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An Overview of the Antimicrobial Activities of Encapsulated Bee Products

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Abstract: Throughout history, bee products have been recognized for their remarkable bioactive properties, particularly their antibacterial capabilities. Honey, royal jelly, propolis, bee venom, and bee pollen are among the most notable substances exhibiting exceptional biological properties. Bee products contain biologically active substances naturally rich in antimicrobial components such as pollen, propolis, and honey. However, encapsulation methods, such as micro or nano-sized encapsulation techniques, are required to harness these ingredients in food applications effectively. Encapsulation enhances the stability of the biologically active components of bee products, ensuring their controlled release and significantly increasing the resistance of food products to microbial spoilage. In the last few years, techniques for encapsulation have become a practical way to enhance the durability and absorption of beneficial substances present in bee products.

In conclusion, the review underscores the substantial potential of encapsulated bee products in various domains, including food preservation, owing to their enhanced antimicrobial properties. Encapsulation techniques ensure bioactive components' stability and controlled release, significantly bolstering resistance against microbial spoilage. As the global challenge of antimicrobial resistance continues to escalate, additional exploration and advancement in this field are crucial for harnessing the full antimicrobial potential of encapsulated bee products and contributing to advancements in public health standards.

Keywords: Bee products, encapsulation, encapsulated bee products, antimicrobial activity.

Enkapsüle Arı Ürünlerinin Antimikrobiyal Aktivitelerine Genel Bakış

Özet: Tarih boyunca arı ürünleri, özellikle antibakteriyal yetenekleri olmak üzere dikkat çeken biyoaktif özellikleriyle tanınmıştır. Bal, arı sütü, propolis, arı zehri ve arı poleni gibi ürünler, dikkate değer biyolojik aktiviteler sergileyen en öne çıkan arı ürünlerindendir. Bu ürünler, doğal olarak antimikrobiyal bileşenler açısından zengin biyolojik aktif maddeler içerir. Ancak bu bileşenlerin gıda uygulamalarında etkili bir şekilde kullanılabilmesi için mikro veya nano boyutlu kapsülleme teknikleri gibi yöntemlerin kullanılması gerekmektedir. Kapsülleme, arı ürünlerinin biyolojik olarak aktif bileşenlerinin stabilitesini artırır, bileşenlerin kontrollü salınımını sağlar ve gıda ürünlerinin mikrobiyal bozulmaya karşı direncini önemli ölçüde güçlendirir. Son yıllarda enkapsülasyon teknikleri, arı ürünlerinde bulunan faydalı bileşenlerin dayanıklılığını ve biyoyararlanımını artırmanın pratik bir yolu olarak öne çıkmıştır.

Bu derleme, enkapsüle edilmiş arı ürünlerinin artırılmış antimikrobiyal özellikleri sayesinde gıda muhafazası gibi farklı alanlardaki potansiyelini vurgulamaktadır. Enkapsülasyon teknikleri, biyoaktif bileşenlerin stabilitesini sağlayarak ve kontrollü salınımını mümkün kılarak mikrobiyal bozulmaya karşı direnci önemli ölçüde artırmaktadır. Antimikrobiyal dirençle ilgili küresel zorluklar artmaya devam ederken, bu alanda daha fazla araştırma ve ilerleme yapılması, kapsüllenmiş arı ürünlerinin antimikrobiyal potansiyelini tam anlamıyla değerlendirmek ve halk sağlığı standartlarına katkıda bulunmak açısından büyük önem taşımaktadır.

Anahtar Kelimeler: Arı ürünleri, enkapsülasyon, enkpasüle edilmiş arı ürünleri, antimikrobiyal aktivite.

Review

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1. Introduction

For centuries, bee-derived products have been esteemed for their numerous bioactive qualities, encompassing both antibacterial and antioxidant capabilities. Propolis, bee venom, honey, and bee pollen are some substances that stand out for their exceptional biological properties. The most widely recognized bee product is honey, which has several uses in medicine, nutrition, and cosmetics and is a natural sweetener (Visweswara et al., 2017). Worker bees secrete a milky substance called royal jelly, which is notable for its high nutritional value and possible health benefits (Bogdanov, 2009). It is also believed to have anti-aging and immune-boosting characteristics. Because of its emollient, protective, and preservation qualities, beeswax finds extensive use in the food, pharmaceutical, and cosmetics sectors. Bees gather resinous material known as propolis from tree buds and sap. It is used in traditional medicine and health supplements because it has antibacterial, antioxidant, and anti-inflammatory qualities. Bees collect pollen and utilize it as a source of protein (El Ghouizi et al., 2023). It is prized for its high nutritional content, which includes vital amino acids, vitamins, minerals, and antioxidants. These elements may be used in functional meals and dietary supplements. The complicated process by which these bee products are synthesized inside the hive is a testament to honeybee biology's incredible complexity and inventiveness, providing a wealth of opportunities for study, innovation, and application in various fields.

