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REVIEW ARTICLE

Bioactivity, Health Benefits and Applications of Cocoa as a Functional Food Ingredient: A Review

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ABSTRACT

Cocoa (*Theobroma cacao* L.) is a highly valuable agricultural commodity that extends far beyond its traditional role as a raw material for chocolate production. In addition to giving chocolate its distinctive flavor and aroma, the fermentation, drying and roasting of cocoa beans affect the concentration and bioavailability of many beneficial substances. Polyphenols, including flavanols, catechins, epicatechins, and procyanidins greatly contribute to its antioxidant potential and health-promoting qualities. Methylxanthines like theobromine and caffeine, dietary fiber, pectin, minerals, vitamins, proteins, lipids, and volatile chemicals are also present in cocoa, all of which add to its nutritional and functional significance. These compounds have been associated with a wide range of biological activities, including antioxidant, anti-inflammatory, cardioprotective, antidiabetic, neuroprotective, antimicrobial, and gut health-promoting effects. Despite the numerous advantages associated with cocoa, challenges remain regarding the preservation of bioactive compounds during processing and storage. Factors such as oxidation, moisture uptake, microbial contamination, flavor deterioration, and fat blooms can impact product quality and shelf-life. However, advancements in processing technologies, bioactive compounds, and sustainable utilization of cocoa by-products are expected to enhance its nutritional, functional, and industrial value. Overall, cocoa represents a multifunctional food resource with significant potential to contribute to human health and sustainable food systems.

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INTRODUCTION

Cocoa (*Theobroma cacao L.*) is a tropical cash crop belonging to the order of *Malvales*, family *Malvaceae* and genus *Theobroma* (Soares & Oliveira, 2022). It serves as one of the most economically and nutritionally important agricultural commodities worldwide. Cocoa has been cultivated and consumed for thousands of years (Esan et al., 2025). In modern times, cocoa has evolved into a globally traded commodity, recognized as one of the most well-known raw materials worldwide, meeting the health expectations of consumers, supporting the livelihoods of millions of farmers and contributing significantly to the food industry as well as pharmaceutical, cosmetic, and nutraceutical (non-food) industries (Mulangu, 2017; Othick, 2025).

Cocoa contains, on a dry basis, approximately 16% proteins, 50% lipids (cocoa butter), and 20% carbohydrates, in addition to alkaloids such as theobromine (0.8–1.4%) and caffeine (0.1–0.7%). These latter compounds are used as criteria to differentiate between fine and bulk cocoa, thus ensuring authenticity, quality, and price (Hashimoto et al., 2018; Castillejos-Mijangos et al., 2023).

However, the relationship between cocoa chemical composition and sensory perception is not yet fully understood. Various compounds including amino acids, reducing sugars, peptides, organic acids, alkaloids, and polyphenols participate in flavor development and influence the final quality of cocoa products. (Santander Muñoz et al., 2020). In addition to flavor functionality, cocoa has attracted substantial scientific interest because of its potential health benefits, cocoa polyphenols, especially flavonoids such as catechins, epicatechins, and procyanidins, possess strong antioxidant properties. These compounds have been associated with anti-inflammatory, cardioprotective, antimicrobial, antiviral, anti-allergenic, anti-carcinogenic, and neuroprotective effects (Rajangam et al., 2025).

The increasing consumer demand for healthier foods has encouraged the development of functional foods and nutraceutical products. In this regard, chocolate has become an ideal carrier for delivering bioactive ingredients because of its high consumer acceptability, desirable sensory properties, and ability to protect sensitive compounds during digestion (Faccinetto-Beltrán et al., 2021). Consequently, researchers and food industries have developed functional chocolate products fortified with probiotics, omega-3 fatty acids, vitamins, minerals, phenolic extracts, sugar substitutes and other nutraceutical ingredients (Gómez-Fernández et al., 2021; Ahmad et al., 2026). In addition to its antioxidant activity, cocoa contains important minerals including magnesium, potassium, iron, zinc, and calcium, which support muscle function, nerve transmission, immune response, and bone health (Cinquanta et al., 2016). Cocoa also contains methylxanthines such as theobromine and caffeine, which contribute to mental alertness, mood enhancement, and cognitive performance (Martín et al., 2020). These bioactive compounds make cocoa-based beverages attractive to consumers seeking both nutritional and health benefits. Their combination of desirable sensory characteristics, nutritional value, and therapeutic potential continues to drive consumer demand and scientific interest in cocoa as a functional beverage ingredient (Barišić et al., 2023).

Therefore, there is a growing need for sustainable processing technologies and efficient utilization of cocoa resources (Imran, 2025; Donkor et al., 2026). This study focuses on the bioactive compounds present in cocoa and its by-products, their health functionality, and various food applications.

METHODOLOGY

This review was conducted using the most comprehensive databases in the fields of sustainable waste valorization, food science and technology, food chemistry and biomedicine: Web of Science, Scopus and Google Scholar. We restricted the search to articles published between 2016 and 2026 and used the standard narrative literature search guidelines to find studies that included the following terms in the title and the abstract: cocoa and cocoa by-products; bioactive compounds in cocoa; functional and health benefits and polyphenols in cocoa.

These criteria were selected to find studies about different health promoting properties and bioactive compounds present in cocoa and its derivatives caused by processing, postharvest transformation processes, and how they influence health. The search resulted in the choice of a list of research papers concerning the antioxidant, anti-inflammatory, antimicrobial, cardio-protective, and therapeutic capacity of cocoa polyphenols, both in vitro and in vivo. The papers on combinations of different products, extracts and purified compounds from cocoa, as well as mixtures with other plants, were included in the scope of this review.

BIOACTIVE COMPOUNDS AND FUNCTIONALITY OF COCOA

For many years, chocolate was consumed purely for pleasure, but recently, research has shown that dark chocolate and cocoa could have more beneficial effects on human health due to high content of polyphenols (Tuigunov et al., 2025). Polyphenols are large and heterogeneous group of biologically active secondary metabolites in plants, where they act as cell wall support materials, colorful attractants for birds and insects, and defense mechanisms under different environmental stress conditions (wounding, infection, excessive light, or UV irradiation (Campos-Vega, 2018). Based on a number of phenolic rings and of the structural elements that link these rings, they are divided into four groups: phenolic acids, lignans (recognized as phytoestrogens), flavonoids (the most abundant polyphenols in human diets), and stilbenes (resveratrol is under investigation for its anticarcinogenic properties). Flavonoid group is subdivided into: anthocyanins, flavonols, flavanols (catechins in tea, red wine, and chocolate), flavanones (citrus fruit are the main source), flavones, and isoflavones (main source is soya) (Grassia et al., 2019).

Polyphenols

Cocoa is widely recognized as one of the richest natural sources of polyphenols among plant-derived foods. Cocoa polyphenols are responsible not only for antioxidant activity, but also for several sensory characteristics such as bitterness, astringency, and color development. Polyphenols constitute approximately 12–18% of the dry weight of unfermented cocoa beans, making it particularly valuable in functional food development. The major classes of cocoa polyphenols (**Figure 1**) include flavanols, catechins, anthocyanins, and procyanidins (Faccinetto-Beltrán et al., 2021**)**. These compounds contribute significantly to the health-promoting properties associated with cocoa and dark chocolate consumption which has contributed to the growing classification of cocoa and dark chocolate as functional foods due to the presence of biologically active compounds (Martini et al., 2018; Sorrenti et al., 2020).

Apart from antioxidant activity, cocoa polyphenols exhibit anti-inflammatory, antihepatotoxic, antimicrobial, antiviral,

antiallergenic, and anticarcinogenic effects (Yang et al., 2024). These activities are associated with the earlier-mentioned four groups of polyphenolics in the cocoa beans.

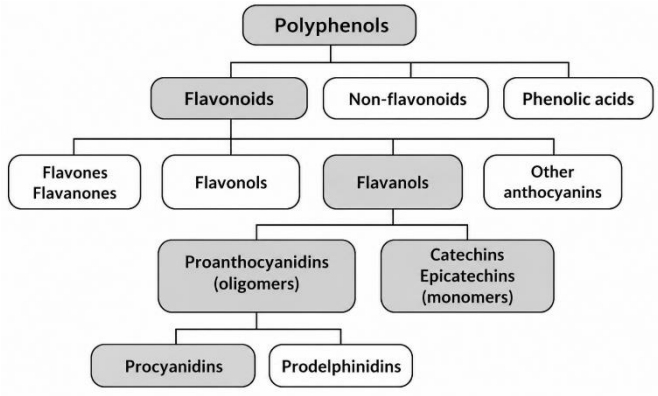

Fig. 1: Cocoa polyphenols: (Martini et al., 2018)

Cocoa polyphenols exert their biological effects through the regulation of several intracellular signaling pathways involved in inflammation, oxidative stress, apoptosis, and cellular survival. Among the most extensively studied pathways are the Nuclear Factor-kappa B (NF-κB), Mitogen-Activated Protein Kinase (MAPK), Phosphatidylinositol 3-Kinase/Protein Kinase B (PI3K/Akt), and Nuclear Factor Erythroid 2-Related Factor 2 (Nrf2) pathways (Dugo et al., 2018). The NF-κB pathway plays a central role in regulating genes involved in inflammatory responses. Cocoa flavanols help to suppress the NF-κB activation, reducing the expression of inflammatory cytokines and enzymes such as cyclooxygenase-2 (COX-2) and inducible nitric oxide synthase (iNOS). Similarly, activation of the Nrf2 pathway stimulates the expression of endogenous antioxidant enzymes including: Superoxide dismutase (SOD), Catalase (CAT), Glutathione peroxidase (GPx) (Caleja et al., 2017; Qin et al., 2017).

