic viability of using CBS in food production.

Moreover, the adoption of CBS in food products can open up new market opportunities and enhance brand reputation. Consumers are increasingly seeking sustainable and health-promoting products, and CBS aligns perfectly with these trends. By highlighting the use of CBS as a sustainable ingredient, companies can attract environmentally conscious consumers and differentiate their products in a crowded market. This can lead to increased sales and customer loyalty, further boosting the economic benefits for manufacturers.

Some companies are developing innovative products by upcycling CBS, transforming what was once considered waste into valuable ingredients, for instance, tea, snack bars, cookies, bread, even cocoa-based soft drinks. These products not only offer a unique flavor profile but also align with sustainability and health trends by making use of the nutritional benefits of CBS. This example highlights how CBS can be effectively incorporated into food products, providing both economic and environmental benefits.

Cocoa Shells are a part of Cocoa & cocoa preparations. They include Cocoa Waste (Shells, Husks, Skins). Based on the data of global trade of cocoa shell in 2022 (https://oec.world/en/profile/hs/cocoa-shells), Cocoa Shells were the world's 1124th most traded product, with a total trade of $263M. Cocoa shell exports increased by 0.61% between 2021 and 2022, from $262 million to $263 million. Cocoa shell trade accounts for 0.0011% of global trade. In 2022 the top exporters of Cocoa Shells were Cote d'Ivoire ($195M), Nigeria ($39.7M), Ghana ($5.59M), France ($5.09M), and Germany ($4.53M). Additionally, The United States ($94.2M), Germany ($35.2M), Mexico ($32.8M), Brazil ($19.6M), and Indonesia ($13.5M) were the top importers of cocoa shells in 2022.

The food industry might look more closely at using cocoa bean shells to make high-fiber, low-calorie snacks or as an ingredient in health supplements as consumer tastes move toward natural and sustainable products. In order to produce chocolate with distinctive flavors or textures, cocoa shells may also be used.

IV. Conclusion

CBS have been suggested as clean-label ingredients in food applications due to their nutraceutical qualities, fiber content, and polyphenol content. The food industry finds that CBS is useful in producing confectionery and bakery goods, low-calorie dietetic foods, and fiber-rich foods. Incorporating CBS in food products can impact various characteristics such as taste, texture, nutritional compositions, mineral values, and phytochemical constituents. Enriching food and beverages with bioactive compounds from CBS not only enhance their nutritional value and functional properties but also provides antioxidant benefits, increases consumer appeal, and offers significant environmental and economic benefits, including waste reduction, and alignment with consumer demand for sustainable products. This upcycling approach has led to the development of innovative food products, which capitalize on CBS's unique flavor profile and nutritional benefits.

Acknowledgment

The authors appreciate the Directorate of Research and Community Services (DRPM) of Universitas Padjadjaran for the opportunity to conduct this review study through the program of Academic Leadership Grant (ALG)

References

[1] J. P. Balentic *et al.*, "Cocoa shell: A by-product with great potential for wide application," *Molecules*, vol. 23, no. 6, pp. 1–14, 2018, doi:10.3390/molecules23061404.

[2] J. Choi, N. Kim, H. Y. Choi, and Y. S. Han, "Effect of cacao bean husk powder on the quality properties of pork sausages," *Food Sci. Anim. Resour.*, vol. 39, no. 5, pp. 742–755, 2019, doi:10.5851/kosfa.2019.e62.

[3] M. Sánchez, A. Laca, A. Laca, and M. Díaz, "Cocoa Bean Shell: A By-Product with High Potential for Nutritional and Biotechnological Applications," *Antioxidants*, vol. 12, no. 5, 2023, doi:10.3390/antiox12051028.

[4] A. Younes, M. Li, and S. Karboune, "Cocoa bean shells: a review into the chemical profile, the bioactivity and the biotransformation to enhance their potential applications in foods," *Crit. Rev. Food Sci. Nutr.*, vol. 63, no. 28, pp. 9111–9135, Nov. 2023, doi:10.1080/10408398.2022.2065659.

[5] R. Campos-Vega, K. H. Nieto-Figueroa, and B. D. Oomah, "Cocoa (Theobroma cacao L.) pod husk: Renewable source of bioactive compounds," *Trends Food Sci. Technol.*, vol. 81, pp. 172–184, 2018, doi: 10.1016/j.tifs.2018.09.022.

[6] D. K. Banerjee *et al.*, "Application of enoki mushroom (Flammulina Velutipes) stem wastes as functional ingredients in goat meat nuggets," *Foods*, vol. 9, no. 4, Apr. 2020, doi: 10.3390/foods9040432.

[7] M. Arlorio *et al.*, "Antioxidant and biological activity of phenolic pigments from Theobroma cacao hulls extracted with supercritical CO2," *Food Res. Int.*, vol. 38, no. 8–9, pp. 1009–1014, 2005, doi:10.1016/j.foodres.2005.03.012.

