

Review

Exploring *Apis mellifera* Propolis Extracts: Bioavailability, Protective Strategies, and Applications in Food Systems

Armando Pelaez-Acero ¹, Marycarmen Cortes-Hernández ², Anuar Jottar-Bernal ¹, Lorena Luna-Rodríguez ³, Armando Zepeda-Bastida ¹, Irma Morales-Rodríguez ¹ and Gabriela Medina-Pérez ^{1,*}

¹ Instituto de Ciencias Agropecuarias, Universidad Autónoma del Estado de Hidalgo, Avenida Universidad Km. 1 s/n Ex Hacienda Aquetzalpa, Tulancingo 43600, Hidalgo, Mexico; pelaeza@uaeh.edu.mx (A.P.-A.); jo133673@uaeh.edu.mx (A.J.-B.); azepeda@uaeh.edu.mx (A.Z.-B.); irma_morales@uaeh.edu.mx (I.M.-R.)

² Sustainability of Natural Resources and Energy Programs, Center for Research and Advanced Studies of the IPN, Saltillo 25900, Coahuila, Mexico; marycarmencohdz@investav.mx

³ Área de Sistemas de Producción Agropecuarios, Departamento de Biología de la Reproducción, Universidad Autónoma Metropolitana, Unidad Iztapalapa, Av. San Rafael Atlixco 186, Leyes de Reforma 1ra Secc., Iztapalapa, Ciudad de México 09340, Mexico; llunaro@xanum.uam.mx

* Correspondence: gabriela_medina@uaeh.edu.mx

Featured Application

Propolis extracts from *Apis mellifera* have demonstrated significant antimicrobial, antioxidant, antidiabetic, and anti-inflammatory activities, making them attractive candidates for use in functional foods. Advances in extraction and encapsulation techniques have improved the stability and bioavailability of their bioactive compounds, enabling their application as natural food preservatives and health-promoting ingredients. Their incorporation into food matrices, such as meat, dairy, and beverages, offers a sustainable alternative to synthetic additives while enhancing the nutritional and therapeutic value.

Abstract

Propolis, a resinous substance produced by *Apis mellifera*, is a chemically diverse natural product rich in polyphenols, flavonoids, terpenes, vitamins, and minerals. These compounds exhibit a range of biological activities, including antimicrobial, antioxidant, antidiabetic, anti-inflammatory, and cardioprotective effects, making propolis an attractive candidate for applications in the food and health sciences. This review summarizes the current understanding of its chemical composition and the environmental, botanical, and genetic factors influencing its variability. Particular attention is given to extraction methods: while conventional approaches such as maceration and Soxhlet extraction remain widely used, they often compromise compound stability. In contrast, emerging techniques—such as ultrasound-, microwave-, and supercritical fluid-assisted extraction—enhance yield, selectivity, and sustainability. Encapsulation strategies, including micro- and nanoencapsulation, are also explored as practical tools to protect propolis bioactives from degradation, improve solubility, and mask their strong taste, thereby ensuring higher bioavailability and consumer acceptability. Recent applications in the meat, dairy, beverage, bakery product, and edible film industries demonstrate propolis' potential to extend shelf life, inhibit microbial growth, and enrich the nutritional and functional quality of these products. Nevertheless, challenges remain, particularly regarding standardization, allergenicity, dosage, and regulatory approval, which limit its widespread industrial adoption. Overall, *Apis mellifera* propolis represents a multifunctional natural ingredient that bridges traditional medicine with modern food science. Advances in extraction and encapsulation technologies are paving the way for the integration of this ingredient into functional foods,



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nutraceuticals, and sustainable food preservation systems, underscoring its value as a natural alternative to synthetic additives.

Keywords: *Apis mellifera*; propolis; bioactive compounds; antioxidant activity; encapsulation; food application; extraction methods; functional food; polyphenols; bioavailability

1. Introduction

Natural products have been an integral part of humanity's history, accompanying us throughout our existence and serving as a vital component of our diet and traditional medicine since ancient times [1]. Currently, the use of these products has been resumed as an alternative to traditional medicinal treatments, thereby helping to prevent various diseases. This growing interest has led to more in-depth research into their composition and the main beneficial effects on our health. Propolis is a natural product that has been attributed multiple therapeutic properties [2]. Propolis is a byproduct made by bees from a mixture of resins and other components, resulting in a sticky substance that covers and protects the hive against diseases and foreign agents. They also use it as a thermal insulator and crack sealant; it is primarily composed of resins, along with wax, essential oils, pollen, and other organic compounds [3,4]. This composition usually depends on various factors that give it different characteristics [3,5]. However, despite these factors, propolis has bioactive compounds, with approximately 500 identified phenolic compounds, aromatic and aliphatic acids, and their esters, vitamins, enzymes, and minerals [4,6,7]. Due to the presence of these compounds within propolis, it has been used as an alternative treatment for various diseases [8–10].

Similarly, multiple health benefits have been recognized, including antioxidants, anti-tumor, antimicrobial, anti-inflammatory, antiviral, immunomodulatory, hepatoprotective, and antidiabetic properties, among others [11–14]. However, the bioactive compounds to which their therapeutic properties are attributed could be affected by extraction and processing conditions, exposure to light, oxygen, temperature, pH, moisture, and gastrointestinal and storage conditions [15–19]. Therefore, there is a need to efficiently extract and protect these types of compounds to deliver them to the body in sufficient quantities, thereby providing us with these benefits. Although this review primarily addresses propolis derived from *Apis mellifera*, it is essential to acknowledge that stingless bees (Meliponini) also produce propolis, often referred to as geopropolis, which has a distinctive chemical profile and biological activity. Studies on the propolis of stingless bees have reported the presence of unique phenolic compounds, terpenes, and polysaccharides that exhibit antioxidant, antimicrobial, and anti-inflammatory effects. However, the scientific literature remains limited, and production is restricted to small scales, which hampers standardization and industrial applications. Incorporating these alternative sources into future investigations would not only broaden the understanding of propolis diversity but also support sustainable beekeeping practices and valorize native bee species, particularly in tropical and subtropical regions where meliponiculture has deep cultural and ecological significance. This review aims to compile existing information about propolis, including its chemical composition, bioactive compounds, extraction and protection methods, and their related therapeutic properties, to promote its use and consumption, thereby benefiting beekeepers. Several reviews have previously addressed the potential of propolis as a functional ingredient in food systems, highlighting its antimicrobial, antioxidant, and preservative properties. These works have provided essential insights into its chemical composition, biological activities, and general applications. However, many of them focus

on specific aspects—such as bioactivity, traditional extraction methods, or limited food applications—without integrating the most recent advances in extraction, encapsulation, and bioavailability. In preparing this review, we carefully considered earlier contributions while aiming to expand their scope by consolidating recent findings from the past five years. Our objective is to provide a more comprehensive perspective that not only summarizes current knowledge but also highlights emerging technologies, safety considerations, and practical applications, thereby offering researchers an updated and integrative reference for future investigations on propolis in food systems [12,20–22].

