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ORIGINAL PAPER

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CAROB (*CERATONIA SILIQUA* L.): NUTRITIONAL BENEFITS AND POTENTIAL FOR FOOD AND FEED APPLICATIONS

Salah Laaraj[1,2,a], Ashiq Hussain[3,a], Latifi Hanane[1], Syeda Ayesha Batool[4], Muhammad Qasim Ali[5], Faiza Iftikhar Gorsi[1], Ayesha Najam[4], Afifa Asif[1], Nida Firdous[6], Nadia Houmy[7], Kaoutar Elfazazi[2✉], Souad Salmaoui[2✉]

[1]Agri-food Technology and Quality Laboratory, Regional Centre of Agricultural Research of Tadla, National Institute of Agricultural Research (INRA)
Avenue Ennasr, BP 415 Rabat principal, Rabat 10090, **Morocco**
[2]Environmental, Ecological, and Agro-Industrial Engineering Laboratory LGEEAI, Faculty of Science and Technology (FST), Moulay Slimane University (USMS)
Beni Mellal, **Morocco**
[3]Institute of Food Science and Nutrition, University of Sargodha
Sargodha, 40100, **Pakistan**
[4]Punjab Food Authority Lahore
Lahore, 54000, **Pakistan**
[5]Faculty of Chemical and Process Engineering Technology, University Malaysia Pahang, Gambang, Kuantan
Pahang 26300, **Malaysia**
[6]Department of Food Science and Technology, MNS-University of Agriculture Multan
66000, **Pakistan**
[7]Agro-Food Technology and Quality Laboratory, Regional Center of Agricultural Research of Oujda National Institute of Agricultural Research
Ennasr Av, BP 415, Rabat 10090, **Morocco**
[a]Authors contributed equally to this work.

ABSTRACT

The carob tree, scientifically known as *Ceratonia siliqua* L., is an evergreen shrub belonging to the Fabaceae family, noted for its nutritional value and economic importance. For centuries, both the pulp and seeds of the carob fruit have been consumed by humans and used as animal feed in various regions. Additionally, it has long been regarded as a valuable remedy in traditional folk medicine. This literature review provides a comprehensive overview of the nutritional and bioactive components of carob, its biological activities, including antioxidant properties, and its potential as a sustainable source of ingredients for human food and animal feed. The high concentration of polyphenols and other bioactive compounds has been linked to a range of beneficial effects, including anticancer, antihyperglycemic, and antihyperlipidemic effects. Carob fractions, rich in sugars, proteins, and minerals, can be incorporated into a wide array of food products, such as cereal-based meals for celiac patients, sweets and substitutes for cocoa, additives in baked goods, and antioxidants for active packaging films. This systematic review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Relevant articles were selected through a search of English-language databases, including Medline, Scopus, EMBASE and Web of Science. With its rich nutritional and bioactive profile, carob fruit represents a promising source of sustainable ingredients for food and feed. Its application spans from gluten-free food products to natural additives and bioactive packaging materials, positioning it as a strong candidate for further research and industrial development to enhance both human nutrition and environmental sustainability.

Keywords: sustainable ingredients, human nutrition, functional foods, bioactive components, pharmacological roles

✉kaoutar.elfazazi@inra.ma, ✉souadsalmaoui@yahoo.fr

INTRODUCTION

The tree species known as carob (*Ceratonia siliqua* L.) is indigenous to the Mediterranean region and is a member of the Fabaceae family. The species has also been observed in tropical and subtropical regions, including Florida and California in the United States, Australia, Argentina, and Africa. The tree is well-known for its delicious, nutrient-dense fruits, which have long been used as a wholesome food source (Basharat et al., 2023; Goulas et al., 2019; Laaraj et al., 2023). The fruit of the carob tree features an elongated, flat, curved or straight pod with thick sutures that are difficult to break. Some edges are slightly sharp, while others are rounded. Its dimensions generally range between 10 cm and 30 cm. Two essential components make up its composition: pulp (90%) and seeds (10%) (Durazzo et al., 2014). The shell, endosperm, and embryo are the three main parts of a carob seed. The seed coat is the outermost layer, followed by the endosperm, which constitutes the bulk of the seed and is high in carbohydrates. The smallest part of the seed, the embryo, is rich in bioactive substances and proteins (Dakia, 2011; Laaraj et al., 2023).