Bee products contain biologically active substances rich in natural antimicrobial components, such as pollen, propolis, and honey. However, for these ingredients to be used effectively in foods, encapsulation methods, that is, micro or nano-sized encapsulation techniques, are required. Encapsulation increases the stability of the biologically active components of bee products, ensures their controlled release, and thus significantly increases the resistance of food products to microbial spoilage. Honey is an excellent opportunity to replace sugar healthily, and propolis's significant antioxidants and antibacterial qualities may be further improved by microencapsulating it (Yupanqui Mieles et al., 2022). Pollen is a food that may be used in a wide range of goods. Furthermore, the quality and preservation of ecologically friendly meals have significantly improved over time thanks to the inclusion of beeswax in oleo gels and its usage as a coating.

Encapsulation methods have been a viable approach to improving the stability and bioavailability of bioactive chemicals found in bee products in recent years (Shahidi and Han, 1993). Encapsulation protects delicate substances, permitting targeted delivery and controlled release. Microencapsulation is an excellent method that extends shelf life by covering up unwanted odours and flavours. It pertains to the containment of small particles, liquids, or gases within a protective barrier to safeguard them from external influences such as water and heat.

Various encapsulation techniques are used to maintain the bioactivity of bee products. Shahidi & Han (1993) states that starch, starch derivatives, proteins, gums, lipids, or any combination can be utilized as encapsulating or wall components. Spray-drying, freeze-drying, fluidized bed coating, extrusion, cocrystallization, molecular inclusion, and coacervation are techniques used to encapsulate food components (Mohammed et al., 2020).

The antibacterial properties of bee products, especially those encapsulated, are of significant interest for various uses, such as cosmetics, medications, and food preservation. Antimicrobial qualities are essential to tackle the rising problem of germ resistance and uphold public health standards. This review aimed to examine the antimicrobial effects of bee product encapsulation since, to our knowledge, a publication has yet to review the numerous research on the antimicrobial effects of encapsulated bee products.

2. Bee Products and Their Antimicrobial Activities

In medical care, bee products' antibacterial properties have garnered more attention lately. This review looked at the possible impacts of bee products on bacteria, specifically focusing on how encapsulating these products may increase their antimicrobial qualities. Products, including honey, propolis, and royal jelly, were also evaluated. Al-Waili et al. (2012) investigated the potential synergistic effect between propolis and honey regarding their antibacterial properties. Their research, conducted using honey sourced from Saudi Arabia and Egypt, supported the notion that the combined use of propolis and honey amplifies their antimicrobial efficacy against *Staphylococcus aureus* and *Escherichia coli.*

Different bee products exhibit varying effectiveness against Gram-positive and Gram-negative bacteria, yeasts, molds, dermatophytes, and biofilm-forming microorganisms. Notably, *Pseudomonas aeruginosa* demonstrates significant resistance to bee products. Analysis of the average minimum inhibitory concentration (MIC) values indicates that bee venom displays the most potent antibacterial activity, while royal jelly exhibits the weakest effectiveness. Using bee products for medical purposes presents challenges related to dosage and safety. These products' complex and variable composition necessitates standardization before achieving safe and predictable clinical applications (Ratajczak et al., 2021).