2. Propolis

Propolis is a mixture of various resinous substances and exudates from different plant sources, including trees, shrubs, bushes, conifers, leaf buds, and sage, which bees collect within the area near their hive [4,23]. Worker bees mix these resins with salivary secretions, enzymes, wax, pollen, and enzymes produced by the same bees, resulting in a sticky, gummy material with different shades that can range from yellow, green, red, brown, or black; it has a strong, bitter taste and is very aromatic [23]. At low temperatures, it has a stiff consistency, while at high temperatures, it becomes soft, malleable, and extremely sticky [14,21]. This mixture is used to seal cracks or crevices in the hive, thereby preventing the entry of external agents (both biotic and abiotic). It also softens the internal walls, maintains stable humidity and temperature, and acts as an antiseptic to prevent microbial infections by molds, yeasts, and bacteria [24]. It is also used to mummify insects or small dead animals that are too heavy for bees to remove [6].

2.1. Composition and Bioactive Compounds of Propolis

The composition of propolis is quite complex and varies depending on the type of bee, geographic region, vegetation, flowering type, time of year, and other climatic and environmental conditions [3,25]. Its composition values (Figure 1) have been reported to range from 50 to 40% resins and balms, 30–20% beeswax, 10–5% essential and aromatic oils, 5% pollen, and 5% other organic compounds [26,27]. Of the latter, bioactive compounds have been identified as an essential part (Table 1), with more than 500 different compounds identified [28]. Some of the most abundant bioactive compounds in propolis are phenolic compounds. In Brazil, the presence of acids such as cinnamic, p-coumaric, caffeic, and ferulic, as well as their derivatives, was reported in green-hued propolis [27]. In Kenya's propolis, two types of stilbenes were identified: schweinfurthin A and schweinfurthin B. Another study of propolis from tropical areas linked the content of lignans present in this propolis to its antioxidant and anticancer activities [29,30].



Figure 1. Composition and bioactive compounds of propolis.

Other substances that have been linked to the therapeutic properties of propolis are flavonoids [31]. Being the most abundant within the bioactive compounds of propolis, finding different groups such as flavonoles, flavones, flavanols, chalcones, dihydrochalcones, isoflavones, isodihydroflavones, flavans, and neoflavonoids, to mention a few, flavonoid glucosides such as rutin, isorhamnetin-3-O-rutinoside, flavone-C-glucoside, and leuteolin, and nirigenin glucosides have also been found in some propolis [12,29]. Flavonones represent the most significant group of flavonoids, with pinocembrin, pinostrobin, nirigenin, sakuranetin, isosakurenin, and liquiritigenin being identified in different propolis from various parts of the world [32,33]. Flavones and flavanols are less abundant and are present in small quantities, such as acacetin, epigenin, chrysin, tectochrysin, galangin, quercetin, and kaempferol [28,34,35].

The compounds responsible for the aroma of propolis are terpenes, which represent approximately 10% of the bioactive compounds in propolis [8,36]. Acyclic and monocyclic monoterpenes have been found, such as myrcene, p-menthanes, and cineole, which give meta and turpentine aromas to some types of propolis, as well as dicyclic monoterpenes, such as camphor, pinene, fenchane, and camphene [3,37,38]. Among the reported diterpenes are cembrane, labdanum, abietane, pimarane, and totarane [39,40].

Table 1. Bioactive compounds of raw propolis.

Group	Chemical Compound	References
Benzoic acid and derivatives	Benzoic acid, salicylic acid, gentisic acid, gallic acid, benzoic acid from phenylmethyl ester, salicylic acid phenylmethyl ester, trans-coniferyl benzoate, trans-p-coumaryl benzoate, protocatechuic acid	[6,41–43]
Benzaldehyde derivatives	Vanillin, caproic aldehydes, isovanillin, p-hydroxybenzaldehyde, protocatechualdehyde	[44]
Cinnamic alcohol, cinnamic acid derivatives,	Cinnamyl alcohol, hydrocaffeic acid, isoferulic acid, cinnamic acid methyl ester, cinnamic acid ethyl ester, Cinnamylacetate caffeic acid, ferulic acid	[19,45]
Aliphatic hydrocarbons	Eicosin, 1-octadecene, tricosane, pentacosane, eicosane, heneicosane	[46,47]
Sugar	D-ribofuranose, D-fructose, sorbitol, D-glucose, thallose, sucrose, fructofuranose-1, fructofuranose-2, galactotyl, gluconic acid, galacturonic acid, 2-O-glycerylgalactose	[19,48–50]
Vitamins and minerals	B1, B2, B6, C, E, Sr, Ba, Cd, Sn, Pb, Ti, Ag, Co, Mo, Al, Si, V, Mn, Cr, Na, Mg, Cu, Ca, Zn, Fe, K	[26,48,51–59]
Chalcones and dihydrochalcones	Alpinetin, nirigin, pinobanksi, 3-acetate, pinostrobin, pinocembrin, sakuranetin, 2,6,a-trihydroxy-4methoxy, 2,6,dihydroconeo-4-methoxy-dihydro, 4,6-trihydroxydihydro	[19,60]
Esters	Methyl palmitate, cinnamyl-trans-4-coumarate, ethyl palmitate, stearic acid methyl ester, phthalate ester, benzyl benzoate, benzyl trans-coumarate, 3-methyl-3-butenyl, 3-methyl-3-butenyl caffeate, 2-methyl-2-butenyl caffeate, 3-methyl-2-butenyl caffeate, benzyl caffeate, benzyl caffeate phenylethyl, cinnamyl caffeate, tetradecyl caffeate, tetradecyl caffeate (isomer), tetradecyl caffeate, hexadecyl caffeate	[8,61,62]
Other acids and derivatives	14-methylpentadecanoic acid phenylmethyl ester, palmitic acid ethyl ester, myristic acid, sorbic acid, phthalic acid butyl-2-methylpropyl ester, stearic acid, acouetic acid methyl ester	[43,63]
Alcohol, ketones, phenols, and heteroaromatic compounds	Benzyl alcohol, hexadecanol acetate, coumarin, pterostilbene. Xanthorrhoeol, scopoletol	[49,64]
Terpenes, sesquiterpenes, alcohol, and derivatives	Geraniol, nerolidol, β -bisabolol, guaiol, farnisol, dihydroeudesmol, α -acetoxylbetulenol,	[60]
Sterols and steroid hydrocarbons	Chostrylene, cholinesterol, stigmaterol, β -dihydrofucosterol, lanosterol, cholesterol	[65,66]

Table 1. Cont.