The remarkable nutritional and therapeutic benefits of components derived from carob seeds have garnered significant attention across a range of industries, including food, medicine, pharmaceuticals, cosmetics, and textiles. According to the most recent data from the Food and Agriculture Organization, global carob fruit production is estimated at 158,609 tons per year, cultivated over approximately 66,874 hectares. At the regional level, Europe accounts for the largest share of production (75.55%), followed by Africa (13%) and Asia (11.3%) (Ikram et al., 2023). The benefits of carob are widely recognized in agriculture, medicine, cosmetics, and cuisine, and they are strongly associated with the Mediterranean region's agro-economy and longstanding cultural and economic history (Krokou et al., 2019a; Laaraj et al., 2024b). Not only are the fruit fractions of the carob tree excellent sources of bioactive components, but its leaves also play a significant role in promoting health and contributing to sustainable livelihoods (Cegledi et al., 2024). Given the broad nutritional and economic importance of this plant and its various constituents, this review paper was designed to collect and comprehensively summarize the latest data regarding the nutritional, bioactive, and functional food components of different carob fractions, along with their multisector uses in the food, feed, and pharmaceutical industries.

PHARMACOLOGICAL ROLE OF CAROB BIOACTIVES

The carob fruit comprises a variety of components, each of which exhibits distinct nutritional characteristics. These include protein, fat, ash, fiber, carbohydrates, vitamins, minerals, amino acids, polyphenols and other compounds. The macronutrient and micronutrient composition of carob varies depending on several factors, including the species, variety, cultivation conditions, harvesting period, soil quality, climate, provenance and geographical location (Boublenza et al., 2019). Figure 1 depicts the chemical composition of carob fruit and its pharmacological functions. The potential of carob to replace cocoa in a variety of food products is highlighted by its beneficial ingredients, distinct sensory qualities, and flavors resembling cocoa that are enhanced by roasting carob powder (Loullis and Pinakoulaki, 2017). The bioactive compounds found in carob fruit and its derivatives have anti-hyperglycemic, antioxidant, and anti-inflammatory properties that help manage a variety of health issues, including diabetes, heart disease, and gastrointestinal disorders (Laaraj et al., 2024a). Thus, items made from carob show significant promise as functional food ingredients (Brassesco et al., 2021).

Dietary fibers encompass a wide variety of nutritional components. They are characterized by their resistance to digestion and absorption in the human small intestine and undergoing either partial or complete fermentation in the large intestine. Carob fiber is a kind of insoluble dietary fiber found in the deseeded husk of carob fruit. Carob fiber is distinct from other common types of insoluble dietary fiber, such as cellulose, soy fiber, and wheat bran (Akouz et al., 2023; Laaraj et al., 2024b). The fruit of the carob plant also contains polysaccharides known as carob bean gum, a galactomannan widely utilized in the food, pharmaceutical, and cosmetics industries. Carob bean gum has demonstrated health benefits in various conditions, including diabetes, colon cancer, heart disease, and bowel movements (Djellal et al., 2024; Zhu et al., 2019).

The use of solvents has been found to have a considerable effect on the phenol content and antioxidant

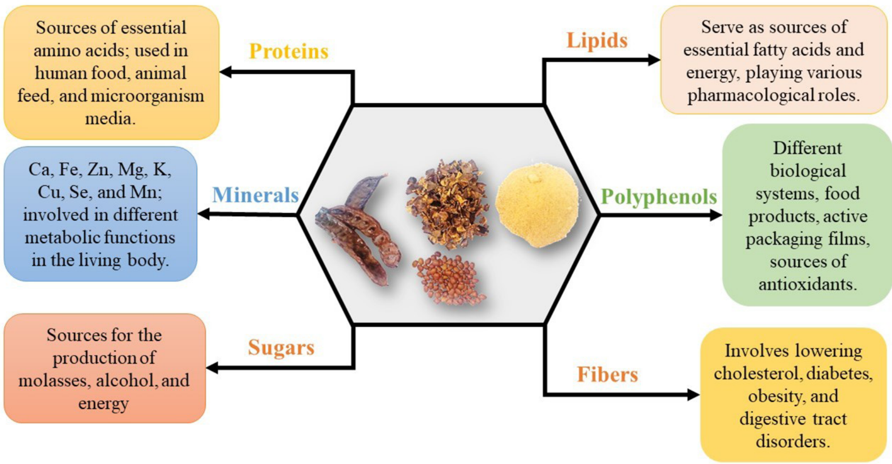

Fig. 1. Different bioactive contents of carob fruit with pharmacological roles
Source:authors' own research based on Cegledi et al., 2024; Elfazazi et al., 2020; Goulas and Georgiou, 2020; Laaraj et al., 2023; Moumou et al., 2023; Rodríguez-Solana et al., 2021; Zhu et al., 2019.

capacity of carob extracts. Analysis of these extracts identifies gallic acid, myricetin, rutin, and catechins as the principal phenolic compounds, with myricetin and quercetin playing key roles in antioxidant activity (Goulas and Georgiou, 2020). Based on the available evidence, it is clear that nutrients and polyphenols – both vital to food and biological systems – are abundant in various fractions of the carob tree and fruit. Consequently, these fractions represent promising candidates for development of functional food ingredients and pharmaceutical formulations.