Inflammatory mediators are biochemical substances released by immune and damaged cells influence inflammatory responses. While inflammation acts as an essential defense mechanism against infection and injury, excessive or chronic production of inflammatory mediators can contribute to the development of numerous diseases including cardiovascular disease, diabetes, arthritis, obesity, asthma, and cancer (Magrone et al., 2017). Major inflammatory mediators include: Tumor Necrosis Factor-alpha (TNF-α), Interleukin-1β (IL-1β), Interleukin-6 (IL-6), Prostaglandins, Leukotrienes, Nitric oxide (NO). Cocoa polyphenols have been shown to suppress the synthesis and release of these mediators by inhibiting pro-inflammatory molecules signaling pathways such as NF-κB and MAPK. This reduction contributes significantly to the anti-inflammatory effects associated with cocoa consumption (Dugo et al., 2017; Natsume, 2018).

The endothelium is a thin, metabolically active layer of specialized cells that lines the entire interior surface of blood vessels, forming an interface between circulating blood and the vascular wall (Kim et al., 2017). Beyond serving as a simple physical barrier, endothelial cells play a central role in maintaining vascular homeostasis by regulating vascular tone, blood flow, blood coagulation, immune responses, and nutrient exchange between blood and tissues. Vascular tone is regulated through the synthesis and release of vasoactive substances that control the contraction and relaxation of vascular smooth muscle. (Álvarez-Cilleros et al., 2020).

Healthy endothelial cells prevent the adhesion of platelets and circulating inflammatory cells, thereby ensuring unobstructed blood circulation (Kim et al., 2017; Dugo et al., 2017). In terms of coagulation, endothelial cells maintain a delicate balance between procoagulant and anticoagulant activities. Under normal physiological conditions, the endothelium promotes blood fluidity by producing anticoagulant molecules such as prostacyclin, nitric oxide, thrombomodulin, and heparan sulfate. However, when vascular injury occurs, endothelial cells rapidly initiate clotting mechanisms to prevent excessive blood loss by exposing tissue factors and promoting platelet activation at the damaged site (Kim et al., 2017). Through these mechanisms, the endothelium ensures efficient delivery of oxygen and nutrients to tissues while facilitating the removal of metabolic waste products. The endothelium is equally important in immune regulation. Endothelial cells act as active participants in inflammatory responses by producing cytokines, chemokines, and adhesion molecules that guide immune cells to sites of infection or tissue injury. During inflammation, endothelial cells express molecules such as vascular cell adhesion molecule-1 (VCAM-1) and intercellular adhesion molecule-1 (ICAM-1), which facilitate the attachment and migration of leukocytes from the bloodstream into affected tissues. This process is essential for host defense but may contribute to chronic inflammatory diseases when excessively activated (Martins et al., 2020; Álvarez-Cilleros et al., 2020).

Endothelial dysfunction occurs when these regulatory mechanisms become impaired and is considered one of the earliest indicators of cardiovascular disease. It is characterized by reduced nitric oxide bioavailability, increased oxidative stress, chronic inflammation, enhanced platelet aggregation, and impaired vasodilatory capacity. Such dysfunction contributes to the development of hypertension, atherosclerosis, thrombosis, and other cardiovascular disorders. Several epidemiological and clinical studies have linked cocoa consumption with reduced blood pressure, improved vascular function, enhanced insulin sensitivity, and better cognitive performance (Grassi et al., 2023). These health effects are largely attributed to the synergistic actions of cocoa polyphenols (Magrone et al., 2017; Álvarez-Cilleros et al., 2020).

Flavanols

Flavanols are the most abundant and biologically important subgroup of cocoa polyphenols. The principal flavanols present in cocoa are catechin, epicatechin, and oligomeric procyanidins (**Figure 2**) (Faccinetto-Beltrán et al., 2021). Flavonoids possess strong antioxidant activity which helps to reduce oxidative damage to lipids, proteins, and DNA within cells. This protective effect has generated substantial scientific interest regarding the role of cocoa flavanols in the prevention of oxidative stress-related diseases (Goya et al., 2022). Cocoa beans are considered one of the richest natural dietary sources of flavonoids, containing approximately 12–18% polyphenols on a dry weight basis (Soares & Oliveira, 2022). Flavanols possess strong free-radical scavenging activity due to their hydroxyl-rich molecular structure. Catechin and epicatechin contain multiple phenolic hydroxyl groups capable of donating hydrogen atoms or electrons to reactive oxygen species (ROS) (Behl et al., 2021). Following electron donation, the resulting flavanol radicals become stabilized through resonance within the aromatic ring system, thereby terminating oxidative chain reactions and reducing cellular damage caused by oxidative stress.

One of the most important physiological effects of cocoa flavanols is their ability to improve endothelial function. Cocoa flavanols stimulate nitric oxide synthesis, leading to

vasodilation and improved blood circulation. This mechanism contributes to lower blood pressure and reduced cardiovascular risk. Cocoa flavanols, particularly (-)-epicatechin, have been shown to improve endothelial function by stimulating endothelial nitric oxide synthase (eNOS), the enzyme responsible for nitric oxide production (Álvarez-Cilleros et al., 2018). Flavanols activate signaling pathways such as phosphatidylinositol 3-kinase/protein kinase B (PI3K/Akt), which phosphorylate and activate eNOS, resulting in increased nitric oxide synthesis (Goya et al., 2022).

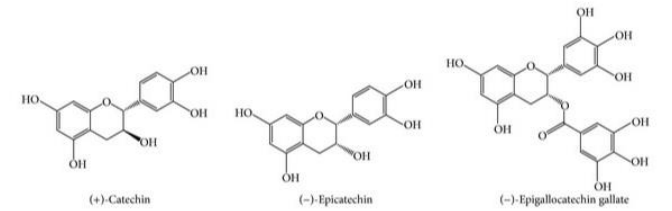

Fig. 2: Major flavanols in cocoa: (Faccinetto-Beltrán et al., 2021)

Elevated nitric oxide levels promote vasodilation, reduce vascular resistance, inhibit platelet aggregation, suppress inflammatory responses, and improve overall vascular health. The neuroprotective effects of flavanols have also attracted scientific attention (Bombardi et al., 2018; Mogulkoc & Baltaci, 2020; Bellavite, 2023). Cocoa flavanols may improve cerebral blood flow and support cognitive functions such as memory, learning, and concentration. Animal studies indicate that flavanols interact with neuronal signaling pathways involved in neuroprotection and brain plasticity (Tavan et al., 2024).

Despite their beneficial properties, flavanols are highly sensitive to processing. Fermentation and roasting can cause significant degradation through oxidation and thermal decomposition. During digestion, phenolic hydroxyl groups present in flavanols form hydrogen bonds and hydrophobic interactions with casein molecules, leading to the formation of protein–polyphenol complexes (**Figure 3**). These complexes may decrease the solubility and intestinal absorption of flavanols, thereby reducing their bio-accessibility and subsequent physiological activity (Hamzalioglu, 2023). Reduced absorption results in lower plasma concentrations of bioactive compounds such as epicatechin, potentially diminishing antioxidant activity, nitric oxide production, and cardiovascular benefits associated with cocoa consumption. Consequently, dark chocolate is generally considered a more effective dietary source of bioavailable flavanols than milk chocolate. (Faccinetto-Beltrán et al., 2021)

These complexes are often larger in size, less soluble, and less accessible to digestive enzymes

As a result, fewer free flavanols remain available for absorption in the small intestine.

The complexes may remain in the gastrointestinal tract and pass into the colon rather than being absorbed efficiently. Dark chocolate produces higher plasma epicatechin concentrations with greater antioxidant capacity than milk chocolate because more flavanols are absorbed. This is one reason dark chocolate is often associated with stronger cardiovascular effects than milk chocolate (Ashfaq et al., 2024).

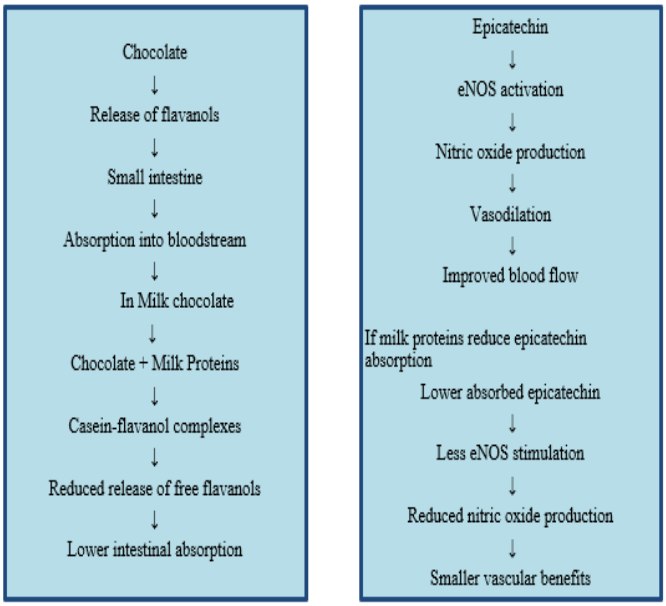

Fig. 3: Milk Interference with flavanol bioavailability

Procyanidins

Procyanidins are oligomeric and polymeric flavanols formed through the condensation of catechin and epicatechin units (Resat & Bayraktar, 2023). They are among the major contributors to cocoa's antioxidant activity. Cocoa procyanidins vary in molecular size from dimers and trimers to highly polymerized structures which influences their bioavailability. Smaller oligomers are more readily absorbed in the gastrointestinal tract, whereas larger polymeric procyanidins are poorly absorbed and therefore reach the colon largely intact and undergo microbial fermentation by the gut microbiota to produce low-molecular-weight phenolic beneficial metabolites which can be absorbed into the bloodstream to exert biological activities that contribute to human health (Ademiluyi, 2025). Among cocoa polyphenols, procyanidins exhibit exceptionally strong antioxidant properties due to their multiple hydroxyl groups and polymeric structure, thereby, contributing to cardiovascular protection by improving endothelial function, immune responses, reducing LDL cholesterol oxidation, and lowering blood pressure (Yang et al., 2018; Yang et al., 2023). Increasing evidence suggests that cocoa procyanidins may exert anticancer effects by influencing multiple cellular signaling pathways involved in cell proliferation, apoptosis, inflammation, angiogenesis, and metastasis (Koteswari et al., 2020; Ademiluyi, 2025).