Group	Chemical Compound	References
Enzymes	Glucose-6-phosphatase, acid phosphatase, adenosine triphosphatase, succinic dehydrogenase	[26,51,67,68]
Ketones	Acetophenone, p-acetophenacetophenone, methylacetophenone, 6-methylketone	[43,66]
Waxy acids	Acid behenic. Acetic, lauric, linoleic, lignoceric, manganic	[69]
	Benzene methanol, cinnamic alcohol, glycerol, α -glycerophosphate, phenethyl alcohol, isobutanol, hydroquinone, prenyl alcohol	[70,71]
Aliphatic acids and aliphatic esters	Acetic, angelic, butyric, crotonic, fumaric, isobutyric, methylbutyric, isobutyl acetate, isopentyl acetate, isopentenyl acetate, Lactic, hydroxyacetic, alic, 5-hydroxy-n-valeric, 2,3-dihydroxypropanoic, pentonic-2-deoxy-3,5-dihydroxy-y-lactone, pentonic-2-deoxy-3,5-dihydroxy-y-lactone (isomer), succinic, 2.3.4.5-tetrahydroxypentanoic 1,4-lactone, 2.3.4.5-tetrahydroxypentanoic 1,4-lactone (isomer), nonanoic, palmitic, oleic, decanoic, dodecanoic, tetradecanoic, heptadecanoic octadecanoic, tetracosanoic, eicosanoic, hexacosanoic, 2-hydroxyhexacosanoic	[21,43]
Other compounds	Phosphoric acid, 1,4-Dihydroxybenzene, 4-Hydroxy-benzaldehyde, 4-Hydroacetophenone, 1,2,3-trihydroxybutane, 1,2,3-trihydroxybutanal, 1,2,3- trihydroxybutanal (isomer), myristicin, 2,4-bis(dimethylbenzyl)-6-t-butyl phenol, 1,8-dihydroxy-3-methyl anthraquinone, myristicin (isomer)	[43,66]

2.2. Phenolic Compounds

Phenolic compounds, considered secondary metabolites, are abundant in plants and serve as a defense mechanism against microorganisms, pests, or other organisms that can alter their metabolism. The amount and type of phenolic compounds in propolis vary depending on factors such as the plant from which bees collect the resins, and they subsequently process them to form propolis [72]. These compounds have excellent antioxidant activity due to their ability to neutralize free radicals and their antimicrobial activity [29,30]. For example, green propolis from Brazil is rich in acids such as cinnamic, p-coumaric, caffeic, and ferulic, which are closely associated with the antimicrobial activity of propolis [73]. Two stilbenes, schweinfurthin A and B, have been identified in Kenya. Another prominent group is lignans, which are present in brown-colored propolis and are known for their antioxidant capacity and anticancer potential, primarily found in tropical areas such as the Canary Islands, Kenya, Chile, and Brazil.

2.3. Flavonoids

More than 150 flavonoids have been identified in propolis [73]. These are the main components of propolis and are related to various pharmacological properties, such as free radical scavenging, protection against lipid oxidation, and vitamin C [31,74,75]. They also exhibit antimicrobial, anti-inflammatory, and anticancer activities [30,34,35]. Flavonoids are divided into groups such as flavanones, flavones, flavonols, flavanonols, chalcones, dihydrochalcones, isoflavones, isodihydroflavones, flavans, isoflavans, and neoflavonoids [74]. Flavonoid glycosides, such as rutin, isorhamnetin, and glucosides of luteolin and naringenin, are rare [73]. These components vary by plant and geographic origin. Flavanones, a critical group, comprise more than 40 compounds identified in propolis worldwide. Typical examples include pinocembrin, pinostrobin, naringenin, sakuranetin, isosakuranetin, and liquiritigenin, which are present in propolis from Europe, China, non-tropical Asia, and North America. Some flavonoids, such as geranyl flavanone derivatives, are found exclusively in Japan, while others are also present in places like the Solomon Islands [33]. Flavones and flavonols are also present in propolis, albeit in smaller amounts. Some ex-

amples are acacetin, apigenin, chrysin, quercetin, kaempferol, and, less commonly, fisetin. Macarangin is a flavonol reported only in Kenyan propolis [30,32].

2.4. Terpenes

Terpenes, which are responsible for the aroma of propolis, account for approximately 10% of its content. They possess antioxidant, antimicrobial, and anti-inflammatory properties, as well as anticancer potential [32,37,76]. Propolis monoterpenes are highly aromatic and are divided into acyclic, monocyclic, and dicyclic. Diterpenes, such as cembrane, labdanum, and abietane, exhibit antibacterial properties, primarily against Gram-positive bacteria [76]. According to [77], triterpenes are more common in propolis from tropical and subtropical areas.

2.5. Sugars

Sugars have been detected in propolis, although their origin is uncertain. Some theories suggest that they come from nectar, honey, or flavonoid glycosides [73]. Glucose is the most common sugar, although others have also been identified in Indian propolis, such as D-mannose and D-fructose [48,64].

2.6. Hydrocarbons

Diverse types of propolis have been found to contain hydrocarbons, including alkanes, alkenes, and fatty acids. Propolis from Turkey has been reported to have a content ranging from 0.31% to 3.88% [78]. Hydrocarbons are not related to the floral origin of propolis but to the metabolism of bees, which depends on plant genetic factors [79].

2.7. Minerals

The mineral content of propolis is closely related to its geographical and botanical origins, as well as the soil characteristics in which it is grown [80,81]. The mineral content in propolis varies depending on location, season, and collection method [56]. Elements such as Ca, K, Mg, and Na are expected, along with some toxic elements, including Pb and Cd, which are used to monitor environmental contamination and trace the origin of propolis [82,83]. One of the factors to consider is the botanical origin, as bees are very selective when collecting resins, choosing certain trees [84,85]. Bees detect chemical signals in plants, collecting resins with greater biological activity [80,86]. Additionally, bees can obtain resins from trees located far from the hive, which can impact their performance [84]. For this reason, beekeepers have started to plant appropriate plants within the flight range of bees to increase propolis production [4]. However, excellent biological activity has been reported in propolis from different regions of the world [23,87–90]. Bee genetics also influence propolis production. Honeybees (*Apis mellifera*) are the most common globally. Still, they have adapted to different climates, giving rise to local ecotypic races such as *A. mellifera caucasica* and *A. mellifera carnica*, among others [72]. Some races require more propolis to maintain the hive, which limits their commercial use, while others need less, making them attractive to the industry. Certain strains prefer specific types of plants, which can impact propolis collection and yield. *Apis mellifera* morphology, such as proboscis and wing characteristics, also influences its ability to collect propolis [53]. Furthermore, bees with highly propolis-producing parents have been found to produce more propolis within the colony [72,91].