INCORPORATING CAROB INTO THE FOOD INDUSTRY AS A FUNCTIONAL INGREDIENT

The food industry faces significant challenges in demonstrating the health benefits of natural ingredients before they can be effectively incorporated into functional food products that are both consumer-friendly and compliant with regulatory requirements. The growing global population has intensified the demand for increased food production that is not only economically feasible but also meets strict quality and safety standards. Ensuring the long-term preservation of food while retaining its taste, appearance, texture, and microbiological safety remains paramount. Despite considerable advances in food additives, several issues remain contentious. Preservatives, nutritional additives, flavoring agents, and texturizers are all evaluated based on their safety, efficacy, and potential toxicity. Moreover, natural additives and extracts are receiving increasing attention due to evolving consumer preferences, with their health benefits and synergistic effects being closely scrutinized (Carocho et al., 2014). Recent studies have highlighted the versatility and potential of various carob-derived products in the development of functional foods (Brassesco et al., 2021; Nasar-abbas et al., 2016). Given its status as a fruit source rich in nutrients, carob can be incorporated into daily diets in numerous ways. Additionally, it contains noteworthy quantities of minerals, protein, amino acids, and vegetable fats. Depending on the processing method, carob fruit can be employed as a natural ingredient in the production of wholesome, fresh, and nutritionally valuable foods (Rodríguez-Solana et al., 2021). The carob fruit exhibits considerable potential for application in the food industry, due to its numerous beneficial properties and its distinctive aroma, which persists even after processing. The presence of acids, esters, and aldehydes/ketones – biogenic volatile organic compounds that facilitate plant growth, reproduction, and defense – in both the carob fruit and powder likely contributes to this characteristic sensory quality (Brassesco et al., 2021). A comparative analysis was conducted between the nutritional profiles of twenty traditional carob products available commercially and the pulp of Cypriot carob cultivars. Carob is classified as a functional food because it is rich in fiber, low in fat, and a good source of minerals. However, the health and nutritional claims made for carob products on the market were only partially validated. Variations in nutritional values were observed depending on the region of the cultivar, the method of product manufacturing, and the chemical synthesis of the ingredients (Papaefstathiou et al., 2018). Carob pulp is milled to produce carob powder, which also contains several other constituents, including simple sugars such as maltose and mannose, unsaturated fatty acids, and minerals such as calcium, potassium, and iron, contributing to the exceptional functional properties of this powder (Červenka et al., 2019).

Carob products are commonly marketed in various forms such as extracts, juices, flour, or powder derived from ground fruit. For animal feed, carob is often sold raw, offering a nutritional value equivalent to barley. Roasting is a common processing method in the food industry and for human consumption (Boublenza et al., 2019; Elfazazi et al., 2020). The multifunctional roles of carob powders, extracts, and isolated or purified components have driven an increase in their application in the food industry, especially as food additives and functional ingredients.

CAROB FRACTIONS IN FOOD FORMULATIONS

The concept of healthy eating and lifestyle choices has gained significant traction in recent times. This shift has prompted the food industry to respond, leading to the emergence of carob as a commercially viable and healthful ingredient across a diverse range of sectors. Despite the naturally high natural phenol content of carob fruits, a considerable amount of the remaining byproducts is discarded or used as animal feed. The abundance of phenolic compounds in carob residues has led to their increasing utilization in food formulations (Achchoub et al., 2021; Goulas and Georgiou, 2020; Hussain et al., 2024). One byproduct of the carob fruit processing industry is carob pulp – a blend of macro- and micronutrients, including functional secondary metabolites, vitamins, minerals, and carbohydrates. To encourage its commercial use, a number of studies have examined the pulp's chemical and biological properties. Its potential as a nutraceutical ingredient in various food and beverage preparations has been extensively evaluated (Rodríguez-Solana, 2021). Carob molasses, made from carob fruit, contains several health-promoting ingredients. Despite its high fiber content, the molasses pulp remaining after production is often undervalued. One study extracted crude carob fiber from raw molasses pulp and used the resulting flour in traditional Turkish sausage dough to successfully produce fermented "sucuk", with favorable physicochemical properties. The study proposed a high-fiber, low-fat "sucuk" formulation with improved health benefits and sensory qualities (Ozdemir et al., 2021). Carob powder also enables the development of innovative, value-added pasta recipes, offering a rich source of nutrients and polyphenols (Lupu et al., 2023). The carob kibble – left after seed removal – is a good source of nutritional fiber, carbohydrates, and bioactive substances like polyphenols and pinitol. These compounds exhibit antidiabetic, antioxidant, and anti-inflammatory properties that may help manage conditions like diabetes, heart disease, and colon cancer. Carob kibble therefore holds strong potential as a functional ingredient (Nasar-abbas et al., 2016).