One of the hallmarks of cancer is uncontrolled cell proliferation, where cells continue to divide despite signals that would normally limit growth. Procyanidins have been shown to suppress this abnormal proliferation by modulating proteins that regulate the cell cycle. Specifically, they can inhibit the activity of cyclins and cyclin-dependent kinases (CDKs), which are essential for progression through the different phases of cell division. At the same time, procyanidins may increase the expression of cell-cycle inhibitory proteins such as p21 and p27, resulting in cell-cycle arrest and reduced tumor growth. In addition to inhibiting proliferation, procyanidins can promote apoptosis, a tightly regulated process of programmed cell death that removes damaged, aged, or abnormal cells from the body. Cancer cells often evade apoptosis, allowing them to survive and accumulate genetic mutations. Procyanidins help restore this protective mechanism by influencing both the intrinsic (mitochondrial) and extrinsic apoptotic pathways (Chimento et al., 2023). Furthermore, the fermentation of procyanidins by

the gut microbiota promotes the growth of beneficial gut bacteria such as *Bifidobacterium* and *Lactobacillus* species while suppressing potentially pathogenic microorganisms. The resulting improvements in gut microbial composition and intestinal barrier integrity may further contribute to the prevention of metabolic, inflammatory, and cardiovascular disorders (Sorrenti et al., 2020). Therefore, even though large procyanidins are not efficiently absorbed in their original form, their microbial metabolites play a significant role in mediating the health benefits associated with cocoa consumption.

Methylxanthines/ Alkaloids

Methylxanthines are naturally occurring alkaloids found in cocoa beans. The two principal methylxanthines present in cocoa are theobromine and caffeine. These compounds contribute to the characteristic bitterness of cocoa and exert mild stimulant effects on the central nervous system (Goya et al., 2022). Theobromine is the predominant methylxanthine in cocoa beans and chocolate products. It occurs in concentrations significantly higher than caffeine. Theobromine acts as a mild central nervous system stimulant, vasodilator, and diuretic primarily through antagonism of adenosine receptors (Zhang et al., 2024). Under normal physiological conditions, adenosine acts as an inhibitory neurotransmitter that promotes relaxation and sleepiness. As adenosine accumulates in the brain throughout the day, it binds to adenosine receptors (A_1 and A_2A receptors), reducing neuronal activity and produces feelings of fatigue. Theobromine competes with adenosine for these receptor sites, reducing the inhibitory effects of adenosine and leading to increased neuronal activity and neurotransmitter release. This produces mild stimulation characterized by increased alertness, improved mood, reduced perception of fatigue, enhanced mental performance. However, theobromine binds less strongly to adenosine receptors than caffeine (Martín-Peláez et al., 2017).

Compared to caffeine, its stimulatory effect is milder but longer-lasting**,** producing a gentle increase in alertness without the pronounced nervousness, restlessness, or rapid heart rate often associated with high caffeine intake (Nemoto et al., 2022). Theobromine also exhibits mild diuretic activity by increasing renal blood flow and reducing the tubular reabsorption of sodium and water in the kidneys. Increased blood flow enhances glomerular filtration, while reduced sodium reabsorption decreases water retention, resulting in greater urine production (Shateri et al., 2023). Additionally, inhibition of phosphodiesterase enzymes contributes to elevated intracellular cyclic AMP levels, further supporting diuretic activity. Through these mechanisms, theobromine promotes fluid elimination and may contribute to blood pressure regulation. Another study suggests that theobromine exhibits bronchodilatory properties through relaxation of bronchial smooth muscle and antagonism of adenosine receptors, making it potentially beneficial in respiratory conditions (Dutra et al., 2024; Ghosh et al., 2024). By inhibiting phosphodiesterase enzymes, theobromine increases intracellular cyclic AMP concentrations, which promote smooth muscle relaxation and widening of the airways. In addition, blockade of adenosine receptors reduces bronchoconstrictive signaling that can contribute to airway narrowing (Kalantarzadeh et al., 2020). These mechanisms improve airflow through the respiratory tract and may be beneficial in conditions characterized by airway constriction, such as asthma and chronic obstructive pulmonary disease.

Furthermore, evidence suggests that theobromine may suppress sensory nerve activity involved in the cough reflex, thereby reducing airway irritation and coughing. This observation has led to interest in theobromine as a potential antitussive (cough-suppressing) agent (Morice et al., 2017; Fernández et al., 2017). However, it is worthy to note that excessive theobromine intake may be toxic to certain animals such as dogs because they metabolize the compound slowly (Bates, 2024). Caffeine is present in cocoa in smaller amounts than theobromine. The caffeine content of chocolate contributes to increased alertness, reduced fatigue, and improved concentration. Combined with theobromine, caffeine contributes to the psychoactive properties of chocolate (Tunick & Nasser, 2019; Terra, 2024). Caffeine also exhibits antioxidant activity, stimulatory effect and may enhance metabolic rate and physical performance (Shin et al., 2022). However, excessive consumption may cause insomnia, nervousness, and increased heart rate in sensitive individuals.

Lipids

Lipids constitute one of the most abundant components of cocoa beans, accounting for approximately 50–57% of the dry weight, primarily in the form of cocoa butter (Kamphuis, 2017). The characteristic melting behavior of cocoa butter is largely determined by its triglyceride composition. At room temperature, cocoa butter remains solid, providing structural stability to chocolate products. However, it melts rapidly at approximately 34–37 °C, which is close to human body temperature (Loke et al., 2024). This unique property produces the desirable sensation of smoothness and rapid melting in the mouth that consumers associate with high-quality chocolate. From a nutritional perspective, cocoa butter possesses a distinctive fatty acid profile. Although it contains significant amounts of saturated fatty acids, particularly stearic acid, studies indicate that stearic acid exerts a neutral effect on blood cholesterol levels because it is rapidly converted to oleic acid in the liver. Oleic acid, a monounsaturated fatty acid also abundant in olive oil, has been associated with cardiovascular benefits including improved lipid profiles and reduced inflammation (Cheng et al., 2019). Furthermore, cocoa butter contains minor bioactive lipid components such as tocopherols (vitamin E), phytosterols, and phospholipids, which contribute additional antioxidant activity and oxidative stability. These compounds help protect both the fat fraction and other bioactive compounds in cocoa from oxidative deterioration during storage (Mohamad et al., 2019). The physical properties of cocoa butter also play a crucial role in chocolate manufacturing. Proper crystallization of cocoa butter during tempering promotes the formation of the stable β(V) crystal form, which provides chocolate with its characteristic gloss, firmness, snap, and resistance to fat bloom. Inadequate crystallization can result in fat migration and bloom formation, negatively affecting product quality and shelf life (Pinto-padilla, 2018).

Proteins and Amino Acids

During fermentation, endogenous proteolytic enzymes become activated as the cocoa bean cells begin to break down. These enzymes hydrolyze storage proteins into smaller peptides and free amino acids (Domínguez-Pérez et al., 2020). The accumulation of amino acids such as leucine, alanine, phenylalanine, valine, and lysine is particularly important because these compounds act as flavor precursors during roasting (Quelal et al., 2023). The most significant role of amino acids in cocoa processing is their participation in the Maillard reaction, a non-enzymatic browning reaction that occurs between amino acids and reducing sugars under high

temperatures. During roasting, amino acids react with glucose and fructose generated during fermentation to produce hundreds of aroma-active compounds.

The simplified Maillard reaction may be represented as:

Reducing sugar + amino acid → Schiff base → Amadori products → flavor compounds + melanoidins

Through a series of complex reactions, Maillard chemistry generates numerous volatile compounds including pyrazines, aldehydes, furans, pyrroles, and ketones that contribute to the characteristic roasted, nutty, caramel-like, and chocolate aromas. For example: leucine contributes to malty and roasted notes, phenylalanine contributes floral and honey-like aromas, alanine contributes sweet and caramel-like notes, valine contributes cocoa and chocolate-like aromas (Ziegleder, 2017). In addition to flavor generation, proteins contribute nutritionally by providing essential amino acids necessary for tissue growth, enzyme synthesis, and metabolic regulation. Tryptophan, an essential amino acid present in cocoa serves as a precursor for serotonin synthesis (Kumar, 2025). Serotonin is a neurotransmitter involved in mood regulation, emotional stability, appetite control, and sleep. Increased serotonin availability is generally associated with feelings of well-being and relaxation. Consumption of chocolate may therefore contribute indirectly to improved mood through enhanced serotonin production. Cocoa proteins also contain bioactive peptides that may exhibit antioxidant and antihypertensive properties following digestion (Nayak et al., 2022). Therefore, proteins and amino acids play a dual role in cocoa by contributing both nutritional value and the formation of desirable sensory characteristics through roasting-induced chemical reactions.