Propolis is used to maintain the hive, and beekeepers have developed strategies to increase its production [72]. Modifying the hive, such as adding rough surfaces, increases propolis deposition [92]. Special traps have increased production by up to 30% by placing perforated mesh inside the hive [93]. The choice of materials for hives, such as wood or polystyrene, also influences production, with wood being the most effective [94].

Climate and environment also affect propolis production. Several studies have highlighted that plant biodiversity promotes greater resin collection [95,96]. Although there is insufficient information on the relationship between temperature and propolis production, it is known that higher-quality propolis is obtained during the rainy season because bees collect more resin to protect their hives. Production tends to increase in late autumn and early winter [72]. Bee health also impacts propolis production. When sick, bees consume propolis to fight infections, such as those caused by bacteria or fungi [97]. If the hive is at risk of infection, the number of resin-collecting bees increases; otherwise, the hive could collapse [72]. Regarding the biological properties of propolis, extensive research has been conducted on its antimicrobial and antioxidant activities [14].

3. Biological Properties of Propolis

3.1. Antimicrobial Activity

The antimicrobial effectiveness of propolis is attributed to its unique phytochemical composition. The antibacterial effect of propolis is approached from two perspectives [98,99]. The direct action on microorganisms includes the alteration of cell membrane permeability, membrane potential, reduction in ATP production, and inhibition of mobility. According to [43], bioactive compounds in propolis block protein synthesis, thereby disrupting bacterial reproduction and affecting cell wall formation, which leads to cytoplasm collapse. Greater activity has been observed against Gram-negative bacteria than Gram-positive bacteria, since propolis compounds inhibit key enzymes in their metabolism, affecting both aerobic and anaerobic bacteria. However, its antibacterial activity depends on various factors, including the extraction solvent used (ethanol, methanol, water, DMSO, dichloromethane, hexane, and supercritical fluids), the concentration of bioactive compounds, the time of collection, the region, and the bee species, which can vary between countries [6,14].

The antifungal activity of propolis (against molds and yeasts) is related to the inhibition of growth and production of conidia [14]. Depending on the concentration, it can present fungistatic or fungicidal effects against strains of interest in human and veterinary medicine [43,98]. Propolis compounds act on the cell membranes of fungi, inducing cell death and decreasing adhesion capacity by inhibiting extracellular phospholipases. In yeasts, they inhibit filamentation and biofilm production [95]. Compared to the antibacterial and antifungal activities, there is less research on the antiviral activity of propolis. However, mechanisms have been proposed that include the inhibition of viral polymerase, alteration of viral genetic material replication, prevention of viral entry into the host cell, and strengthening of innate immunity [14,41]. Ref. [14] indicates that the antiparasitic activity of propolis is related to cell lysis, caused by alterations in phospholipid metabolism and adhesion mechanisms. It also affects the expression of metabolic enzymes and alters the mitochondrial membrane, inducing cell lysis [100].

3.2. Antioxidant Activity

Free radicals are generated during human metabolism; however, the body has natural antioxidant systems, including superoxide dismutase, catalase, and glutathione peroxidase, as well as non-enzymatic antioxidants such as vitamins C and E, which combat reactive oxygen species [101]. Excess of these species can cause diseases such as cancer and cardiovascular disorders, as well as damage DNA and contribute to cellular aging and neurodegenerative diseases [102]. The antioxidant activity of propolis is attributed to its high content of phenolic compounds, which protect cells by donating hydrogen ions to neutralize free radicals [43,74,103]. The antioxidant capacity of propolis varies depending on its botanical and geographical origin, the extraction method, and the solvent used [6–8,19,32].

3.3. Antidiabetic Activity

A key mechanism of antidiabetic activity is the inhibition of the enzymes α -amylase and α -glucosidase. α -Amylase breaks down starch during digestion, while α -glucosidase releases glucose from carbohydrates, which is absorbed in the intestine and transported to the blood. By inhibiting these enzymes, postprandial glucose is reduced, representing a promising strategy for treating diabetes [104]. Ref. [105] reports that an ethanolic propolis extract applied to diabetic mice reduced blood glucose levels by approximately 40%, preventing body weight loss. Insulin was also detected in the treated mice, whereas the untreated mice experienced damage to their pancreatic islets. Ref. [62] treated diabetic rats with propolis. The authors observed a decrease in plasma glucose levels and an improvement in insulin levels, suggesting that propolis may help repair damage to the intestinal mucosa, thereby improving hyperglycemia. Ref. [106] evaluated acidic extracts from cactus fruits. The authors concluded that they contain bioactive compounds, such as phenols and flavonoids, with effective inhibitory properties against critical enzymes related to diabetes mellitus.

3.4. Anti-Inflammatory Activity

Propolis, which contains a high concentration of polyphenolic compounds, exhibits anti-inflammatory activity in both acute and chronic inflammatory processes. It has been observed that this activity of propolis is associated with a decrease in the synthesis of prostaglandin E2 (PGE2), thromboxane A2, leukotriene B4, and nitric oxide (NO), which are involved in inflammatory reactions. Additionally, studies have demonstrated the inhibitory activity of propolis against NADPH oxidase, ornithine decarboxylase, myeloperoxidase, and hyaluronidase, attributed to the presence of active flavonoids and cinnamic acid derivatives [107]. The anti-inflammatory effect of propolis has also been shown to be the same as that of non-steroidal drugs, but without the side effects of these drugs [14].

3.5. Cardioprotective Activity

The cardioprotective properties of propolis, related to its bioactive compounds, have been investigated. Flavonoids, such as quercetin, kaempferol, and rhamnetin, contained in propolis block the transport of calcium through cell membranes into the cytoplasm, which causes dilation of blood vessels and a decrease in blood pressure. On the other hand, the protective properties of propolis on the cardiovascular system are due to its antihypertensive activity, due to the inhibitory activity of flavonoids on the angiotensin-converting enzyme (ACE) and the Camp-converting enzyme (3'/5'-cyclic adenosine triphosphate), as well as cyclooxygenase, which is related to effects on vascular resistance and platelet aggregation [108].