2.1 Propolis

Propolis is a natural resinous blend crafted by honeybees from materials gathered from various plant sources, making it significant in both food and health contexts (Günhan et al., 2022). Raw propolis comprises roughly 50% resins, 30% waxes, 10% essential oils, 5% pollen, and 5% other organic components (Burdock, 1998). Gabrys et al. (1986) found propolis rich in proline and arginine, critical components of cationic antimicrobial peptides. These peptides are known for their broad-spectrum antimicrobial properties, capable of inhibiting bacteria, fungi, viruses, and protozoan parasites. Gao et al. (2008) discovered that pinocembrin (5,7-dihydroxy flavanone) is a compound in high levels of propolis. Pinocembrin is the predominant flavonoid in propolis and has been demonstrated to be the agent behind its antimicrobial properties. Propolis is a rich source of esters and cinnamic acid because it is made chiefly of plant exudate. Hydroxycinnamic acid has been shown in numerous studies to have antimicrobial properties against a variety of microorganisms, including *Streptococcus pyogenes, Micrococcus flavus, Pseudomonas aeruginosa, Salmonella enterica* serotype Typhimurium*, Enterobacter cloacae, Escherichia coli, Listeria monocytogenes, Mycobacterium tuberculosis, Bacillus* spp., and *Staphylococcus* spp. (Yilmaz et al., 2018). Propolis has such a robust antimicrobial effect that the London pharmacopeias of the seventeenth century approved it as a medication.

Disc diffusion is one of the most often utilized techniques for determining antibacterial activity. Agar-based plates are infected by evenly distributing a suspension of an effective indicator bacterium across their surface, followed by the placement of blank paper discs holding the sample that will be examined for antimicrobial activity on top. Following ideal temperature incubation, the diameter of the growth inhibition zones around the disc is used to assess antibacterial effectiveness (Kujumgiev et al., 1999). Propolis's antibacterial capabilities have been studied, and the results confirm that the substance is primarily active against Gram-positive bacteria and either completely inert or has minimal action against Gram-negative bacteria (Yaghoubi et al., 2007).

2.2 Pollen

In addition to propolis, pollen is another bee product with remarkable biological properties. Pollen is the male reproductive cell that carries the reproductive cells of flowers and is vital for the reproduction of plants. It is also a nutritious food source for humans. Pollen contains many nutrients such as vitamins, minerals, proteins, and antioxidants and is thought to affect health positively. For this reason, pollen is a frequently used and well-known functional food. About 50% of pollen comprises polysaccharides, 1-20% of fats and lipids, 6-28% of protein, 6% of amino acids, and 4-60% of simple sugars. Terpenes, carotenoids, and flavonoids are also some of the secondary plant products (Kadı Hızır, 2019). Exosome-like vesicles, polyphenols, fatty acids, and alkaloids give pollen an antimicrobial effect (Didaras et al., 2020). Pollen contains flavonoids (1.4%), primarily kaempferol, isorhamnetin, and quercetin, and 0.2% of it contains phenolic acids, which are chlorogenic (Ramnath et al., 2013). The collection of pollen and pollen products from bees has managed benign prostatitis and the oral desensitization of allergic children effectively (Campos, 1997; Mizrahi, 1997). Furthermore, bee pollen exhibits antimicrobial properties (Kacániová et al., 2012).

The active compounds derived from the Greek pollen under investigation and the individual flavonoids isolated from it were assessed for their ability to inhibit the growth of six Gram-negative and Gram-positive bacteria and three different pathogenic fungi. The findings, detailed in Table 1, indicated that the dichloromethane extract exhibited minimal activity. In contrast, the methanol and aqueous extracts demonstrated noteworthy antibacterial effects, particularly against Gram-positive bacteria (with MIC values ranging from 0.50 to 0.80 mg/mL). The examined extracts and isolated flavonoids displayed varying levels of antifungal activity, with MIC values ranging from 3.00 to 5.95 mg/mL. The isolated flavonoids exhibited strong antimicrobial activity against Gram-positive bacteria. Among the tested bacterial strains*, E. coli* demonstrated the highest resistance, impervious to all the examined extracts and isolated compounds. The observed antimicrobial potency of the methanolic and water pollen extracts can be primarily attributed to their substantial flavonoid content, particularly the presence of quercetin and kaempferol glucosides, renowned for their antibacterial efficacy (Loizzo et al., 2004). Furthermore, the literature suggests that the antimicrobial activity of pollen extracts, especially against human pathogenic bacteria and fungi, has been infrequently investigated. Among the existing studies, the extract of Turkish bee pollen has been reported to exhibit potent antibacterial activity against plant pathogenic bacteria while displaying weaker activity against food-related microorganisms (Graikou et al., 2011).