Anthocyanins

Anthocyanins are natural pigments responsible for the purple coloration of fresh cocoa beans. During fermentation, anthocyanins undergo enzymatic degradation and oxidation, resulting in the characteristic brown color of fermented cocoa beans. Anthocyanins contribute to antioxidant defense mechanisms by scavenging free radicals and reducing oxidative stress (Goya et al., 2022). They may also exhibit anti-inflammatory and cardioprotective effects.

The anti-inflammatory activity of anthocyanins results from a combination of mechanisms including inhibition of NF-κB and MAPK signaling pathways, suppression of pro-inflammatory cytokine production, reduction of inflammatory enzyme, attenuation of oxidative stress, and protection of vascular endothelial function (Dugo et al., 2017; Natsume, 2018). However, anthocyanin concentrations in finished chocolate products are relatively low due to extensive degradation during fermentation and roasting. The loss of anthocyanins during processing is considered one of the major biochemical transformations in cocoa flavor and color development (Urbańska et al., 2019).

Minerals and Vitamins

Cocoa contains several essential minerals and vitamins important for human health. Major minerals present in cocoa include Mg, K, P, Ca, Fe, Zn, & Cu (Soares & Oliveira, 2022). Magnesium is particularly abundant in cocoa and contributes to muscle function, nerve transmission, and energy metabolism (Fatima et al., 2024). Iron supports oxygen transport and hemoglobin synthesis (de Souza Braga et al., 2020) while zinc contributes to immune function and enzymatic activity (Camps-Bossacoma et al., 2018). Cocoa also contains trace amounts of vitamins such as vitamin E, vitamin B complex, and vitamin C in cocoa pulp products. The mineral-rich nature of cocoa contributes to its nutritional value and supports its classification as a functional food ingredient.

Dietary Fibre

Cocoa bean shells, pod husks, and cocoa powder contain considerable amounts of insoluble and soluble fibres (Campos-Vega et al., 2018; Figueroa et al., 2020). Dietary fibre plays an essential role in digestive health by promoting bowel movement, improving gut microbiota composition, and reducing constipation. Adequate fibre intake may lower the risk of gastrointestinal disorders such as diverticular disease and hemorrhoids. Soluble and fermentable fibres also act as prebiotics**,** serving as substrates for beneficial gut microorganisms such as *Bifidobacterium* and *Lactobacillus* species.

During fermentation in the colon, these microorganisms convert fibre into short-chain fatty acids (SCFAs) including acetate, propionate, and butyrate (Lončarević et al., 2021; Peña-Correa et al., 2023). These metabolites help maintain intestinal health by providing energy to colon cells, strengthening the intestinal barrier, reducing inflammation, and inhibiting the growth of pathogenic microorganisms. Soluble fibres may also help regulate blood glucose and cholesterol levels by forming a viscous gel-like substance when mixed with water in the gastrointestinal tract (Edo et al., 2025). This gel slows gastric emptying and delays the digestion and absorption of carbohydrates in the small intestine. As a result, glucose enters the bloodstream more gradually, preventing rapid spikes in postprandial (after-meal) blood sugar levels. Improved glycemic control reduces the demand for insulin secretion and may enhance insulin sensitivity over time. These effects are particularly beneficial for individuals with diabetes or those at risk of developing type 2 diabetes. This combination of fibre and antioxidants enhances the functional value of cocoa products. The incorporation of cocoa fibre into food formulations has gained interest in the development of functional foods such as bakery products, beverages, and dietary supplements. CBS fibre has also been explored as a fat replacer and texture enhancer in food products due to its functional properties (Delgado-Ospina et al., 2021).

Pectin

Pectin is a complex polysaccharide abundantly present in cocoa pod husk. It consists mainly of galacturonic acid units and is classified according to its methoxyl content (Anoraga et al., 2024). Cocoa pod husk pectin is generally classified as low methoxyl pectin because of its low degree of esterification. Low methoxyl pectins form gels in the presence of calcium ions and are widely used in the food industry (Said et al., 2023). Pectin performs several technological functions including gelling, thickening, emulsifying, stabilizing, and film-forming properties which makes it useful in jams, jellies, confectionery products, beverages, and edible coatings (Ouattara et al., 2021; Barrios-Rodríguez et al., 2022). Research has demonstrated that cocoa pod husk pectin possesses good thermal stability and favorable physicochemical characteristics comparable to commercial citrus and apple pectin (Musita, 2021). In addition to food applications, cocoa pectin exhibits potential pharmaceutical and nutraceutical uses due to its swelling capacity, pseudoplastic behavior, and antimicrobial activity (Barrios-Rodríguez et al., 2022). Cocoa pod husk pectin also

contains minerals such as Ca, Mg, K, and P, enhancing its nutritional value.

Volatile Compounds

Volatile compounds are present in relatively small concentrations compared with other cocoa constituents, yet, these compounds have a profound influence on flavor perception because the human olfactory system can detect many volatile molecules at extremely low concentrations. Volatile compounds include aldehydes, ketones, alcohols, pyrazines, esters, and organic acids (**Table 1**) (Quelal et al., 2023). These compounds serve as important indicators of cocoa quality and processing efficiency. Premium cocoa varieties typically contain higher concentrations of desirable floral, fruity, and roasted aroma compounds, whereas poor-quality or improperly processed cocoa may contain excessive acidic, smoky, moldy, or earthy volatiles (Qin et al., 2017). Consequently, aroma profiling using gas chromatography–mass spectrometry (GC–MS) has become an important analytical tool for quality control, authentication, and flavor optimization in the cocoa and chocolate industry (Yang et al., 2024).

EFFECT OF PROCESSING ON BIOACTIVE COMPOUNDS

Processing operations significantly influence the concentration, composition, and bioavailability of cocoa bioactive compounds (Goya et al., 2022). Fermentation initiates important biochemical transformations necessary for flavor development but also causes substantial polyphenol losses (Yang et al., 2023). Enzymatic oxidation mediated by polyphenol oxidase converts flavanols into insoluble brown pigments, reducing bitterness and astringency (Goya et al., 2022). Drying further decreases polyphenol content through continued oxidation reactions, especially under prolonged exposure to high temperatures and oxygen. Roasting produces desirable chocolate aroma through Maillard reactions and Strecker degradation. However, high roasting temperatures can degrade heat-sensitive compounds such as catechins, epicatechin, anthocyanins, and certain vitamins (Oracz & Żyżelewicz, 2020; Rojas et al., 2022). Alkalization or Dutch processing causes even greater reductions in flavanol content due to pH-induced degradation and oxidation. Although alkalization improves color and flavor, it substantially lowers antioxidant capacity (Sioriki et al., 2021; Sahin et al., 2024). Conversely, some processing steps may enhance bioavailability. Moderate roasting can break cellular structures and improve the release of certain compounds during digestion. The extent of bioactive compound retention depends on processing parameters including temperature, time, pH, oxygen exposure, and cocoa variety (Oracz et al., 2020; Soares & Oliveira, 2022).

Table 1: Volatile compounds and their flavor perception

Volatile compounds	Examples	Function	References
Aldehydes (amino acid degradation during fermentation and roasting)	Phenylacetaldehyde Benzaldehyde Acetaldehyde	Honey-like aroma Almond-like aroma Fruity aroma	Caporaso et al., 2018; Gigl et al., 2021; Barrios-Rodríguez et al., 2021.
Pyrazines (Maillard reactions during roasting between amino acids and reducing sugars).	Tetramethylpyrazine Trimethylpyrazine Dimethylpyrazine	Roasted notes Nutty notes, cocoa like aroma, toasted characteristics	Zakidou et al., 2021; Cao et al., 2023
Ketones (generated through lipid oxidation and Maillard reaction pathways during roasting).	Acetoin 2-Heptanone 2-Nonanone	Buttery, creamy, caramel-like, and fruity notes.	De-Melo Pereira et al., 2019; Cao et al., 2023
Alcohols (by yeast metabolism during fermentation).	Ethanol Phenylethyl alcohol Linalool	Floral and fruity sensory notes. Floral notes associated with premium cocoa	Koné et al., 2016; Rottiers et al., 2019; Holt et al., 2019
Esters (microbial fermentation when alcohols react with organic acids).	Ethyl acetate Isoamyl acetate	Esters impart fruity and sweet aromas	Anita-Sari et al., 2023; Xiao et al., 2024; Tofalo & Perpetuini, 2025
Organic acids (by acetic acid bacteria during fermentation).	Acetic acid Lactic acid Citric acid	Organic acids contribute both flavor and fermentation dynamics.	Aprotosoaie et al., 2016; Rottiers et al., 2019; Quelal et al., 2023

Because of these processing effects, dark chocolate with high cocoa content generally retains more bioactive compounds and exhibits greater antioxidant activity than milk chocolate or heavily processed cocoa products (Jaćimović et al., 2022).

HEALTH BENEFITS OF COCOA

Antioxidant activity

Antioxidants are compounds capable of neutralizing reactive oxygen species (ROS) and free radicals that contribute to oxidative stress within the body. Oxidative stress occurs when there is an imbalance between the production of reactive oxygen species and the body's antioxidant defense system. Excessive ROS can damage lipids, proteins, and DNA, leading to chronic diseases such as cardiovascular disorders, diabetes, neurodegenerative diseases, cancer, and premature aging (Garcia-Llorens, et al., 2025). The antioxidant activity of cocoa polyphenols is primarily attributed to the presence of hydroxyl (-OH) groups attached to aromatic rings in the flavonoid structures (Oracz et al., 2020).