4. Extraction Methods

Propolis has a complex structure; extraction is a technique that favors the use of bioactive compounds in propolis. Different solvents, such as water, methanol, ethanol, chloroform, dichloromethane, ether, and acetone, are used to extract chemical compounds [109,110]. The aqueous extract exhibits an antioxidant capacity, rich in polyphenols and flavonoids, primarily phenolic acids, which is favorable for use in the food industry because it does not contain ethanol and adds functional and biological characteristics to the product [19,111]. Previously, the extraction of bioactive compounds using conventional techniques presented problems, including degradation and loss of bioactive compounds due to the elevated temperatures and long extraction times to which the samples were subjected. In addition, the use of toxic solvents for extraction has repercussions on human health and the environment, which is why emerging technologies are sought to be

green and sustainable for the extraction of bioactive compounds. The emergence of new extraction technologies, such as microwave-assisted extraction, ultrasound-assisted extraction, and supercritical fluid extraction, has enabled the development of more efficient extraction methods. The latest technologies offer several advantages in the extraction process compared to traditional methods, as they have a minimal negative impact on the environment. This is achieved by significantly reducing the use of organic solvents or utilizing non-polluting solvents, which also improves the yield and quality of the bioactive compounds obtained [112].

Extraction methods are divided into two main categories: (a) Conventional methods include maceration, distillation, hydrodistillation, steam stripping, Soxhlet extraction, leaching, infusion, and organic solvent extraction [113,114]; (b) Unconventional or emerging methods include processes that use microwaves, high pressures, ultrasound, and critical point systems. Using conventional extraction methods leads to the decomposition and loss of functionality of bioactive compounds due to factors such as elevated temperatures and prolonged extraction times. Additionally, these methods often employ toxic, volatile organic solvents that have a negative impact on health, safety, and the environment. Due to this, there is a need to implement sustainable and environmentally friendly technologies for extracting bioactive compounds [115,116]. Among traditional methods, maceration is one of the oldest, in which the sample is left to rest for periods varying from 24 h to several weeks, accompanied by constant agitation to improve the interaction between the solvent and the sample. However, new technologies such as microwave-assisted extraction, ultrasound, and supercritical fluids have been explored to optimize extraction processes [117].

The ultrasonic extraction method is based on sonic waves, with a frequency range of 20 to 100 Hz for food applications. This process involves transmitting waves in a liquid medium, which generates alternating cycles of compression and rarefaction that produce negative pressure, creating cavities or bubbles within the liquid. Ultrasonic waves cause the rupture of cell walls, releasing their internal components [118,119]. This method has gained popularity over the past two decades because it is efficient, simple, clean, fast, and considered “green”. Additionally, it offers advantages such as lower costs, reduced extraction times, and higher yields in the extraction of bioactive compounds [120]. The efficiency and optimal conditions for ultrasound extraction have been reported. Ref. [109] reported high phenolic content and high antioxidant activity in propolis extract, using a 1:10 ratio with a temperature of 34 °C and a time of 30 min in ultrasonic waves with a constant frequency of 35 kHz. According to the results obtained by ref. [121], the sonication time, concentration, and ratio of solvent to material were statistically significant and may influence the chemical and biological activities of the propolis extract. There are areas for improvement in propolis extracts, as noted in [111], by combining the maceration technique with the ultrasound technique to obtain better results. Another opportunity would be to implement the combination of frequencies, using multi-frequency ultrasound in this type of sample.

Microwaves are electromagnetic fields ranging between 300 MHz and 300 GHz, corresponding to wavelengths between 1 cm and 1 m within the electromagnetic spectrum. These fields, composed of electrical and magnetic elements, are utilized in microwave-assisted extraction, where the energy interacts with the polar components of the solvent, converting this energy into heat. Microwave equipment typically operates at a frequency of 2450 MHz, producing power ranging from 600 to 700 watts [122–124]. Compared to traditional methods, this technique reduces extraction times, improves yields, uses fewer reagents, increases compound selectivity, and facilitates automation [125,126]. Extraction using supercritical fluids is characterized by the use of inert solvents, considered ecologically safe or “green”, such as carbon dioxide (CO₂). This gas is commonly used due to its solvent properties, low cost, accessibility, and environmental effectiveness [37]. Under

supercritical conditions, CO₂ enables the extraction of bioactive components without denaturing them, thanks to its ability to behave both as a liquid with high solute solubility and as a gas with excellent diffusion capacity [127].

The extraction methods analyzed in this document exhibit distinct advantages and limitations in terms of efficiency, preservation of bioactive compounds, and applicability. Conventional solvent extraction, although widely used due to its simplicity and cost-effectiveness, often requires longer processing times and can result in partial degradation of thermolabile compounds. In contrast, advanced techniques such as ultrasound-assisted and microwave-assisted extraction offer higher yields and reduced extraction times, preserving the integrity of sensitive phenolic and flavonoid components. Supercritical fluid extraction, particularly using CO₂, offers a solvent-free alternative with excellent selectivity for bioactive compounds; however, it requires specialized equipment and higher operational costs. Overall, the choice of extraction method depends on the target compounds, desired purity, and scalability considerations, highlighting a trade-off between efficiency, compound stability, and practical feasibility.

5. Bioavailability of Propolis Extracts

The bioaccessibility and bioavailability of propolis compounds are influenced by their extraction method, the complexity of the extracts, and the digestive process. Crude propolis extracts, rich in bioactive phenolics such as artepillin C, offer superior bioavailability and antioxidant efficacy compared to isolated compounds. These findings underscore the potential of propolis as a functional food ingredient and a natural therapeutic agent. Further research is needed to elucidate the long-term health benefits and optimal delivery mechanisms for propolis-derived bioactive compounds.