As interest grows in repurposing natural resources, especially by-products, industries are adopting sustainable strategies to incorporate these materials in their final goods. Once regarded as waste, carob seeds have recently come to light as a natural resource with intriguing nutritional values and practical qualities that make them an excellent addition to a variety of industries, such as food, pharmaceuticals, cosmetics, and more. Carob seeds are made up of an embryo, an endosperm, and a shell. This combination guarantees a remarkable content of macro- and microelements along with a balanced content of proteins, carbohydrates, polyphenols, and galactomannans that ensure optimal swelling and effective oil retention capability (Djellal et al., 2024; Laaraj et al., 2023). The literature has shown that no part of the carob tree can be considered waste because of the presence of fibers, lignans, sugars, proteins, amino acids, fatty acids, minerals, and secondary metabolites. When different carob fractions are incorporated into a range of food products, the aforementioned components contribute to the nutritional, rheological, technological, and functional

Table 1. Different carob fractions used in different food and feed formulations

Carob Fraction	Form/Processing	Uses	Advantages
Carob kibbles	whole	animal feed	source of nutrients
Carob kibbles	crushed	human food	source of nutrients
Carob powder	extraction	human food and animal feed	source of sugars and molasses
Carob powder	drying	human food	dietic food products
Carob powder	fermentation	human food and cultures	source of alcohol and microbial protein
Carob powder	drying	pharma foods	pharmaceutical products
Carob powder	extraction	food ingredient	cocoa substitute
Seed endosperm	grinding	food products	additive
Seed germ	grinding	human food and animal feed	source of nutrients
Carob fiber	powder	sausages	source of nutrients and dietary fiber
Essential oil	extraction	pasta	preservative effects
Carob powder	drying and grinding	minced beef meat	increased nutrients and polyphenols
Carob flour	drying and grinding	gluten-free macaron	nutritional product for celiac persons, with increased antioxidant activity
Carob powder	drying and extraction	spreads	improved organoleptic characteristics
Pods and seeds hull	grinding	animal feed and leather industry	source of fibers and tannins
Pods and seeds	extraction and fermentation	fermentation products	production of ethanol, citric acid, lactic acid, and microbial cell protein
Unripe carob pods	extraction	gummies	improved structural and biological characteristics

Source: Ayaz et al., 2009; Boublenza et al., 2019; Brassesco et al., 2021; Custódio et al., 2011; Ikram, 2018; Laaraj et al., 2024; Loullis and Pinakoulaki, 2017; Mohammed et al., 2021; Nasar-abbas et al., 2016; Raquel Rodríguez-Solana, 2021; Yatmaz and Turhan, 2018.

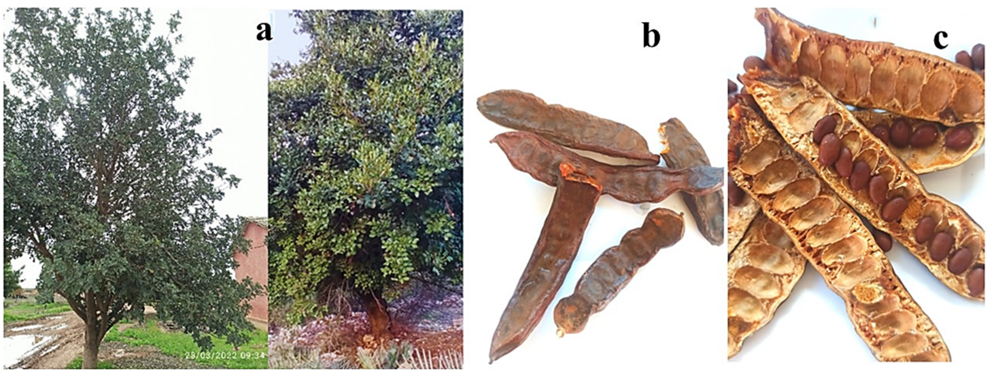

Fig. 2. Different fractions of carob tree and its fruit: a) the carob tree, b) mature carob pod, c) constituents of carob pod (phot. authors)

characteristics of those products (Table 1). Figure 2 provides a graphical overview of the carob tree, its fruit, and the different fractions of both tree and fruit.