[8] Z. Ö. Cinar *et al.*, "Cocoa and cocoa bean shells role in human health: An updated review," *J. Food Compos. Anal.*, vol. 103, no. August, 2021, doi: 10.1016/j.jfca.2021.104115.

[9] N. Pavlović, M. Miškulin, K. Aladić, and S. Jokić, "Cocoa Bean Shell – a Promising By-Product Rich in Bioactive Compounds," *Food Heal. Dis.*, vol. 8, no. 2, pp. 116–122, 2019.

[10] C. Okoli, "A guide to conducting a standalone systematic literature review," *Commun. Assoc. Inf. Syst.*, vol. 37, no. 1, pp. 879–910, 2015, doi: 10.17705/1cais.03743.

[11] A. Liberati *et al.*, "The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration.," *J. Clin. Epidemiol.*, vol. 62, no. 10, pp. e1-34, Oct. 2009, doi: 10.1016/j.jclinepi.2009.06.006.

[12] O. Rojo-Poveda, L. Barbosa-Pereira, G. Zeppa, and C. Stévigny, "Cocoa bean shell—a by-product with nutritional properties and biofunctional potential," *Nutrients*, vol. 12, no. 4, pp. 1–29, 2020, doi:10.3390/nu12041123.

[13] C. Chronopoulos, D., Zuurbier, R., Brandstetter, B., & Jung, "Food Comprising Alkalized Cocoa Shells and Method Therefor," vol. 1, no. 19, pp. 1–3, 2011.

[14] L. Handojo, H. Triharyogi, and A. Indarto, "Cocoa bean shell waste as potential raw material for dietary fiber powder," *Int. J. Recycl. Org. Waste Agric.*, vol. 8, no. s1, pp. 485–491, 2019, doi: 10.1007/s40093-019-0271-9.

[15] E. Öztürk and G. Ova, "Evaluation of Cocoa Bean Hulls as a Fat Replacer On Functional Cake Production," *Turkish J. Agric. - Food Sci. Technol.*, vol. 6, no. 8, pp. 1043–1050, 2018, doi:10.24925/turjaf.v6i8.1043-1050.1934.

[16] O. Rojo-Poveda, L. Barbosa-Pereira, L. Mateus-Reguengo, M. Bertolino, C. Stévigny, and G. Zeppa, "Effects of particle size and extraction methods on cocoa bean shell functional beverage," *Nutrients*, vol. 11, no. 4, pp. 1–19, 2019, doi: 10.3390/nu11040867.

[17] M. Rinaldi, P. Littardi, M. Paciulli, A. Caligiani, and E. Chiavaro, "Effect of cocoa bean shells granulometries on qualitative properties of gluten-free bread during storage," *Eur. Food Res. Technol.*, vol. 246, no. 8, pp. 1583–1590, 2020, doi: 10.1007/s00217-020-03513-z.

[18] C. Hernández-Hernández *et al.*, "Extra virgin olive oil jam enriched with cocoa bean husk extract rich in theobromine and phenols," *LWT*, pp. 1–29, 2019.

[19] V. Barišić *et al.*, "Effect of high-voltage electrical discharge treatment on multi-element content in cocoa shell and chocolates with cocoa shell," *Lwt*, vol. 155, 2022, doi: 10.1016/j.lwt.2021.112944.

[20] F. Nogueira Soares Souza *et al.*, "Impact of using cocoa bean shell powder as a substitute for wheat flour on some of chocolate cake properties," *Food Chem.*, vol. 381, no. April 2021, 2022, doi:10.1016/j.foodchem.2022.132215.

[21] C. S. Siow, E. W. C. Chan, C. W. Wong, and C. W. Ng, "Antioxidant and sensory evaluation of cocoa (Theobroma cacao L.) tea formulated with cocoa bean hull of different origins," *Futur. Foods*, vol. 5, no. December 2021, p. 100108, 2022, doi: 10.1016/j.fufo.2021.100108.

[22] S. M. Dos Anjos Lopes, M. V. Martins, V. B. de Souza, and F. L. Tulini, "Evaluation of the Nutritional Composition of Cocoa Bean Shell Waste (Theobroma cacao) and Application in the Production of a Phenolic-rich Iced Tea," *J. Culin. Sci. Technol.*, vol. 21, no. 5, pp. 818–828, 2023, doi: 10.1080/15428052.2021.2016531.

[23] J. Langkong, M. Mahendradatta, M. M. Tahir, A. N. F. Rahman, N. Abdullah, and N. Marina, "Utilization of Cocoa Bean Husk Extract (Theobroma cacao L) on The Product Chocolate Cookies," *Canrea J. Food Technol. Nutr. Culin. J.*, vol. 3, no. 1, pp. 42–48, 2020, doi:10.20956/canrea.v3i1.279.