Studies monitoring the concentrations of propolis compounds in serum after oral administration highlight a significant difference in the bioavailability of isolated polyphenols compared to crude propolis extracts. Isolated polyphenols demonstrated lower absorption, with plasma C_{max} values ranging between 15 and 20 µg/mL, whereas crude extracts showed plasma C_{max} values of 40–50 µg/mL. These findings underscore the superior bioavailability of crude propolis extracts, positioning them as promising candidates for antioxidant food supplements [103]. Brazilian propolis has been shown to contain diverse phenolic compounds, including artepillin C, p-coumaric acid, kaempferol derivatives, and naringenin, with artepillin C being particularly abundant (21 mmol/100 g). Research involving intestinal Caco-2 and hepatic HepG2 cells demonstrated that artepillin C is effectively absorbed, transported across cell layers, and retains its antioxidant activity. Specifically, artepillin C reduced lipid peroxidation and oxidative DNA damage by 16% and 36%, respectively, at a concentration of 20 µM. These findings establish artepillin C as a bioavailable antioxidant, contributing to the health-promoting properties of Brazilian propolis [128]. The impact of digestion on the antioxidant properties of propolis has also been evaluated using in vitro human digestion models. Propolis extracts prepared with ethanol (EtOH) displayed significantly higher phenolic and flavonoid content, along with superior antioxidant capacity, compared to those prepared with glycerol or water. Furthermore, simulated digestion stages, particularly the oral phase, enhanced the bioaccessibility of these compounds. Notably, ethanol-based extracts and their orally digested products demonstrated remarkable cyclooxygenase-2 (COX-2) inhibitory activity in human oral carcinoma KB cells, highlighting their potential therapeutic applications [129].

6. Encapsulation Methods of Propolis Extracts

Propolis contains various bioactive compounds (phenols, flavonoids, aromatic acids, aliphatic acids, terpenes, vitamins, minerals, and enzymes), providing different biological

activities [26]. However, these compounds can be lost or decreased as they are metabolized and absorbed in the human body [67,130]. During this process, the bioactive compounds can interact with other molecules (proteins, lipids, and polysaccharides) or be affected by enzymes and pH, causing shallowing and hydrolysis of bioactive compounds, decreasing their biological properties, which is why research has focused on protecting bioactive compounds during digestion and thus maintaining their bioavailability in the body [131]. Throughout numerous studies, propolis from different regions has been encapsulated, with Brazil standing out as one of the countries with the most research in this field due to its role as a leading producer of propolis worldwide. Generally, propolis encapsulation has been conducted for various purposes, such as protecting it from environmental factors, preventing physical and chemical alterations, improving the solubility, functionality, and bioavailability of its bioactive compounds, and masking its pungent, spicy, and astringent taste [130]. Various technologies have been employed throughout the encapsulation process, with nanoencapsulation, microencapsulation, and emulsion techniques being the most common and yielding excellent results (Table 2). These allow for obtaining different particle sizes, which directly depend on the type of technology used and the encapsulation conditions. It is essential to note that, regardless of the origin of propolis, an adequate encapsulation process must be conducted to ensure that the bioactive compounds can exert their desired beneficial effects on health [132,133].

Table 2. Encapsulation of propolis.

Encapsulation Type	Particle Size	Covering Material	Reference
Microencapsulation	21.8–266.7 µm	Arabic gum, vegetable fat (cottonseed, soybean, and palm)	[134]
Microencapsulation	5.7–33.9 µm	Maltodextrin, tara gum	[135]
Microencapsulation	6.7–6.8 µm	Ovoalbumin	[136]
Nanoencapsulation	99.76–242.22 nm	Maltodextrin, Arabic gum	[137]
Nanoencapsulation	10.34–89.34 nm	Whey protein	[138]
Microencapsulation	10.34–89.34 µm	Maltodextrin	[58]
Nanoemulsion	-	Phospholipids cholesterol Labrasol, labrafac, cremophor RH	[139]
Nanoemulsion	11.7–44.7 nm	40, castor oil, sesame oil, sunflower oil, coconut oil, Tween 20	[140]
Nanoemulsion	611–4064 nm	Sodium caseinate, maltodextrin	[141]
Microemulsion	1.42–74.39 µm	Maltodextrine, lactose, arabic gum, gelatin, sodium caseinate, whey protein isolate, sunflower oil	[142]
Nanoencapsulation	4.6 ± 0.3 µm	Ethylcellulose, Polylactic-co-glycolic acid, Polycaprolactone, Polyvinyl alcohol	[143]
Nanoemulsion	126–723 nm	Phospholipids, soy lecithin, Phosphatidylcholine	[144]
Nanoemulsion	374–759 nm	Phospholipidose	[145]
Nanoemulsion	42–69 nm	Polylactic co-glycolic acid	[146]
Emulsion	-	Chitosan, pectin	[147]
Nanoencapsulation	51–281 nm	Glyceril monostearate, Tween 80, soybean lecithin, Polietilglycone 400	[148]
Nanoencapsulation	75–170 nm	Whey protein isolate, sodium alginate, sunflower oil	[149]
Microencapsulation	500–800 µm	Sodium alginate, Tween 80	[150]
Nanoemulsion	50–561 nm	Corn oil, Span 80, Tween 80	[151]
Microencapsulation	5–20 µm	Rice protein, soybean protein, ovoalbumin	[152]

Encapsulation of propolis extracts has emerged as a promising strategy to overcome the inherent limitations associated with the stability and bioavailability of their bioactive compounds. Among its advantages, encapsulation effectively protects sensitive molecules such as phenolic acids and flavonoids from degradation caused by environmental factors, including light, oxygen, temperature, and pH [131]. It also enhances solubility and absorption, thereby improving bioavailability and biological efficacy. Furthermore, encapsulation technologies enable the controlled release of propolis, prolonging its functional effects and masking its pungent taste and odor, which facilitates its incorporation into a wide range of food matrices [22]. Despite these benefits, encapsulation also presents notable limitations. Advanced techniques, such as nanoencapsulation or supercritical fluid encapsulation, often involve excessive costs, complex processes, and technical challenges that hinder scalability from laboratory to industrial levels. In addition, inappropriate choice of carrier materials or encapsulation conditions may reduce the biological activity of the compounds. Regulatory considerations further add to these challenges, as some encapsulating agents or nanostructured systems require rigorous safety assessments before approval for food applications [153]. Taken together, these advantages and disadvantages highlight both the opportunities and the constraints of encapsulation, reinforcing the need for continued optimization and evaluation to ensure its feasibility in functional foods and nutraceuticals.