Studies have demonstratedd that cocoa possesses greater antioxidant capacity than several commonly consumed antioxidant-rich foods such as green tea and red wine (Żyżelewicz et al., 2021; Jaćimović et al., 2022). The oxygen radical absorbance capacity (ORAC) of cocoa products is

particularly high due to the synergistic interaction among the different polyphenolic compounds. Epicatechin and procyanidins have been shown to inhibit lipid peroxidation, a destructive oxidative process in which free radicals attack membrane lipids, leading to cellular dysfunction and tissue damage (Yang et al., 2018). Cocoa antioxidants also preserve the integrity of low-density lipoproteins (LDL), thereby reducing oxidized LDL formation, a major contributor to atherosclerosis (Silva et al., 2022). Cell membranes are composed largely of phospholipids that contain polyunsaturated fatty acids (PUFAs). These fatty acids possess multiple double bonds, making them particularly susceptible to free radical attack (Islam, et al., 2023).

The process begins when reactive oxygen species (ROS), such as the hydroxyl radical (*OH), remove a hydrogen atom from a polyunsaturated fatty acid molecule within the cell membrane. This reaction produces a highly unstable lipid radical (L*). The lipid radical rapidly reacts with molecular oxygen to form a lipid peroxyl radical (LOO*), which in turn attacks neighboring lipid molecules, generating additional lipid radicals and perpetuating a chain reaction.

As lipid peroxidation progresses, membrane integrity becomes compromised. The membrane loses its fluidity and selective permeability, impairing normal cellular functions such as nutrient transport, ion exchange, signal transduction, and energy metabolism. Furthermore, degradation of lipid hydroperoxides produces toxic secondary products such as malondialdehyde (MDA) and 4-hydroxynonenal (4-HNE), which can damage proteins, enzymes, and DNA (Bekyarova et al., 2019). Epicatechin and procyanidins help prevent lipid peroxidation by donating hydrogen atoms or electrons to neutralize reactive oxygen species before they attack membrane lipids. By stabilizing free radicals, these polyphenols terminate the propagation phase of lipid peroxidation and interrupt the oxidative chain reaction (Yang et al., 2018).

The resulting phenoxyl radical is resonance-stabilized and far less reactive than the original lipid radical, preventing further membrane damage (Lewandowska et al., 2026). In addition, epicatechin and procyanidins can chelate transition metals such as iron (Fe^{2+}) and copper (Cu^{2+}), which catalyze the formation of highly reactive hydroxyl radicals through Fenton-type reactions (Lomozová et al., 2022). By reducing metal-catalyzed radical generation, these compounds further limit lipid oxidation. Through inhibition of lipid peroxidation, cocoa flavanols help preserve cell membrane integrity, maintain normal cellular function, reduce oxidative tissue injury, and contribute to the prevention of chronic diseases associated with oxidative stress. However, antioxidant activity varies considerably depending on cocoa processing. Fermentation, roasting, and alkalization decrease flavonoid concentrations through oxidation and thermal degradation (Sioriki et al., 2021; Soares & Oliveira, 2022; Sahin et al., 2024). Some studies have also suggested that milk proteins may reduce flavonoid bioavailability by forming insoluble complexes during digestion, although findings remain controversial (Jaćimović et al., 2022; van de Langerijt, et al., 2023). Despite these variations, cocoa continues to be regarded as one of the most important functional foods with substantial antioxidant potential.

Anti-inflammatory Effects

Inflammation is a natural biological response designed to protect tissues from infection, injury, and harmful stimuli (Harvanová & Duranková, 2025). However, chronic inflammation contributes to the development of several diseases including obesity, diabetes, arthritis, neurodegenerative disorders, and cancer (Chen et al., 2017). Cocoa polyphenols exhibit significant anti-inflammatory properties through modulation of various inflammatory signaling pathways. Flavanols, catechins, and procyanidins inhibit the activation of nuclear factor-kappa B (NF-κB), a major transcription factor responsible for the expression of pro-inflammatory cytokines and enzymes. When NF-κB is activated, inflammatory mediators such as tumor necrosis factor-alpha (TNF-α), interleukin-6 (IL-6), cyclooxygenase-2 (COX-2), and inducible nitric oxide synthase (iNOS) are produced (Dugo et al., 2017; Natsume, 2018). Cocoa flavonoids suppress these inflammatory mediators, thereby reducing tissue inflammation. (Aprotosoaie et al., 2016). Epicatechin has been shown to decrease leukocyte adhesion to endothelial cells, an important early step in inflammation and atherosclerosis development (Dugo et al., 2017; González-Barrio et al., 2020; Baranowska et al., 2020). In addition, cocoa flavonoids inhibit oxidative stress-induced inflammatory cascades by scavenging reactive oxygen species. Animal studies have demonstratedd that cocoa supplementation reduces inflammatory biomarkers and improves tissue protection under inflammatory conditions (Camps-Bossacoma et al., 2017; Grassi et al., 2023). Human studies similarly indicate reductions in C-reactive protein (CRP) levels following cocoa consumption (Magrone et al., 2017; Caleja et al., 2017; Davis et al., 2020; Moua et al., 2020). According to available data, no side effects, no allergic reactions to cocoa or cocoa products have been reported. However, some argue that dosage, frequency of intake, and individual metabolic differences significantly influence outcomes. It is stated that high amounts of cocoa or cocoa products in the amount of 100 g per day can cause sweating, chills and headaches (Popa et al., 2019; Grassi et al., 2023). The anti-inflammatory properties of cocoa are now considered one of the key mechanisms underlying its protective effects against chronic diseases (Barišić et al., 2023)

Cardioprotective effects

Among all health benefits associated with cocoa, cardiovascular protection is the most extensively studied and scientifically supported. It has been stated that it plays a role in the reduction of death events caused by cardiovascular diseases (Singh et al., 2022; Sesso et al., 2022), it also reduces the occurrence of hypertension primarily through enhancement of endothelial function (Magrone et al., 2017; Dugo, et al., 2018). Cocoa flavanols stimulate endothelial nitric oxide synthase (eNOS), leading to elevated nitric oxide levels. Nitric oxide relaxes blood vessels, improves vasodilation, and lowers blood pressure (Aydin, 2019; Krittanawong et al., 2021). Numerous clinical studies have demonstratedd that cocoa consumption improves flow-mediated dilation (FMD), a widely used indicator of vascular health and significant reductions in systolic and diastolic blood pressure (Garcia-Yu, et al., 2020; Amoah et al., 2022; Murphy et al., 2025). Improved endothelial function contributes to better circulation and reduced cardiovascular risk. Cocoa flavonoids also inhibit LDL oxidation, which plays a major role in plaque formation during atherosclerosis (Dugo et al., 2017; Martins et al., 2020). The Kuna Indians of Panama, well known for consuming large quantities of cocoa beverages (about 5cups; approximately 900 mg per day, making up the highest intake worldwide) which, moreover, was determined to be rich in flavanols,

reportedly exhibited remarkably low rates of hypertension, aging, and cardiovascular disease despite having a high salt diet compared to other communities (Ludovici et al., 2017). Although cocoa demonstrates promising cardiovascular benefits, excessive consumption of commercial chocolate products high in sugar and fat may counteract these positive effects.

Antidiabetic Effects

Cocoa has attracted attention for its potential role in diabetes prevention and management due to its effects on glucose metabolism, insulin sensitivity, and inflammation. Insulin resistance is a hallmark of type 2 diabetes and occurs when cells fail to respond effectively to insulin. Cocoa flavanols may improve insulin sensitivity by enhancing endothelial function and reducing oxidative stress and inflammation (Álvarez-Cilleros et al., 2020). One proposed mechanism involves nitric oxide-mediated improvement in blood flow to insulin-sensitive tissues such as skeletal muscle. Enhanced circulation facilitates glucose uptake and utilization (Qaed et al., 2023). Cocoa polyphenols may also influence carbohydrate digestion by inhibiting digestive enzymes such as α-amylase and α-glucosidase. This inhibition slows glucose absorption and reduces postprandial blood glucose spikes (Ayua et al., 2021). Several studies have shown improved glucose tolerance, improved insulin sensitivity, and reduced fasting insulin levels following cocoa supplementation (Davis et al., 2020; Joseph et al., 2021; Oliveira et al., 2022; Anari et al., 2025). The antidiabetic benefits of cocoa are influenced by product formulation. Although cocoa shows promise in diabetes management, researchers emphasize the need for long-term clinical trials to establish optimal dosage and therapeutic effectiveness.