The use of carob by-products, such as molasses pulp and carob kibble, has the potential to enhance food formulations, given their rich bioactive content and capacity to promote health benefits and support sustainable practices. Future research should prioritize the optimization of extraction techniques and the validation of carob's health benefits, particularly for chronic diseases. Expanding its use in innovative products and encouraging interdisciplinary collaboration will be critical to integrating carob into sustainable food systems.

CAROB INCORPORATION INTO ANIMAL FEED TO IMPROVE MEAT AND CARCASS QUALITY

Across the world, during periods of seasonal scarcity, when both forage availability and quality are limited, livestock diets often include pods from leguminous plants. Among these, carob is utilized as a feed supplement in animal farming, particularly in areas affected by drought, and is primarily fed to ruminants due to its high natural sugar content (Abu Hafsa et al., 2017). Furthermore, livestock production is severely limited by the high cost of animal feed, making the use of imported concentrates often unavoidable. Thus, the practice of feeding animals with agro-industrial byproducts has spread globally. Because it can be obtained more affordably than other commodities, this method is seen as sustainable (Basharat et al., 2023). The fruit of the carob tree is rich in flavonoids, which are organic antioxidants and may support reproductive performance. Nemati et al. (2022) investigated the impact of carob fruit supplementation on the immune system, testicular histology, blood parameters, semen characteristics, and reproductive performance in older broiler breeder roosters. The findings indicated that supplementing aging roosters' diets with carob fruit resulted in improvements in testicular spermatogenetic indices, seminal antioxidant activity, blood antioxidant capacity, and sperm motility (Nemati et al., 2022). The impact of incorporating carob powder into a weaning diet on gut morphology, biochemical variables in the blood, and antioxidant biomarkers was evaluated by Rtibi et al. (2021). It was demonstrated that carob powder may enhance rabbit growth by improving key inflammatory markers, protein-carbonyl residues, gut, and immune functions, in addition to boosting antioxidant activity and productive performance (Rtibi et al., 2021). These findings suggest that dietary supplementation with carob powder provides novel insights into the potential benefits of a range of bioactive compounds with diverse mechanisms of action. In a series of trials conducted in eastern Algeria, Meziane et al. (2023) evaluated the effects of varying levels of carob supplementation on carcass quality and survival rates of indigenous rabbits. Their results indicated that carob supplementation improved both the growth rate and dressing percentage of native rabbits (Meziane et al., 2023).

According to Mahmoudi et al. (2022), up to 7% of a broiler diet can consist of carob pulp powder as an alternative feed ingredient without adverse effects on growth performance, carcass quality, sensory attributes, or oxidative stability. It can also increase the level of unsaturated fatty acids without compromising overall performance. Carob pulp may serve as a viable substitute for conventional feed ingredients to enhance meat quality, potentially offering greater health benefits to consumers (Mahmoudi et al., 2022). In another experiment, the impact of carob pods on growth performance and meat quality in fattening pigs was investigated, including the chemical composition and fatty acid profile of steaks. The findings showed that adding 75 or 100 g/kg of carob pods to the diet improved carcass weight and slaughter body weight. Consequently, carob pods may be recommended as a potential feed ingredient for fattening pigs without compromising meat quality (Kotrotsios et al., 2012). In a separate study, lambs were individually stalled and fed concentrate diets for 56 days, with 24% or 35% of barley replaced with carob pulp. Carob pulp reduced saturated fatty acids and increased polyunsaturated fatty acids, such as rumenic acid, in muscle tissue. The oxidative stability of the meat remained unaffected, with no significant signs of oxidative deterioration. These findings suggest that including carob pulp in lamb diets may enhance the polyunsaturated fatty acid content of the meat without compromising its oxidative stability (Gravador et al., 2015). Other studies in the literature (Table 1) highlight the diverse functional roles of carob in the diets of various animal species.

In summary, carob and its byproducts have shown notable benefits for animal nutrition, particularly during fodder shortages. Carob supplementation has been linked to improved growth, reproductive performance, and carcass quality in broilers, rabbits, pigs, and lambs. It also enhances meat quality by improving fatty acid composition and antioxidant capacity, representing a sustainable and cost-effective alternative to conventional diets. These findings suggest that carob could serve as a valuable nutritional additive to improve both animal health and meat quality.