2.3 Bee Venom

Moving from pollen to another potent bee product, bee venom is a highly complex mixture of peptides, enzymes, and amines. It is well-recognized that bee venom has antibacterial, anti-inflammatory, neuroprotective, and anticancer properties. It has been demonstrated that bee venom has antimicrobial capabilities against bacteria, viruses, and fungi both *in vitro* and *in vivo*. There have also been reports of bee venom and antibiotics having synergistic therapeutic interactions. Moreover, bee venom has demonstrated trypanocidal action and seems to shield neurons against prion peptide-induced cell death (Didaras et al., 2020).

Bee venom demonstrates antibacterial properties against both gram-positive and gram-negative bacteria owing to its diverse composition of peptides, amines, phospholipids, volatile compounds, aminocytes, sugars, and enzymes (Carpena et al., 2020). Melittin, apamin, and phospholipase C are the fundamental constituents responsible for these properties. The presence of active ingredients in bee venom that induce the formation of pores in cell membranes and the destruction of membrane phospholipids underscores its significance as an antibacterial agent (Funayama et al., 2012; Gökmen et al., 2023).

2.4 Beeswax

Building upon the wide range of antimicrobial properties seen in bee venom, another notable bee product with significant potential is beeswax. Beeswax is a naturally occurring compound consisting of esters (67 wt%), hydrocarbons (14 wt%), fatty acids (12 wt%), alcohol (1 wt%), and various other chemicals, such as aromatic compounds and colors (6 wt%) (Fratini, 2016). Beeswax has been shown to possess antibacterial properties against a variety of microorganisms, including molds from *Aspergillus* and *Geotrichum,* yeast from the genera *Rhodotorula* and *Candida*, and bacteria from the genera of *Bacillus, Escherichia, Listeria, Proteus, Pseudomonas, Salmonella,* and *Staphylococcus* (Kacániová, Vuković et al., 2012). Beeswax has moisturizing and emollient properties that can help reduce skin water loss. Squalene, 10-hydroxy-trans-2-decenoic acid, and flavonoids like chrysin are some of the components that give it antibacterial activity, the capacity to protect the skin from pathogenic microorganisms, and the ability to reduce trans-epidermal water loss. This product's antibacterial properties come from the inclusion of squalene, 10-hydroxy-trans-2-decenoic acid, and flavonoids (chrysin) found in beeswax, which shield the skin from pathogenic microorganisms (Gupta & Anjali, 2023).

Beeswax is a very versatile substance suitable for human skin. It is used in textiles, candles, cosmetic, and pharmaceutical industries. Some studies suggest that it may even be beneficial for eczema. Beeswax is the material that makes up the structure of a honeycomb, secreted by bees to construct the cells that hold honey (Fratini et al., 2016a). Beeswax is employed as a coating for cheese during the maturation process or as a dietary supplement to enhance the luster of food products.is used as a film to wrap cheese for maturing or as a food additive (E901) to give the product shine (Fratini ,2016).

Up to the advent of modern medicine, honey was used as a wound treatment in traditional medicine. New medications are required to battle diseases due to the growth in antibiotic resistance worldwide. As a result, there is renewed interest in evaluating honey's antimicrobial and wound-healing properties. Honey has been found to inhibit various bacteria, including antibiotic-resistant strains and biofilms (Yupanqui Mieles et al., 2022). It contains bioactive molecules such as flavonoids and polyphenols, which act as antioxidants. These molecules enable honey to exhibit antioxidant, antimicrobial, anti-inflammatory, antiproliferative, anticancer, and antimetastatic effects. Growing evidence supports using honey in managing and treating wounds, diabetes mellitus, cancer, asthma, cardiovascular, neurological, and gastrointestinal diseases (Samarghandian et al., 2017).

Using an agar diffusion assay, the antifungal activity of many kinds of honey against dermatophytes were assessed. The strongest effectiveness against *Trichophyton rubrum* and *Trichophyton mentagrophytes* was demonstrated by Agastache honey at a 40% concentration, according to the findings. It had an impact ranging from 20 to 10 mm on *T. mentagrophytes* and 19.5 to 12 mm on *T. rubrum*. On the other hand, tea tree honey had a less noticeable effect on dermatophytes. Manuka honey had limited activity against *T. mentagrophytes* and no discernible impact on *T. rubrum*. Other honeys, such as jelly bush, super manuka, and jarrah, showed no antifungal activity against the tested dermatophyte isolates.