Neuroprotective Effects

Cocoa flavonoids have demonstratedd considerable potential in supporting brain health and cognitive function. Their neuroprotective effects are linked to antioxidant activity, anti-inflammatory action, and improved cerebral blood flow (Bakoyiannis et al., 2019). The brain is particularly vulnerable to oxidative stress due to its high oxygen consumption and lipid-rich composition. Cocoa antioxidants help protect neurons from oxidative damage and neuroinflammation associated with aging and neurodegenerative diseases. Flavanols increase cerebral blood flow by stimulating nitric oxide production and improving vascular function. Enhanced blood circulation supplies oxygen and nutrients to brain tissues, supporting cognitive performance (Nemoto et al., 2022; Shateri et al., 2023). Research suggests that cocoa flavonoids interact with neuronal signaling pathways involved in memory, learning, and synaptic plasticity. Epicatechin may activate pathways associated with brain-derived neurotrophic factor (BDNF), which supports neuronal growth and survival (Lamport et al., 2020; Shateri et al., 2023). Animal studies have demonstratedd improvements in spatial memory and cognitive performance following cocoa flavanol supplementation. Human studies also report enhanced attention, executive function, and mental processing speed after cocoa consumption with evidence suggesting that regular cocoa intake may reduce the risk of neurodegenerative diseases such as Alzheimer's disease and Parkinson's disease through reduction of oxidative stress and inflammation (Barrera-Reyes et al., 2020; Martín et al., 2020; Zhu et al., 2021). Methylxanthines such as caffeine and theobromine may further contribute to improved alertness, mood, and cognitive performance through stimulation of the central nervous system. However, researchers caution that cognitive benefits may vary depending on flavanol dosage, age, health status, and processing methods affecting bioactive compound retention (Montagna et al., 2019).

Antimicrobial Activity

Cocoa and cocoa by-products possess antimicrobial properties against several bacteria, fungi, and viruses. These effects are mainly attributed to polyphenols, methylxanthines, and certain bioactive peptides. Polyphenols can disrupt microbial cell membranes, interfere with microbial enzyme systems, and inhibit nucleic acid synthesis (Makarewicz et al., 2021; De Rossi et al., 2025). Studies have demonstratedd inhibitory effects of cocoa extracts against both gram-positive and gram-negative bacteria. Cocoa pod husk extracts and cocoa bean shell polyphenols have shown antimicrobial activity against foodborne pathogens and spoilage microorganisms (Kayaputri et al., 2020; Al-Shalah et al., 2023). Adi-Dako et al. (2016) reported that cocoa pod husk pectin exhibited antibacterial activity against microorganisms including Escherichia coli. Cocoa flavonoids may also interfere with viral replication and reduce microbial adhesion to host tissues. The acidic nature of cocoa honey and fermentation by-products further contributes to microbial inhibition by creating unfavorable conditions for pathogenic organisms.

Anti-obesity Potential

Obesity is associated with chronic inflammation, oxidative stress, insulin resistance, and metabolic dysfunction. Cocoa polyphenols may contribute to obesity management through several biological mechanisms (Magrone et al., 2017; Aloo et al., 2023). Research indicates that cocoa flavanols influence lipid metabolism by regulating genes involved in fat synthesis and oxidation. Some studies suggest that cocoa polyphenols reduce adipogenesis, the process of fat cell formation (Rebollo-Hernanz et al., 2019; Jang et al., 2018). Cocoa compounds may activate AMP-activated protein kinase (AMPK), a key regulator of cellular energy metabolism. Activation of AMPK enhances fatty acid oxidation and glucose uptake while inhibiting lipid accumulation (Joseph et al., 2021; Ayua et al., 2021). Animal studies have demonstratedd reduced body weight gain and decreased visceral fat accumulation following cocoa supplementation (Aranaz et al., 2019; Abu-Zaid et al., 2024). Cocoa polyphenols may also improve satiety and reduce appetite regulation disturbances. The anti-inflammatory effects of cocoa further contribute to obesity management by reducing obesity-associated chronic inflammation. However, the caloric density of commercial chocolate products remains a limitation. High sugar and fat content may negate potential anti-obesity effects if consumed excessively. Consequently, research focuses increasingly on low-sugar and functional cocoa products designed to maximize health benefits while minimizing caloric burden (Rabie et al., 2026).

Gut microbiota modulation

The interaction between cocoa polyphenols and gut microbiota is bidirectional. Many cocoa polyphenols are poorly absorbed in the small intestine (smaller procyanidin oligomers are more readily absorbed than larger polymeric procyanidins due to their high molecular weight) and therefore reach the colon, where they are metabolized by the gut microbiota into bioactive metabolites through enzymatic fermentation (Ademiluyi, 2025). During this process, the intestinal microorganisms degrade complex procyanidin structures into smaller phenolic metabolites, including phenylacetic acids, phenylpropionic acids, hydroxybenzoic acids, and valerolactones, which can

subsequently be absorbed into systemic circulation (Peña-Correa et al., 2023). These microbial metabolites retain biological activity and may contribute significantly to the health benefits associated with cocoa consumption. Dietary fibre present in cocoa by-products and cocoa flavonoids act as prebiotic-like compounds further supporting gut health by serving as fermentable substrate for these intestinal bacteria such as Lactobacillus and Bifidobacterium, leading to production of short-chain fatty acids such as butyrate while suppressing pathogenic microorganisms (Lončarević et al., 2021; Damián et al., 2022; Edo et al., 2025). These effects may contribute to improved intestinal barrier integrity and reduced gut inflammation. The gut epithelium acts as a protective barrier that prevents harmful microorganisms and toxins from entering systemic circulation (Martín-Peláez et al., 2017). Microbial metabolites of procyanidins may enhance the expression of tight-junction proteins such as: Occludin, Claudin, and Zonula occludens (ZO-1). This helps maintain intestinal integrity and reduces "leaky gut" phenomena associated with chronic inflammation (Bianchi, et al., 2019; Shin et al., 2022). These cocoa-induced microbiota changes have been linked with reduced obesity, improved lipid metabolism, and enhanced immune regulation (Konar et al., 2022; Sorrenti et al., 2020). Although evidence regarding gut microbiota modulation is promising, researchers continue investigating the complex interactions among cocoa compounds, microbial metabolism, and host physiology.

Skin and Cosmetic Benefits

Cocoa bioactive compounds have attracted attention in dermatology and cosmetic science because of their psychoactive (antioxidant, anti-inflammatory, and photoprotective) properties (psychoactive). Skin aging is strongly associated with oxidative stress induced by ultraviolet radiation, pollution, and environmental factors. Cocoa flavonoids help neutralize reactive oxygen species that damage skin cells and collagen fibers (Bjørklund et al., 2022; Čižmárová et al., 2023). Cocoa butter is widely used in cosmetic formulations because of its emollient and moisturizing properties (Garcia et al., 2021). It forms a protective barrier that reduces transepidermal water loss and enhances skin softness. Studies have demonstratedd that cocoa flavanols improve skin microcirculation, hydration, elasticity, and dermal density (Scapagnini & Davinelli, 2017; Singh et al., 2020). Enhanced blood flow improves nutrient and oxygen delivery to skin tissues. Cocoa antioxidants may also reduce UV-induced skin damage by protecting against photooxidative stress and inflammation. Some clinical studies have shown improved skin texture and reduced roughness following cocoa flavanol consumption. Additionally, cocoa polyphenols may inhibit matrix metalloproteinases (MMPs), enzymes responsible for collagen degradation during aging (Loo et al., 2023; Annisa et al., 2025). This inhibition contributes to anti-aging effects. Cocoa-derived compounds are increasingly incorporated into creams, lotions, soaps, and nutraceutical cosmetics aimed at skin protection and rejuvenation (Yoon, et al., 2016). The major non-food applications of cocoa and its by-products, particularly in dermatology and cosmetics are summarized in **Table 2**.

Table 2: Non-food uses of cocoa and its by-products

Product name	Source	Benefits	Uses	References
Cocoa Tannin Gel Toothpaste	Cocoa tannin extracted from cocoa powder	Inhibit tooth plaque, Anti-mouth bacteria	As personal care for brushing teeth	Yumas et al., (2022); Polontalo et al., (2025)
Cocoa Oral Rinse	Cocoa tannin extracted from cocoa powder	Inhibit tooth plaque Anti-mouth bacteria	As personal care for gargle	Fideles et al., (2023)
Cocoa Body Scrub	Cocoa butter as cream base + Ground cocoa pod husk	Body C and M. Natural exfoliating agent	For bathing and removal of dirt	Sahari et al., (2023)
Cocoa Shower Cream	Cocoa butter as base	Cleansing and at the same time moisturizing	For bathing & dirt removal	Mustarichie et al., (2022)
Cocoa Bath Gel	Cocoa tannin extracted from cocoa powder	Cleansing with antibacterial	For bathing and antibacterial	Abdul Karim et al., (2016)
Cocoa Cream for Crack Heel	Cocoa butter as base	Removal of cracked heel	Personal care for cracked heel	Khan et al., (2026)
Cocoa Shaving Cream	Cocoa butter as base – replace animal fat	cream base for shaving, remove beard / face hair with	Men personal care product for shaving	Akinrotohun et al., (2021)
Cocoa After shave	Cocoa butter as base Tannin extracted from cocoa powder	Moistening skin after shaving Antibacterial effect	Men personal care product for after shave	Akinrotohun et al., (2021)
Cocoa-base lipstick and lipbalm	Cocoa butter Wax derived from cocoa butter deodorizer distillate.	Protect chapped lips.	Lips care.	Farrugia, (2017); Loke et al., (2024); Rosli, (2025)
Methyl salicylate Ointment	Cocoa butter Wax derived from cocoa butter/ butter deodorizer distillate	Enhance drug percutaneous abs. rate through skincompared with normal paraffin base.	Pain relief.	Loke et al., (2024); Aremu, (2024)

Product name	Source	Benefits	Uses	References
Cream-to-powder foundation	Cocoa butter /powder Cocoa tannin extracted as active ingredient.	Natural moisturizer. Cocoa powder as natural pigments and antioxidant.	Color cosmetic	Patel, (2024); Nayana et al., (2025)
Compact powder	Cocoa butter /Cocoa tannin extracted as active ingredients	Cocoa butter as natural moisturizer Cocoa powder as natural pigments	Color/ decorative/ cosmetic	Wongwad et al., (2025); Anatachodwanit et al., (2025)
Palmityl Theobromate	Cocoa butter/ cocoa butter deodorizer distillate	Ability to enhance spread ability of lipstick/lip-balm. Producing greener product	wax for cosmetic, pharmaceutical products and Aromatherapy candle Dev.	Chee et al., (2018); Veludurthi & Vadaga, (2024)
Activated carbon	Cocoa bean shell	Green product, valorization	Enviroment removal of toxic metal contaminant in water sources.	Tiegam et al., (2021); Haritha et al., (2023); Esidje et al., (2024)
Fuel pellets	Cocoa Bean Shell	Fuel pellets low in alkali metals will reduce maintenance problems - hot corrosion & sintering	Useful source of heating energy.	Thompson & Rough, (2021); Aunillah et al., (2024)
Charcoal		Green product and value addition	Added advantage; odorless and smokeless.	