[24] M. Kova *et al.*, "Application of Cocoa Bean Shell Extracts in the Production of Corn Snack Products," vol. 10, pp. 69–76, 2021.

[25] C. Collar, C. M. Rosell, B. Muguerza, and L. Moulay, "Breadmaking performance and keeping behavior of cocoa-soluble fiber-enriched

wheat breads," *Food Sci. Technol. Int.*, vol. 15, no. 1, pp. 79–87, 2009, doi: 10.1177/1082013208102643.

[26] O.-A. Mujidat Adenike, "Evaluation of Nutritional, Phytochemicals, Microbiological and Sensory Properties of Cookies Enriched with Cocoa Bean Shells," *Int. J. Curr. Sci. Res. Rev.*, vol. 05, no. 09, pp. 3776–3787, 2022, doi: 10.47191/ijcsrr/v5-i9-61.

[27] V. Barišić *et al.*, "Cocoa Shell as a Step Forward to Functional Chocolates—Bioactive Components in Chocolates with Different Composition," *Molecules*, vol. 25, no. 22, pp. 1–12, 2020, doi:10.3390/molecules25225470.

[28] C. Cantele *et al.*, "In vitro bioaccessibility and functional properties of phenolic compounds from enriched beverages based on cocoa bean shell," *Foods*, vol. 9, no. 6, 2020, doi: 10.3390/FOODS9060715.

[29] C. Gómez Hoyos, L. D. Botero, A. Flórez-Caro, J. A. Velásquez-Cock, and R. Zuluaga, "Nanocellulose from Cocoa Shell in Pickering Emulsions of Cocoa Butter in Water: Effect of Isolation and Concentration on Its Stability and Rheological Properties," *Polymers (Basel).*, vol. 15, no. 20, 2023, doi: 10.3390/polym15204157.

[30] R. Lucas-Gonzalez, E. Sayas-Barberá, J. M. Lorenzo, J. Á. Pérez-Álvarez, J. Fernández-López, and M. Viuda-Martos, "Changes in bioactive compounds present in beef burgers formulated with walnut oil gelled emulsion as a fat substitute during in vitro gastrointestinal digestion," *J. Sci. Food Agric.*, vol. 103, no. 13, pp. 6473–6482, 2023, doi: 10.1002/jsfa.12725.

[31] O. Rojo-Poveda *et al.*, "Polyphenolic and methylxanthine bioaccessibility of cocoa bean shell functional biscuits: Metabolomics approach and intestinal permeability through CaCo-2 cell models," *Antioxidants*, vol. 9, no. 11, pp. 1–21, 2020, doi:10.3390/antiox9111164.

[32] J. Delgado-Ospina, L. Esposito, J. B. Molina-Hernandez, J. Á. Pérez-Álvarez, M. Martuscelli, and C. Chaves-López, "Cocoa Shell Infusion: A Promising Application for Added-Value Beverages Based on Cocoa's Production Coproducts," *Foods*, vol. 12, no. 13, pp. 1–21, 2023, doi: 10.3390/foods12132442.

[33] V. Barišić *et al.*, "Physical properties of chocolates enriched with untreated cocoa bean shells and cocoa bean shells treated with high-voltage electrical discharge," *Sustain.*, vol. 13, no. 5, pp. 1–14, 2021, doi: 10.3390/su13052620.

[34] O. Rojo-Poveda, L. Barbosa-Pereira, D. Orden, C. Stévigny, G. Zeppa, and M. Bertolino, "Physical properties and consumer evaluation of cocoa bean shell-functionalized biscuits adapted for diabetic consumers by the replacement of sucrose with tagatose," *Foods*, vol. 9, no. 6, 2020, doi: 10.3390/foods9060814.

[35] I. D. Soares, M. E. M. Cirilo, I. G. Junqueira, F. M. Vanin, and C. E. da C. Rodrigues, "Production of Cookies Enriched with Bioactive Compounds through the Partial Replacement of Wheat Flour by Cocoa Bean Shells," *Foods*, vol. 12, no. 3, 2023, doi:10.3390/foods12030436.

[36] A. T. Borchers, C. L. Keen, S. M. Hannum, and M. E. Gershwin, "Cocoa and chocolate: Composition, bioavailability, and health implications," *J. Med. Food*, vol. 3, no. 2, pp. 77–105, 2000, doi:10.1089/109662000416285.

[37] M. Franzen and M. Borgerhoff Mulder, "Ecological, economic and social perspectives on cocoa production worldwide," *Biodivers. Conserv.*, vol. 16, no. 13, pp. 3835–3849, 2007, doi: 10.1007/s10531-007-9183-5.

[38] V. Barišić *et al.*, "Difficulties with use of cocoa bean shell in food production and high voltage electrical discharge as a possible solution," *Sustain.*, vol. 12, no. 10, 2020, doi: 10.3390/SU12103981.