3. Encapsulation Techniques Used in Bee Products

Encapsulation serves as a crucial method to enhance the stability, bioavailability, and overall efficacy of bee products. To prevent the breakdown of bioactive substances found in products like propolis, bee pollen, and royal jelly and to enable their targeted distribution within the human body, a variety of encapsulating techniques have been developed. From liposome encapsulation, which increases the bioavailability of sensitive substances, to spray drying, which effectively retains active components by quick water removal, each process has specific benefits and uses. In addition, techniques like coacervation and microencapsulation offer extra defenses and regulated release, guaranteeing the effectiveness of these priceless natural ingredients. The main encapsulation methods used in bee products are reviewed in this section along with their benefits, mechanics, and applications in food and medicine. (Fernandes et al., 2014)

3.1. Spray Drying

Spray drying stands out as one of the most efficient methods for quickly preserving liquid bee products by exposing them to fine spray in a hot air stream. This technique allows the preservation of products such as propolis and bee pollen in microcapsules. It provides rapid water removal without exposure to high temperatures, which helps preserve bioactive components. Additionally, microcapsules produced by spray drying extend shelf life and remain stable during storage and transportation. Spray drying has been demonstrated to be more effective than freeze-drying for the encapsulation of oils, despite the heat energy required in the process (Mohammed et al., 2020).

3.2. Liposome Encapsulation

Moving from physical methods of encapsulation, another highly efficient encapsulation method is liposome encapsulation. Liposomes are vesicles composed of phospholipid bilayers surrounding biologically active components. Liposome encapsulation protects and increases the bioavailability of flavonoid and phenolic compounds in bee products. This technique protects the flavonoids and phenolic components of propolis and other bee products from oxidation and effectively transports them to target areas throughout the digestive tract. Liposomes offer an ideal encapsulation environment to achieve a controlled release of biomolecules (Mozafari, Johnson, Hatziantoniou, & Demetzos, 2008). These days, lipid-oriented encapsulation techniques are thought to be the best option for encasing delicate ingredients. These techniques concentrate on foods and dietary supplements that contain both hydrophilic and hydrophobic molecules in addition to bioactive compounds, and food ingredients that are supplemental systems for medicinal purposes (Subramani et al., 2020).

3.3. Microencapsulation

As another common encapsulation method, microencapsulation serves to enclose active ingredients in tiny capsules, protecting the nutritional and bioactive properties of bee products. This method is advantageous for products like bee pollen and propolis as it allows for targeted release in the gastrointestinal tract. Additionally, microencapsulation enhances the sensory properties of products and significantly extends their shelf life, making it a preferred method in both the food and pharmaceutical industries (Bakry et al., 2016).

3.4. Coacervation

Following microencapsulation, coacervation represents another important technique, particularly for encapsulating proteins and polysaccharides in bee products. Coacervation helps stabilize these bioactive compounds, providing protection from environmental factors and ensuring their controlled release. Compared to spray drying, coacervation offers a higher encapsulation efficiency and more precise control over the release of core materials, making it especially useful for thermolabile components (Wang et al., 2018).

3.5. Emulsion-Based Techniques

Lastly, transitioning from coacervation, emulsion-based techniques play a pivotal role in maintaining the stability of bee products in both oil and water phases. These methods are crucial for the preservation and controlled release of lipophilic components in bee products such as royal jelly and beeswax. Emulsions ensure homogeneous distribution and protect against oxidation, making them widely used in the pharmaceutical and skincare industries (Kakran et al., 2014).

4. Effects of Encapsulation on the Antimicrobial Properties of Bee Products

Encapsulated bee products possess antibacterial and antifungal effects. It is crucial to investigate their impact to create novel therapeutic agents and to promote the use of natural antibacterial resources.

Because encapsulated products maximize their interaction with microorganisms by enhancing the stability of the active components, encapsulation is an efficient technique to boost the antibacterial benefits of bee products. Nanoencapsulation of propolis can minimize the oxidation of flavonoids, thereby enhancing their longevity and effectiveness. Furthermore, the regulated and sustained release of antimicrobial compounds in encapsulated products increases their efficacy and facilitate usage. The encapsulating approach, therefore, makes it possible to employ antibacterial activity more effectively and may open an enormous variety of applications in diverse clinical settings (Günhan et al., 2022).

Table 1 presents a comprehensive overview of the various methods of encapsulating bee products. It includes details on the wall materials utilized in each method, the primary aims of the respective studies, key findings derived from the research, and the references for further reading. This summary aims to facilitate a better understanding of the diverse encapsulation techniques and their outcomes, offering valuable insights for researchers and practitioners in the field.