CAROB AS AN EFFECTIVE COCOA SUBSTITUTE

The beans of the cocoa tree (*Theobroma cacao* L.) are the primary source of chocolate. It is a highly valued commodity and the main ingredient used in chocolate production. Its distinctive sensory qualities and rich flavors contribute significantly to its market value and perceived quality. The increasing cost and growing demand for cocoa have prompted a search for viable alternatives. Carob has emerged as a promising cocoa substitute. Carob is widely recognized for its valuable locust bean gum and for the carob pulp used to produce carob powder and syrup (Loullis and Pinakoulaki, 2017). Due to its low-fat content, absence of theobromine and caffeine, and comparable sensory, chemical, and biological properties to cocoa, carob pulp is considered a potentially healthier alternative to chocolate. Various products, such as beverages, baked goods, snacks, pasta, and yogurt, are made from carob pulp flour or syrup, the latter derived from concentrated aqueous extracts of kibbles (Rodríguez-Solana, 2021).

Because locust bean gum can achieve high viscosity at low concentrations and can function as an effective water binder, it is widely utilized as an ingredient in both the food and non-food industries. As it is indigestible, locust bean gum is considered a dietary fiber in food applications. It contributes to the development of low-calorie foods by increasing dietary fiber content without adding calories. It has also been used in the treatment of hyperlipidemia. For individuals with diabetes, it can be turned into starch-and sugar-free flour. Another benefit of this gum is its therapeutic potential in alleviating gastrointestinal disorders, particularly infantile diarrhea (Dakia, 2011). A specialized cocoa-like powder made from carob was evaluated in a prior study. To obtain an expanded granule powder suitable for various food formulations, a hydro-thermo-mechanical treatment known as instant controlled pressure-drop (crucial unit operation) was used. This technique consists of texturing and roasting unseeded carob kibbles. The process aims to precisely control the chemical transformations that produce the desired flavor, dryness to remove excess moisture, deodorization to eliminate off-notes, and texturing to enhance the microstructural properties of the final product (Mounir et al., 2021).

Due to their ingredients and preparation methods, commercial chocolate and hazelnut-based sweet spreads typically exhibit low nutribiochemical levels. However, the contemporary food industry demands sustainable food items that offer both improved nutritional profiles and reduced environmental profile impact. Consequently, an experimental study was carried out to create a novel hazelnut/carob-based spread using carob pulp as a substitute for cocoa. The final product demonstrated notable nutritional quality and favorable sensory characteristics, indicating its potential as a sustainable and functional food innovation (Principato et al., 2024).

CAROB AS A FUNCTIONAL COATING MATERIAL FOR INNOVATIVE FOOD PACKAGING

The use of edible films and coatings in modern food applications is becoming increasingly prevalent. These materials undergo structural and compositional changes to achieve the desired mechanical properties, which are employed in food protection to reduce spoilage and maintain the quality of fresh produce, meat products, and fruits. The most common ingredients in these edible films and coatings are lipids, proteins, and polysaccharides, either alone or combined with specific modifiers (Cerqueira et al., 2011). In one study, citrus fruits were coated with an edible film made of lipid and carob bean gum to enhance their appearance and prolong their shelf life. The coating was shown to lower the ethanol level of mandarins, thereby reducing the possibility of flavor deterioration (Parafati et al., 2016).

A growing number of novel and environmentally friendly films and coatings based on biodegradable polymers have been developed recently. Carob gum, a naturally occurring edible and biodegradable polymer, is used to create edible coatings or films that mitigate the adverse effects of light processing on freshly cut fruit. Additionally, due to its tensile strength, elongation-at-break under specific circumstances, and selective permeability to carbon dioxide, oxygen, and water vapor, carob bean gum can be utilized as an additive and a carrier of bioactive compounds in edible films and coatings (Aydinli and Tutas, 2000). The development of novel biomaterials with antibacterial and antioxidant qualities has attracted significant attention in the food sector. While a number of biopolymers have been considered for application in food packaging, polyphenolic coatings have not been thoroughly investigated. By polymerizing carob phenolics, an experimental study created an antibacterial and antioxidant layer for food packaging. It was noted that low-cost carob polyphenols served as effective precursors for dual-function coatings in food packaging (Goulas et al., 2019).

In another study, two antioxidant bio-based packaging materials were created, each containing an 8% aqueous solution of either carob seed acetone macerate or ethanol macerate. Fresh salmon fillets were stored under refrigeration using both active and control films. Physicochemical analyses revealed promising results, highlighting the effectiveness of carob extracts in active packaging films (Ouahioune et al., 2022).

CAROB AS AN ANTIOXIDANT IN DIVERSE FOOD AND BIOLOGICAL SYSTEMS

One significant process that shortens the shelf life of many foods, particularly meats, is lipid oxidation. Vegetables and plants contain phenolic compounds, which naturally function as food antioxidants. Condensed tannins (16–20%), which are abundant in carob pods, can prevent lipid oxidation. It was discovered that carob pod extracts gave frozen hamburgers increased oxidative stability (Rosa et al., 2013). While carob seeds have primarily been seen as food waste, carob fruit has been utilized in the food industry for generations. Recovering waste plant matrices as potential sources of functional chemicals with medicinal qualities has drawn significant attention recently. During a study, the unripe and ripe carob seed extract showed notable antioxidant activity. For this reason, carob seed extracts may be considered an intriguing source of bioactive antioxidant chemicals with prospective uses in the food supplement and nutraceutical industries (Santonocito et al., 2020).