FOOD APPLICATIONS OF COCOA AND ITS PRODUCTS

6.1 Functional chocolate and nutraceuticals

Chocolate, which is the most important confectionery product derived from cocoa has long been consumed primarily as a pleasurable confectionery. It is produced in several forms including chocolate bars, candies, truffles, cocoa powder, cocoa liquor, cocoa paste, and coated confectionery products (Gutiérrez, 2017; Tuigunov et al., 2025). In addition to direct consumption, cocoa-derived ingredients are extensively utilized in the production of cookies, breakfast cereals, desserts, bakery products, chewing gums, beverages, and ice cream (Morales et al., 2025). Besides its sensory appeal, chocolate has become increasingly recognized for its nutritional and functional properties due to the presence of naturally occurring flavonoids and antioxidants (Aprotosoaie et al., 2016; Damián et al., 2022; Tuigunov et al., 2025).

Modern consumers increasingly demand foods that combine convenience, sensory appeal, and health benefits. Historical evidence indicates that indigenous populations in Mesoamerica also used cocoa for medicinal purposes (McNeil, 2026). The Kuna Indians of Panama, for example, consume cocoa beverages rich in procyanidins and exhibit lower incidences of hypertension, cardiovascular disease, diabetes, and stroke (Faccinetto-Beltrán et al., 2021). The global chocolate industry has continued to expand due to increasing consumer awareness of these health benefits and the demand for premium, functional, and health-oriented chocolate products, as a result, chocolate has gained attention as a functional food matrix capable of delivering nutraceutical compounds. Consequently, manufacturers are now focusing on the development of chocolate products enriched with bioactive ingredients (including polyphenols, omega-3 polyunsaturated fatty acids, probiotics, phenolic extracts, methylxanthines, vitamins and minerals, proteins, and plant extracts) and reduced sugar formulations (Nouri et al., 2019; Gómez-Fernández et al., 2021). For adults, consuming approximately 20–30 g (about 1–2 small squares) of dark chocolate per day may be considered as part of a balanced diet (Gomes et al., 2021; Damián et al., 2022). However, it is imperative to be mindful of portion sizes and overall calorie intake, as chocolate is calorically dense, and excessive consumption may contribute to weight gain and other health issues (Caponio et al., 2020; Joesph et al., 2021). Theobromine and caffeine extracted from cocoa also possess stimulant properties useful in energy-enhancing nutraceutical formulations (Sesso et al., 2022). These extracts are incorporated into dietary supplements, capsules, powders, tablets, functional beverages, and energy products aimed at promoting cardiovascular health, cognitive performance, and immune support. Cocoa pod husk pectin has attracted pharmaceutical interest because of its swelling behavior, pseudoplastic characteristics, mineral content, and antimicrobial properties (Ouattara et al., 2021; Barrios-Rodríguez et al., 2022). Functional chocolates therefore represent an innovative strategy for delivering health-promoting compounds to consumers (Faccinetto-Beltrán et al., 2021). Chocolate also serves as an excellent medium for masking undesirable flavors due to its unique lipid matrix, which protects sensitive compounds during storage and digestion (Santander et al., 2025).

Cocoa butter provides a hydrophobic environment that enhances the stability of lipophilic bioactive compounds and masks undesirable taste and flavor associated with some nutraceutical ingredients, thereby improving sensory acceptability. Naturally, cocoa itself contains flavonoids, methylxanthines, minerals, and antioxidant compounds that already contribute to health promotion (Faccinetto-Beltrán et al., 2021; Soares & Oliveira, 2022). However, further enhancement of chocolate formulations through fortification has become an important research area in food science and industrial product development. Phenolic compounds derived from fruits and vegetables are being added to chocolate to enhance antioxidant activity and health benefits (Trigo et al., 2020; González-Barrio et al., 2020; Żyżelewicz et al., 2021; Poliński et al., 2022). Flavonoids present in these extracts can act synergistically with natural cocoa flavonoids to reduce inflammation and oxidative stress. Functional chocolates can be incorporated into other food products to improve their nutritional quality and shelf-life stability.

Fat replacers in bakery products

Cocoa and cocoa by-products are widely used in bakery applications due to their flavor, color, antioxidant properties, and functional characteristics. Cocoa fibre and cocoa bean shells have attracted attention as a functional ingredient in bakery formulations because of its high fibre content and antioxidant activity (Rojo-Poveda et al., 2020). The incorporation of cocoa ingredients contributes important bioactive compounds such as polyphenols, dietary fibre, and minerals to bakery products. Cocoa fibre in reduced-fat foods improves nutritional value by increasing dietary fibre content while lowering caloric density. Pectin extracted from cocoa pod husk also exhibits thickening and stabilizing properties useful in low-fat formulations (Masood et al., 2020; Barrios-Rodríguez et al., 2022). Its gel-forming capacity contributes to texture enhancement and moisture retention in foods (Souza et al., 2022). Fat replacement strategies involving cocoa ingredients are particularly relevant in the development of healthier functional foods targeting obesity and cardiovascular disease prevention (Delgado-Ospina et al., 2021; Barišić et al., 2024; Bulatović et al., 2025). These studies have shown that cocoa bean shell can partially replace flour in bakery products while increasing dietary fibre content and antioxidant potential, while the fat can replace a substantial portion of vegetable oil in cakes and muffins without significantly affecting consumer acceptability. Cocoa powder also improves the sensory appeal of baked products by contributing characteristic chocolate flavor and aroma generated through roasting reactions. Volatile aromatic compounds in cocoa enhance consumer preference and product marketability. However, thermal processing during baking may reduce polyphenol content due to heat-induced degradation. Therefore, optimization of baking conditions is necessary to preserve functional compounds while maintaining product quality. The use of cocoa by-products in bakery applications also supports sustainability by reducing agro-industrial waste and promoting circular economy practices within the cocoa industry.

Beverages

Cocoa-based beverages represent one of the oldest and most important applications of cocoa products. Historically, cocoa beverages were consumed by ancient Mayan and Aztec civilizations for ceremonial, medicinal, and nutritional purposes (Soares & Oliveira 2022). Modern cocoa beverages include hot chocolate, chocolate milk, cocoa drinks, nutritional beverages, sports recovery drinks, and functional health beverages fortified with bioactive compounds (Prosapio & Norton, 2019; Barišić et al., 2023). Cocoa beverages are valued for their rich sensory properties, antioxidant activity, and stimulant effects resulting from methylxanthines (Goya et al., 2022). The pleasant flavor profile of cocoa enhances consumer acceptance of fortified beverages containing nutraceutical ingredients. Cocoa pulp juice, also known as cocoa honey or sweatings, is a valuable by-product generated during cocoa fermentation due to degradation by pectinolytic enzymes surrounding cocoa beans, producing a liquid known as cocoa honey (Bastidas et al., 2022; Rodríguez-Castro et al., 2024). It has also emerged as an important beverage ingredient due to its sweet-sour flavor profile and nutritional composition. Cocoa honey contains carbohydrates (fermentable sugars), minerals, vitamin C, organic acids and bioactive compounds that support beverage applications (Rocha et al., 2025). Cocoa pulp juice can be consumed directly as a fruit beverage or blended with other fruit juices. It can also be processed into fruit drinks, juices, wine, vinegar, gin, brandy, jam, and marmalade. Its natural acidity and sugar content helps inhibit spoilage microorganisms, thereby improving microbial stability (Nunes et al., 2020; Figueroa et al., 2020; Kongor et al., 2024; Rodríguez-Castro et al., 2024). Recent studies have also explored the extraction of commercial-grade pectin from cocoa pulp and its utilization in food processing industries (Posso et al., 2024; Huamani-Palomino et al., 2025). These applications demonstrate the potential of cocoa pulp valorization within sustainable food systems. The beverage industry also explores encapsulation technologies to improve the stability and bioavailability of cocoa flavonoids in liquid formulations (Muhamad et al., 2020; Indiarto et al., 2022). Encapsulation protects sensitive compounds against oxidation and degradation during processing and storage. Despite their health benefits, some commercial cocoa beverages contain excessive sugar levels, necessitating reformulation strategies involving low-calorie sweeteners and sugar substitutes.