4.1. Propolis

Propolis has a decisive antibacterial action, but its limited solubility in water restricts its application in many other contexts. Nanocapsules, among other microcapsules, could alter propolis' solubility. Food ingredients or functional substances (core) are encapsulated in a particular material (shell) in a process known as microcapsules. Microcapsules are capable of miscibility, evaporation, reactivity, stress, and controlled release, among other things (Pang et al., 2020).

Recent studies underscore the antimicrobial potential of propolis, particularly in addressing foodborne pathogens. For example, it was demonstrated that a propolis-silver nanoparticle nanocomposite effectively inhibited the growth of bacteria responsible for foodborne illnesses, including *Escherichia coli* and *Staphylococcus aureus* (Khalil et al., 2021).

A promising anti-biofilm agent was identified in a chitosan-propolis nano-formulation, showing potential for treating infections associated with biofilm formation, particularly in surgical site infections and chronic wounds (Ong et al., 2017). Additionally, a comparative study revealed that encapsulated propolis exhibited a lesser *in vitro* impact on bacterial inhibition than its ethanolic extract, suggesting that encapsulated compounds may have delayed release from their matrix, affecting their immediate action on bacterial cell walls.

Moreover, microencapsulation of propolis extract via a complex coacervation method utilizing gelatin and gum Arabic significantly improved its antimicrobial properties, demonstrating substantial antibacterial effects against *Staphylococcus aureus* and *Listeria monocytogenes* (Nori et al., 2011). Besides, the encapsulation of propolis with cyclodextrins was explored, focusing on its physicochemical properties and antimicrobial activity. This study indicated that encapsulation methods, particularly those involving silver nanoparticles or a combination of gelatin and gum Arabic through complex coacervation, exhibited the highest inhibitory effects against common foodborne pathogens (Ferro et al., 2016; Righi et al., 2013).

The study performed by Vaseghi et al. (2024) examined the antimicrobial and antioxidant properties of propolis extracted with methylal (PM) and ethanol (PE). Their experimental design involved combining propolis with methylal and storing it for 24 hours, while ethanol extraction was performed at 37°C for 48 hours and then filtered using Whatman filter paper. The study also assessed the efficacy of chitosan-encapsulated forms of these extracts against both planktonic and biofilm-forming *Staphylococcus aureus* and *Staphylococcus epidermidis*. The results indicated that chitosan-encapsulated forms (PM-CH) at a concentration of 300 µg/mL effectively reduced bacteria viability, particularly against established biofilms, demonstrating strong antibiofilm activity over a 24-hour period. In conclusion, the investigation underscored that PM and its chitosan-encapsulated forms (PM-CH and PE-CH) possess significant antimicrobial and antioxidant properties. Notably, PM demonstrated effectiveness against both gram-positive and gram-negative bacteria, suggesting its potential as a natural antibiotic. Moreover, chitosan encapsulation appears to enhance these antimicrobial effects, although the study also cautioned about the careful handling of methylal at higher concentrations.

In another relevant study, the effects of varying concentrations of propolis (5% and 7%, w/v) combined with surfactants like poloxamer (1%, 3%, and 4%, w/v) and soy lecithin (0.25%, 0.7%, and 1%, w/v) was explored. The primary goal was to assess the anti-*Staphylococcus aureus* properties in mammary tissue while evaluating cytotoxicity on epithelial cells, specifically mammary alveolar cell-T, ultimately aiming to develop propolis nanoparticles for treating bovine mastitis (Pinheiro Machado et al., 2019).

A recent study explored the encapsulation of propolis flavonoids through liposome encapsulation using soy lecithin, aiming to evaluate the physical and chemical properties of the encapsulated flavonoids and their *in vitro* antioxidant activity. The encapsulation efficiency peaked at an 8:1 weight ratio of phosphatidylcholine to cholesterol, achieving approximately 85% efficiency (Ramli et al., 2021). A study using an emulsion method with poly(lactic-co-glycolic acid) as the encapsulating material demonstrated strong inhibition of biofilms formed by *Pseudomonas aeruginosa* and *Staphylococcus aureus* (de Mélo Silva et al., 2020).