Research has explored the possibility of using carob extracts as antioxidant agents in food systems, such as emulsions, cooked comminuted pork, and sunflower oil. The results are promising for their use in this capacity. These extracts' fractionation, purification, and encapsulation could be a way to increase their antioxidant activity in food systems (Goulas and Georgiou, 2020). The creation of meat products with bioactive ingredients is touted as an excellent nutritional tactic. In healthy animals, carob fruit extract lowers postprandial hyperglycemia and hyperlipidemia and demonstrates impressive antioxidant qualities *in vitro* (Macho-González et al., 2019). Because carob fruit extract-enriched meat has been shown to have anti-diabetic effects in a rat study, it has been shown to have an impact on T2DM in its early stages. The findings showed that increasing the consumption of meat with carob fruit extract significantly improved insulin signaling and counterbalanced diabetic dyslipidemia, indicating that it is a suitable functional ingredient for type 2 diabetes (Macho-González et al., 2020). Dietary fiber and proanthocyanidins may have a significant impact on gut microbiota, colonic integrity, and overall health, according to epidemiological and experimental research. The changes in colonic indicators and gut flora are particularly noticeable in type 2 diabetes mellitus. It was discovered that eating functional beef enhanced with carob fruit extract helped reduce dysbiosis and loss of intestinal barrier integrity in a late-stage type 2 diabetes rat model that was brought on by a combination of various extrinsic factors and a high-saturated-fat diet (Macho-González et al., 2021).

Both humans and animals are thought to benefit significantly from carob as a functional food due to its high nutritional content. Carob offers numerous health benefits, including potential preventative effects against cancer, metabolic syndrome, diabetes, diarrhea, hyperlipidemia, and gastroesophageal reflux disease. The most effective method for interpreting metabolic changes brought on by nutritional interventions is metabolomic analysis. The physiological and biochemical adaptations resulting from the nutritional intervention were ascribed to the metabolic changes observed in the fecal samples of carob-fed rats. It has been demonstrated that fecal-targeted metabolomics is appropriate for highlighting and capturing these changes (Begou et al., 2019). Other research has focused on the practical effects of carob supplementation in livestock. The purpose of the study was to assess the impact of carob pods on the growth performance, antioxidant levels, and carcass features of developing rabbits. It was demonstrated that adding 5% of carob pods to the diet improved the growth of the rabbits, and as a result, it could be a novel, risk-free source of feed for rabbits (Abu Hafsa et al., 2017).

Processing conditions notably affect the chemical composition and antioxidant activity of various carob fractions. In one study, the effects of varying the roasting time and temperature combinations on the antioxidant capacity, gastrointestinal solubility of polyphenols, and production of several classes of Maillard reaction products during the thermal processing of carob powder were examined. The roasting conditions significantly impacted the antioxidant activity of carob powder. It was found that roasting carob powder for 30 minutes at 130°C yielded the highest antioxidant capacity with the lowest levels of harmful Maillard reaction products (Vitali Čepo et al., 2014). Carob seeds are a rich source of essential oils, which have antimicrobial effects. In minced beef, the antibacterial activity of carob seed essential oil was readily apparent, and its presence had a potent inhibitory effect on the pathogens at 7°C. According to study findings, carob seed essential oils have cytotoxic and antibacterial qualities, making them promising candidates for food and pharmaceutical applications (Hsouna et al., 2011). When carob flour was added to macaron biscuits, Bissar and Özcan (2022) found that the nutritional value and phytochemical content of the resulting macarons rose (Bissar and Özcan, 2022). The objective of the study conducted by Spizzirri et al. (2024) was to ascertain whether unripe carob pods represent a viable source of antioxidant compounds for the environmentally friendly synthesis of a gelatin conjugate. The resulting gummies demonstrated notable health benefits for humans. It was determined that the functions of the product were retained by the gelatin conjugate synthesis, which proved beneficial in producing gummies with notable structural and biological characteristics (Spizzirri et al., 2024). In hyperlipidaemic mice, the hypolipidaemic activity of unripe carob pod extract and its fractions was evaluated by Moumou et al. (2023), along with their in vitro lipoprotein oxidation-preventing potential. The results indicated that carob green pod extract might help reduce atherosclerosis and associated cardiovascular issues by inhibiting lipoprotein oxidation and promoting cholesterol clearance (Moumou et al., 2023).