7. Potential Applications in Foods

The inclusion of propolis in the human diet has gained significant attention due to its numerous biological activities that promote health. Propolis meets the increasing consumer demand for natural antioxidants and antimicrobials, serving as a sustainable alternative to synthetic additives. Its incorporation into food products has shown potential to enhance food quality while offering health benefits. Several compounds in propolis are recognized as Generally Regarded as Safe (GRAS) substances, and a safe daily intake of 1.4 mg/kg of body weight, approximately 70 mg per day, has been suggested [154]. Propolis is widely used in food formulations, including meat, dairy products, juices, fruits, oils, and seafood, to extend shelf life, prevent lipid oxidation, and provide health benefits. It can be incorporated as an ingredient or applied to the food surface [155]. However, its pungent taste and odor, due to the presence of phenolic and volatile compounds, may alter sensory properties, limiting its application in food products [21]. Studies have aimed to address these challenges by determining optimal levels of propolis addition. For example, in a study, 50 mg per 100 g was found to be the suitable amount for *Torró d'Agramunt*, a traditional confectionery, based on sensory and aroma profiling [156]. In meat products, propolis extracts improve stability against lipid oxidation and inhibit microbial growth; for example, ref. [157] found that treatments with non-commercial propolis (2% *w/w*) in beef patties enhanced antioxidant activity and suppressed bacterial growth during cold storage. Additionally, ref. [158] noted that propolis extended the shelf life of meat products. Similarly, other research has demonstrated that propolis reduces the presence of *Micrococcaceae* bacteria, yeasts, and molds on fermented sausages without adversely affecting their sensory qualities [159]. Ref. [160] reported that ethanolic propolis extract (0.8%) showed antimicrobial activity against pathogens in sausages while maintaining favorable physicochemical and sensory properties, positioning propolis as a viable alternative to nitrites. Microencapsulation has been proposed as a solution to address the sensory challenges of propolis food applications; several recent studies are cited in Table 3.

Table 3. Recent Applications (2021–2025) of *Apis mellifera* Propolis in Food Systems.

Food Matrix/Application	Propolis Type/Formulation	Main Effect Observed	Reference
Yogurt (<i>stirred style</i>)	Spray-dried microencapsulated ethanolic propolis extract (0.5–2%)	Lower pH, higher antioxidant activity, and phenolic content; slight sensory losses at higher concentrations after 21 days of storage	[161]
Grapes (<i>postharvest</i>)	Gelatin edible coating with red propolis extract (5–25%)	Lower weight loss, good sensory acceptability (>78%), antimicrobial effect against <i>S. aureus</i> and <i>P. aeruginosa</i> , improved storage stability at 5–25 °C	[162]
Ripened cheese/ <i>dairy industry</i>	Sodium alginate active film with ethanolic propolis extract (EEP)	Inhibition of filamentous fungi improved functional properties and antimicrobial protection in ripened cheese	[163]
Vacuum-packed cooked ham	Propolis extract as bio-preservative/partial nitrite replacement	Control of major foodborne pathogens (<i>Listeria monocytogenes</i> , <i>Staph. aureus</i> , <i>Bacillus cereus</i> , <i>Clostridium sporogenes</i>) during storage; sustainable potential as preservative	[164]
Active edible films (<i>coffee pulp pectin base</i>)	Coffee pulp pectin + propolis + honey, with varying ratios of plasticizers	Improved mechanical and functional properties; higher antioxidant capacity and antimicrobial activity compared with controls without propolis	[165]
Strawberries (<i>postharvest</i>)	Chitosan edible film loaded with oil-in-water emulsion of propolis (PEF film)	Higher retention of phenolics, anthocyanins, vitamin C; better antioxidant properties; lower degradation of organic acids and soluble solids vs. non-coated fruit	[166]
Biodegradable films from potato starch waste	Potato starch waste + ethanolic propolis extract + natural clay + plasticizers	Increased antimicrobial activity of films; improved barrier properties; thermal stability evaluated	[167]
Lamb carcasses	Propolis extract as a natural feed additive	The red propolis extract improved the lipid profile of the lamb meat.	[168]
Cassava starch films incorporated with beeswax and propolis	Cassava starch + propolis + beeswax	The films reduced the growth of <i>Aspergillus niger</i> by 51%	[169]
Toast bread dough	Propolis ethanolic extract as a natural preservative additive	The bread with propolis ethanolic extract 0.5% had the lowest mold count after 5 days of storage	[170]
Tilapia fish salami	Red propolis hydroalcoholic extract (RPHE)	Salami with 0.4% RPHE showed high sensory acceptance and effectively delayed deterioration and lipid oxidation of salami.	[171]
Pan-fried beef	Samples were marinated overnight with different concentrations (0%, 0.25%, 0.5%, and 1%) of blueberry or propolis extracts.	Natural propolis antioxidant-based marinades had mitigating effects on HAAs formation in beef samples pan-fried at 150 °C and 200 °C.	[172]
Milk powder	Water extracted propolis nano emulsion, Propolis powder	Inhibitory action against Aflatoxin from <i>Aspergillus flavus</i>	[173]
Fresh juice	Propolis water extracts (PWE) and propolis ethanol extracts (PEE)	The PEE improved the safety of fresh juices by acting as a novel natural antiviral preservative for fresh juices	[174]
Apple Pectin-Based Film	Honey and/or propolis ethanolic extract (PEE)	Antiradical and antimicrobial properties against <i>Listeria innocua</i> and <i>Staphylococcus aureus</i> .	[175]

8. Possible Allergenicity and Toxicity of Propolis, Limiting Situations for Its Use in Food

Although propolis is widely recognized for its nutraceutical potential, several restrictions limit its safe use for human consumption. The most common concern is the risk of allergic reactions, particularly in individuals sensitive to bee products, who may experience dermatitis, urticaria, or even anaphylaxis [176,177]. The chemical composition of propolis varies according to its botanical and geographical origin, complicating efforts to establish safe intake levels. Toxicological data remain limited; however, some studies suggest a tolerable daily intake of approximately 70 mg (≈ 1.4 mg/kg), while higher or prolonged dosages lack robust safety evidence [178]. In rare cases, excessive consumption has been associated with renal dysfunction or other adverse outcomes [179]. Another restriction is its potential to interact with medications: *in vivo* studies have shown that propolis can reduce the anticoagulant activity of warfarin, thereby altering blood coagulation parameters [180]. For this reason, its use is discouraged in pregnant or lactating women, children, patients with bleeding disorders, or individuals under pharmacological treatments, unless guided by medical supervision [181]. These documented restrictions underscore the importance of standardized dosing, product quality control, and professional oversight when incorporating propolis into dietary supplements or functional foods.

9. Future Research Directions

To fully realize the promise of propolis in food applications, future work should extend beyond existing studies into dairy, bakery, and beverage matrices, investigating how propolis interacts with different food components during processing (e.g., heat, pH, shear) and storage. Research should also focus on controlled release systems—for example, encapsulation strategies responsive to pH or enzymatic triggers—to ensure the optimal delivery of bioactive compounds in the digestive tract. Sensory evaluation and consumer acceptance remain underexplored, especially when propolis is added in higher percentages. *In vivo* and human clinical trials focused on bioavailability, long-term effects, and safety are needed. Furthermore, advanced analytical techniques—notably metabolomics, LC-MS/MS, NMR spectroscopy, and single-cell or spectroscopic imaging methods—should be more widely employed to map metabolic pathways, assess compound stability, investigate interactions with other food ingredients, and account for geographical/plant-origin variability. Regulatory, economic, and scalability studies are crucial for transitioning from laboratory to industrial applications.