Food preservatives in meat products

Cocoa by-products possess significant potential as natural food preservatives due to their antioxidant and antimicrobial properties. Lipid oxidation is a major problem in meat processing because it leads to rancidity, off-flavors, discoloration, and reduced shelf life. Cocoa polyphenols exhibit strong antioxidant activity capable of delaying oxidative deterioration in meat products (Oracz & Żyżelewicz, 2020). Cocoa pulp/cocoa honey produced during fermentation process has a natural sugar content and acidity which contributes to inhibiting spoilage microorganisms, and improving the microbial stability of food products (Nunes et al., 2020). Cocoa bean shell, another major by-product generated during roasting, contains substantial amounts of dietary fibre, polyphenols, lignin, cellulose, and volatile aromatic compounds. These compounds make cocoa bean shell valuable for applications in bakery products, functional foods, and food preservation systems (Sánchez et al., 2023). A Study by Choi et al., (2019), demonstrated that cocoa bean shell extracts effectively reduced lipid oxidation in beef products. Their antioxidant effectiveness was comparable or superior to synthetic antioxidants such as butylated hydroxytoluene (BHT) and β-tocopherol. Manzano et al. (2017), also observed improved oxidative stability of soybean oil through the addition of polyphenolic extracts from cocoa bean shells. In addition to food preservation, cocoa shell ash has been investigated as an alkalizing agent in cocoa processing. Cocoa by-products have also been incorporated into biodegradable bio-elastomers and active packaging materials to enhance food shelf life through antioxidant activity (Suganthi et al., 2024). Cocoa extracts may therefore function as dual-purpose natural preservatives possessing both antioxidant and antimicrobial activities. The use of natural preservatives derived from cocoa aligns with growing consumer demand for clean-label foods containing fewer synthetic additives. Cocoa ingredients may also contribute flavor enhancement and color stabilization in processed meat products (Delgado-Ospina et al., 2021; Goya et al., 2022). However, excessive incorporation levels may affect sensory acceptability due to bitterness associated with cocoa polyphenols. Research into cocoa applications in meat systems remains an emerging field with substantial industrial potential for developing healthier and more stable meat products.

Food Packaging

Active packaging systems containing cocoa polyphenols can help extend food shelf life by reducing oxidative deterioration and microbial spoilage (Singh et al., 2022). Cocoa bean shell

extracts incorporated into packaging films provide antioxidant protection against lipid oxidation in packaged foods. Cocoa-derived bioactive compounds can also be integrated into biodegradable polymers and bio-elastomers to produce environmentally friendly packaging materials (Singh et al., 2022; Fadiji et al., 2023). Cocoa pod husk fibres and pectin are particularly valuable in packaging applications due to their film-forming and structural properties (Barrios-Rodríguez et al., 2022). Pectin-based films derived from cocoa waste represent promising alternatives to synthetic plastics (Dirpan et al., 2024; Vallejos-Jiménez et al., 2025). The development of cocoa-based packaging materials supports sustainability objectives by reducing agricultural waste and dependence on petroleum-based packaging products. However, industrial implementation requires further optimization regarding mechanical strength, water resistance, scalability, and cost-effectiveness.

Encapsulation Technologies

Encapsulation helps improve stability and preservation of cocoa polyphenols as these compounds are highly susceptible to degradation caused by oxygen, light, moisture, pH changes, and heat (Vargas-Munévar et al., 2024). Various encapsulation techniques including spray drying, freeze drying, coacervation, liposomal encapsulation, nanoencapsulation, and microencapsulation are applied in cocoa-based products to protect sensitive bioactive compounds, improve stability, control release, and enhance bioavailability (Grassia et al., 2021; González Morales et al., 2025). Chocolate itself acts as a natural encapsulating matrix due to its lipid-rich composition. Cocoa butter protects incorporated bioactive compounds against oxidative degradation and masks undesirable flavors. Encapsulation is especially important for incorporating sensitive ingredients such as probiotics, omega-3 fatty acids, vitamins, and plant extracts into chocolate and cocoa products (Hossain et al., 2021; Drosou & Krokida, 2024). Microencapsulation improves the survival of probiotic bacteria during gastrointestinal digestion and storage, thereby enhancing their functional effectiveness (Reque & Brandelli, 2021). Nanoencapsulation technologies are also being explored to improve the absorption and targeted delivery of cocoa flavonoids and nutraceutical compounds (Ayala-Fuentes & Chavez-Santoscoy, 2021; Trindade et al., 2021). The advancement of encapsulation technologies continues to expand opportunities for developing next-generation functional cocoa products with improved health benefits and shelf stability.

Cocoa Waste Valorization

The cocoa industry generates substantial quantities of agricultural and industrial by-products including Cocoa pod husk, bean pulp, and bean shell. Traditionally, these materials were considered waste and often discarded, creating environmental challenges (Kamphuis, 2017; Sundarraj & Ranganathan, 2017; Figueroa et al., 2020; Soares & Oliveira, 2022). Recent advances in food science and biotechnology have emphasized cocoa waste valorization, which involves converting by-products into valuable functional ingredients, nutraceuticals, biofuels, packaging materials, and industrial products. Cocoa pod husk, one of the most abundant cocoa by-products contains pectin, dietary fibre, minerals (Ca, Mg, K, P, Fe), polyphenols, and bioactive compounds. It has applications in pectin extraction, animal feed production, fertilizer development, soap production, and biodegradable packaging materials (Anoraga et al., 2024; Morales et al. 2025). By converting waste into value-added products, the cocoa sector can reduce environmental pollution while generating additional revenue streams. The integration of cocoa waste valorization into industrial food systems represents a major advancement toward sustainable and circular bioeconomy development (Lungaho et al., 2025; Asiedu et al., 2026).

FUTURE PERSPECTIVES

The global cocoa industry is undergoing a major transformation driven by increasing consumer awareness of health, sustainability, functional foods, and environmental conservation. The future of cocoa research and industrial utilization lies in the integration of food science, biotechnology, sustainability, medicine, and circular economy principles. One of the most promising future directions is the development of next-generation functional foods enriched with cocoa bioactive compounds. These innovations are expected to focus on personalized nutrition approaches such as developing personalized cocoa-based functional foods targeted towards specific health conditions and population groups. Like in the pharmaceutical and biomedical sectors, cocoa flavonoids have demonstratedd potential anti-inflammatory, antihypertensive, neuroprotective, antimicrobial, and anticancer activities, therefore, future clinical and pharmacological studies may facilitate the development of cocoa-derived therapeutic agents, functional supplements, wound-healing formulations, and natural pharmaceutical excipients.

The future of cocoa research also strongly emphasizes sustainable valorization of cocoa by-products. Many studies, as discussed in this review, have demonstrated that cocoa by-products are rich sources of pectin, dietary fibre, antioxidants, minerals, bioactive peptides, and antimicrobial compounds. Future industrial strategies are likely to focus on converting these wastes into high-value products such as nutraceutical formulations, natural antioxidants, animal feed, biofuels, bioplastics, pharmaceutical excipients etc. Other applications are low-glycemic chocolates for diabetic patients, high-polyphenol beverages for cardiovascular health, neuroprotective cocoa supplements for elderly populations, commercial production of biodegradable/active packaging materials for food preservation and pharmaceutical applications, fortified cocoa products for children and athletes. Cosmetic industry could explore the anti-aging, photoprotective, antioxidant, and anti-inflammatory activities of cocoa polyphenols to incorporate them into sunscreens, anti-aging creams, hair care products, and therapeutic dermatological formulations.

Another major future perspective involves the advancement of processing technologies aimed at preserving cocoa bioactive compounds. Conventional processing methods such as fermentation, roasting, and alkalization often reduce polyphenol content and antioxidant activity. Therefore, emerging non-thermal and mild processing technologies including pulsed electric fields, ultrasound-assisted extraction, microwave-assisted processing, supercritical fluid extraction, cold plasma technology, and high-pressure processing are receiving increasing scientific attention. These technologies may help improve the retention of flavonoids, aroma compounds, vitamins, and other sensitive bioactives while maintaining desirable sensory qualities. Encapsulation and nanotechnology are also expected to play increasingly important roles in cocoa research. Advanced encapsulation systems using nanoemulsions, liposomes, biopolymer matrices, and microcapsules could improve the protection, controlled release, absorption, and functionality of cocoa-derived

nutraceuticals. Such technologies may significantly enhance the therapeutic potential of cocoa polyphenols and methylxanthines.

CONCLUSION

Cocoa is no longer viewed solely as a confectionery ingredient but as a multifunctional biological resource with immense scientific and industrial potential. Industrially, cocoa represents an important raw material capable of supporting innovation in functional foods, nutraceuticals, sustainable packaging, and green processing technologies. The growing recognition of cocoa processing by-products as valuable sources of dietary fibre, pectin, polyphenols, and other functional compounds has strengthened efforts toward waste valorization and circular bioeconomy practices. Advances in processing technologies and bioactive compound preservation strategies are expected to enhance the functional efficacy, stability, and commercial value of these products. As consumer demand continues to shift towards health-oriented and environmentally sustainable products, cocoa is well positioned to play a pivotal role in the development of next-generation functional foods and nutraceutical formulations. Continued interdisciplinary research involving food science, nutrition, biotechnology, medicine, and sustainability studies will further expand the applications of cocoa and contribute significantly to future sustainable food and health systems.

Author contributions statement

V.N.E. & T.A.A –Conceptualization and design of the work

P.J.A. & T.A.A. –Analysis and interpretation of data.

V.N.E & P.J.A. –Drafting of paper

V.N.E. & P.J.A. -Revising the manuscript critically for intellectual content

All authors gave final approval and agree to be accountable for all aspects of the work

CONFLICT OF INTEREST

The authors declare that there are no competing financial interests or personal relationships that could be seen to influence the publication of this article.

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