The biological activity of locust beans is commonly attributed to their main constituents. The carob fruit has long been valued for its rich content of bioactive compounds that offer multiple health benefits. These effects stem from a variety of substances, including polyphenols, fats, sugars, fibers, tannins, and inositols such as pinitol. The identification and measurement of these substances and the study of their effects have been emphasized by new analytical techniques. It is well established that dietary polyphenols have positive effects on human health and that inositols impact food quality. They are recognized to be beneficial for a number of chronic diseases (Boublenza et al., 2019). The use of plant foods for human nutrition has a long history, from traditional folk medicines to newly developed herbal remedies, and with the advancement in processing technologies, plant-based foods are receiving growing attention (Hussain et al., 2023a; 2023b; 2024). The carob pod's non-toxic nature and high purity make it suitable for industrial applications, underscoring its economic importance (Martins-Loução et al., 2024). Therefore, carob could be recommended as a nutritional plant for humans and animals in various forms and conditions. Table 2 presents the different biological roles associated with carob fractions and their bioactive compounds.

CONCLUSION

Carob (*Ceratonia siliqua* L.) is one of the most widely used crops for food and medicine in Asia and Africa This unique plant produces fruit with exceptional nutritional value and functional qualities. Carob is especially economical and rich in minerals, fiber, sugars, and polyphenols. Both the pulp and seeds of carob fruit are abundant in various nutritious and bioactive compounds. In the culinary, pharmaceutical, and

Table 2. Biological roles of carob fractions and their bioactive

Carob bioactive components	Carob fractions as source	Biological roles	References
Flavonoids	fruit	*in vivo* antioxidant activities	Nemati et al., 2022
D-pinitol	pulp	hypoglycemic potential	Nasar-abbas et al., 2016
Galactomannan	seeds	anti-inflammatory activity	Djellal et al., 2024
Polyphenols	pulp and seeds	antioxidant and antidiabetic roles	Ikram, 2018
Tannins, lignin, pectin, cellulose and hemicellulose	pods	cholesterol metabolism	Boublenza et al., 2019; Kotrotsios et al., 2012
Quercetin, catechin and myricetin	pods	anticarcinogenic potential	Gregoriou et al., 2021
Fiber	pods	gastrointestinal benefits	Mahmoudi et al., 2022
Tannins	pods	antidiarrheal potential	Basharat et al., 2023
Pectin and tannins	carob seeds	antidiarrheal potential	Dahmani et al., 2023
Polyphenols	seed germ extracts	cytoprotective effects	Custódio et al., 2011; Krokou et al., 2019b
Extracts	fruit	antihyperglycemic and antihyperlipidemic effects	Macho-González et al., 2019; 2020; 2021
Pulp	fruit	antioxidant effects	Gravador et al., 2015
Green pods extracts	pods	antioxidant effects	Moumou et al., 2023
Whole fruit	pods	antioxidant effects	Abu Hafsa et al., 2017
Extracts	fruit flour	antioxidant effects	Rosa et al., 2013
Extracts	fruit	antioxidant effects	Rtibi et al., 2021
Pulp	fruit	growth regulation and enhancement effects	Meziane et al., 2023
Essential oils	seeds	antibacterial effects	Hsouna et al., 2011
Flour	fruit	antioxidant and celiac protective effects	Bissar and Özcan, 2022
Powder	fruit	*in vivo* antioxidant effects	Begou et al., 2019
Extracts	fruit	anti-inflammatory and antioxidant activity	Gioxari et al., 2022

feed industries, carob finds extensive use as an antioxidant, preservative, thickener, stabilizer, and in the synthesis of lactic and citric acids as well as alcohol. With numerous *in vitro* and *in vivo* studies utilizing various carob fractions, the growing demand for natural products further underscores the significance of carob across various fields due to its outstanding nutritional and therapeutic profile. Various carob fractions are excellent food ingredients with the potential to be incorporated into a range of nutritious food and feed products. Moreover, carob products enhance physicochemical profiles by imparting functional qualities to foods, boosting their nutritional profile, and extending the shelf life of the final product when used as a food ingredient in diverse formulations. Without a doubt, carob offers benefits for human health in addition to its economic and ecological importance. The clinical effects of isolated and purified bioactive compounds from carob warrant further investigation.

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DATA AVAILABILITY

Data related to this study are provided within the manuscript.

DECLARATIONS

Data statement

All data supporting this study has been included in this manuscript.

Ethical Approval

Not applicable.

Competing Interests

The authors declare that they have no conflicts of interest.

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