Recent studies that exemplify these directions include the following. Ref. [161] investigated microencapsulated propolis in yogurt production, tracking phenolic content, antioxidant activity, and sensory attributes over storage time. Also, ref. [182] reports antioxidant and anticancer properties from regional propolis sources in Turkey, highlighting compositional variations and potential applications in functional foods. In ref. [183], the physicochemical properties and antibacterial activity of propolis microcapsules were evaluated, suggesting encapsulation as a viable route to preserve their functionality. The metabolomics-based discrimination of Chinese propolis by ref. [184] illustrates how the geographic/climatic origin affects the chemical composition—a point that must be integrated into future standardization efforts.

Emerging research is focused on the human and animal microbiome effects of propolis consumption. suggests that propolis can modulate the human gut microbiome and oral microbiome, with potential implications for health. A recent *in vitro* study by ref. [185] evaluated a standardized poplar-type propolis extract across microbiota from healthy adults, obese individuals, celiac patients, and food-allergic children. After simulated digestion and fermentation, the propolis extract promoted increases in short-chain fatty acid (SCFA)

production and induced shifts in gut microbial composition, indicating possible prebiotic effects. Another clinical investigation in patients undergoing hemodialysis (propolis 400 mg/day for two months) looked at whether supplementation could affect gut microbiota richness and reduce uremic toxins. While no significant changes in alpha-diversity or plasma uremic toxins were found, the study is among the few in human subjects and underscores the need for longer or higher-dose trials [186]. These studies point toward several gaps that future work should address: (i) human clinical trials with longer duration and varied dosing to establish whether propolis can reliably shift gut microbiome composition and function; (ii) use of metagenomic and metabolomic tools to identify which microbial taxa or functions are most influenced; (iii) investigation of oral microbiome effects in vivo in addition to in vitro; and (iv) evaluation of safety and potential unintended effects (e.g., suppression of beneficial microbes) in diverse populations.

10. Conclusions

In conclusion, *Apis mellifera* propolis represents a multifunctional natural product with remarkable potential for applications in food systems and human health. Its chemical complexity, comprising hundreds of bioactive compounds such as phenolic acids, flavonoids, terpenes, minerals, and vitamins, provides a broad spectrum of biological activities that have been consistently reported across diverse geographical origins. These compounds exhibit antioxidant, antimicrobial, antidiabetic, anti-inflammatory, and cardioprotective properties, aligning with the growing demand for natural alternatives to synthetic additives and therapeutic agents. Nevertheless, the variability in chemical composition caused by environmental, botanical, and genetic factors poses challenges to standardization and reproducibility, underscoring the need to establish harmonized analytical and quality control methods.

Advances in extraction technologies have substantially improved the efficiency, sustainability, and selectivity of bioactive compound recovery. Conventional approaches, such as maceration and Soxhlet extraction, although historically significant, have been associated with the degradation of sensitive compounds and the use of toxic solvents. Emerging techniques, including ultrasound-assisted extraction, microwave-assisted extraction, and supercritical fluid extraction, have demonstrated superior yields, reduced environmental impacts, and better preservation of biological activity. These innovations provide a solid foundation for integrating propolis into industrial applications while meeting safety and sustainability standards. However, optimization and scaling up remain necessary to bridge the gap between laboratory studies and industrial feasibility.

The biological properties of propolis extracts further reinforce their potential as nutraceuticals and food preservatives. Studies have demonstrated robust antimicrobial activity against bacteria, fungi, and viruses, in addition to antioxidant capacities that combat oxidative stress, thereby contributing to the prevention of chronic diseases such as diabetes, cardiovascular disorders, and cancer. Furthermore, propolis extracts modulate inflammatory pathways and support immune responses, highlighting their value as multifunctional health-promoting agents. Nevertheless, these beneficial effects are often influenced by extraction method, solvent choice, and geographical origin, which complicates the direct translation of experimental findings into practical dietary recommendations.

Bioavailability remains one of the most pressing challenges for the effective utilization of propolis-derived compounds. Evidence suggests that crude extracts exhibit superior absorption and efficacy compared to isolated compounds, underscoring the importance of preserving chemical complexity. Still, digestive conditions can compromise compound stability, limiting systemic delivery. Encapsulation technologies, including microencapsulation, nanoencapsulation, and emulsion-based systems, have emerged as promising strategies to overcome these limitations. By protecting sensitive compounds from degra-

dation, enhancing solubility, and masking undesirable sensory properties, encapsulation has the potential to expand the applicability of propolis in various food matrices while ensuring consistent bioactive delivery.

The applications of propolis in food systems demonstrate its versatility. Incorporation into meat, dairy products, beverages, fruits, and bakery items has been shown to extend shelf life, inhibit microbial growth, prevent lipid oxidation, and enhance nutritional quality. Moreover, encapsulated formulations have addressed the sensory challenges associated with their pungent taste and aroma, making them a viable alternative to synthetic preservatives, such as nitrites. These findings underscore the dual role of propolis as both a functional food ingredient and a contributor to food safety and sustainability. However, balancing efficacy with consumer acceptability and cost-effectiveness remains a key challenge for the broader commercialization of these products.

Despite its vast potential, restrictions regarding human consumption must be carefully considered. Allergic reactions, particularly in individuals sensitive to bee products, remain a significant safety concern. In addition, variations in composition complicate the establishment of universal dosage guidelines, although current evidence suggests a tolerable intake of approximately 70 mg per day. Reports of rare adverse effects, as well as potential interactions with pharmacological agents such as anticoagulants, highlight the need for cautious and medically supervised use, especially among vulnerable populations such as pregnant women, children, and patients with chronic conditions. Regulatory frameworks should therefore emphasize quality control, standardized labeling, and safety testing to ensure that health benefits are maximized without compromising consumer well-being.

Overall, *Apis mellifera* propolis stands at the intersection of traditional medicine and modern food science, embodying both opportunities and challenges. Its multifunctionality, rooted in its rich chemical profile, offers valuable prospects for the development of functional foods, nutraceuticals, and natural preservatives. However, its successful integration into food systems and therapeutic strategies depends on advancing research in extraction and encapsulation technologies, addressing variability and safety concerns, and promoting regulatory harmonization. By doing so, propolis can be transformed from a traditional bee product into a scientifically validated, globally accessible ingredient that enhances both human health and the sustainability of food production systems.

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