The findings indicated that the MIC values of liposomes ranged from 256 to 128 µg/mL for fungi and from 512 to 128 µg/mL for bacteria. While blank liposomes showed no antibacterial activity, the incorporation of propolis significantly enhanced their effectiveness against microbial growth. Furthermore, all propolis samples displayed antifungal activity against *Candida albicans*, *Candida parapsilosis*, and *Candida krusei*, which are known to cause superficial and systemic infections (Aytekin et al., 2020).

In 2023, the impact of nanoencapsulation of propolis at various concentrations (0, 0.4, 0.8, 1.0, and 1.2%) within polyvinyl alcohol (PVA) nanoparticles through the electro spraying method was examined. The study evaluated the structural, physical, antioxidant, antimicrobial, and thermal properties of the encapsulated propolis. Antibacterial efficacy was evaluated using the broth dilution method, revealing that PVA nanoparticles containing propolis exhibited potent inhibitory activity against *S. aureus* at lower concentrations, while no inhibitory effect was observed against *E. coli* O157:H7.

The study concluded that the PVA nanoparticles produced through electro spraying have the potential to serve as a novel natural and bioactive agent in the food and pharmaceutical industries (Subaşı-Zarbaliyev et al., 2023).

4.2. Pollen

Encapsulation of pollen can enhance its antimicrobial effects by increasing the stability of pollen's biologically active components and increasing their effectiveness by providing controlled release. As a result, encapsulated pollen is anticipated to have more potent antibacterial properties than wild pollen. A variety of techniques have achieved pollen encapsulation. These approaches include emulsion techniques, nanoparticle technologies, complicated coacervation, spray drying, and freeze-drying. The benefits of each method for boosting pollen's antibacterial properties could vary.

A study investigating the antimicrobial and antioxidant properties of chitosan compounds encapsulated with pollen and apple cider vinegar revealed significant effectiveness against various pathogens. The research focused on two different encapsulated chitosan formulations: one designated as Chitosan Compound X (CSx) and the other as Chitosan Compound Y (CSy). According to the antibacterial analysis results, both CSx and CSy demonstrated varying levels of effectiveness against bacterial species, including *Listeria monocytogenes*, *Staphylococcus aureus*, *Escherichia coli*, and *Salmonella* Typhimurium. The most notable inhibitory effect was observed against *Listeria monocytogenes*, with the CSy compound exhibiting an inhibitory zone measured at 1134 mm². In comparison, the inhibitory zone for the CSx compound against the same bacterial species was determined to be 804 mm². Furthermore, the CSy compound, which was similarly effective against other bacteria, produced inhibitory zones of 707 mm², 314 mm², and 616 mm² against *Staphylococcus aureus*, *E. coli*, and *Salmonella* Typhimurium, respectively. These findings show that chitosan compounds enriched with pollen and apple cider vinegar, particularly the CSy formulation, exhibit strong antimicrobial properties against pathogenic bacteria. As such, these encapsulation methods could be effectively employed in food packaging materials. The encapsulation process enhances the molecular weight and antimicrobial activity of chitosan, ensuring adequate protection and use of the bioactive compounds derived from pollen (Baysal et al., 2022). To quantify the encapsulation success, the % encapsulation efficiency (%EE) formula was used. The antibacterial and surface activity characteristics of the produced CSx and CSy compounds were thoroughly examined against *Salmonella*, *E. coli*, *Staphylococcus aureus*, and *Listeria monocytogenes* using good diffusion techniques. Detailed results are provided in Table 1.

As a result, encapsulating pollen with chitosan increases its antioxidant and antibacterial activities, making pollen a more effective biomaterial. This method could increase pollen's usability in a broader range of biomedical applications and offer a potential alternative for treating various infections.

In a study on the microencapsulation of bioactive bee pollen protein hydrolysate with maltodextrin and whey protein using the spray drying method and the examination of the structural changes and stability of the resulting microcapsules treated with UV radiation as an accelerated oxidation model system, encapsulation significantly increased the strength and antioxidant capacity of the pollen over time. It has improved dramatically with whey protein concentrate and maltodextrin (Maqsoudlou et al., 2020).

Encapsulated pollen's bioactive chemicals become more stable and bioavailable over time and exhibit a more regulated and prolonged release. This implies that encapsulated pollen might be a more valuable component of functional meals and dietary supplements that support good health.

Further study assesses the effects of date pollen (*Phoenix dactylifera* L.) nanoencapsulation on fortified yogurt's functional and nutritional qualities. The study results showed that date pollen has a high potential for antioxidants, particularly catechin, and is rich in protein, carbs, minerals, unsaturated fatty acids (ω-3, ω-6, and ω-9), and phenolic compounds. Yogurt was enhanced as part of the study, utilizing date pollen in three distinct ways: grains, ethanol extract, and nano-encapsulated extract. Nanoencapsulation was a particularly effective technique for enhancing yogurt, which increased the date pollen's functional qualities. Yogurts displayed probiotic qualities and excellent Date pollen nanoencapsulation enhanced sensory and microbiological quality. These results support the viability of nanoencapsulation in food fortification procedures (El-Kholy et al., 2019).

4.3. Bee Venom

Bee venom is a natural product with many therapeutic properties, such as anti-inflammatory, analgesic, anti-cancer, and immunomodulatory. However, its direct use may be problematic because its pure form may cause side effects. Therefore, researchers have developed various methods to use bee venom more safely and effectively. One of these methods is to encapsulate bee venom. Bee venom can be encapsulated in a variety of ways. These include polymer-based encapsulation techniques, liposomes, nano emulsions, and microencapsulation. While each approach has benefits and drawbacks, bee venom may be preserved and released in a regulated manner by encapsulation, which can generally boost its medicinal effectiveness. Numerous uses exist for bee venom encapsulation. For instance, rheumatoid arthritis and other inflammatory conditions can be treated with encapsulated bee venom. It could potentially help enhance immune function and treat cancer. In dermatology and cosmetics, encapsulated bee venom is used to develop anti-aging products and acne remedies, among other things (Bava et al., 2023). Because the Poly (lactic-co-glycolic acid)-encapsulation method prevents immediate exposure to the allergen components of bee venom, such as histamine, melittin, phospholipase A, and apamin, it may be a potential approach to reduce the unpleasant side effects of bee venom (Lariviere & Melzack, 1996). Poly(lactic-co-glycolic acid is a biodegradable copolymer made from lactic acid and glycolic acid, commonly used in various biomedical applications.

4.4. Beeswax

Beeswax is commonly utilized as an encapsulation material for pharmaceuticals. It is available in stores in both white and yellow wax forms. Encapsulation processes may involve granulation, emulsion coagulation, and mechanical mixing. Beeswax's capacity to encapsulate molecules significantly enhances the controlled release of pharmaceuticals. This controlled-release feature allows certain medications to remain effective for extended periods, boosting their antibacterial properties. Beeswax delays the release of medicines, providing long-term benefits. Research indicates beeswax can be a controlled release mechanism to enhance medications' antibacterial properties and effectiveness (Kılınç and Önal, 2021). In particular, the encapsulation of drugs such as salicylate, clozapine, ranolazine, and flurbiprofen using wax has yielded significant results in slowing down the release rates of these drugs and thus ensuring longer-term effectiveness. The data obtained from encapsulation showed that the release time was prolonged, and the release rate increased as the wax concentration increased, which reveals that wax is a potential material for controlled release systems in pharmaceutical applications (Shaltooki and Farahbakhsh, 2015).

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Based on the studies mentioned, the table below illustrates the use of beeswax for encapsulating different bioactive components and the areas where these techniques are applied. Beeswax provides benefits such as improving stability, enabling controlled release, and enhancing the bioavailability of bioactive components. Many factors affect the encapsulation efficiency of beeswax. Among these, the wax type plays an important role. Different waxes have different properties and may perform differently during the encapsulation process (Janković et al., 2018). The encapsulation material is also essential; the properties of the material may affect encapsulation efficiency (Silva et al., 2018). Additionally, the encapsulation method used also has a significant impact. Different techniques may give different results (Seijo et al., 2012). The environmental conditions in which the encapsulation process takes place are also necessary. Temperature, humidity, and other factors can affect encapsulation efficiency (Fernandes et al., 2014). The ratio between wax and seed material is also essential; this ratio must be balanced. Finally, the stabilization agents used in the encapsulation process also play an indispensable role. These substances may increase or decrease encapsulation efficiency. All these factors can affect the encapsulation efficiency of the wax and should be considered to achieve the best results. When the results were evaluated, it was observed that encapsulation efficiency was most effective in the omega-3 fatty acids.

4.5. Honey

Honey has been utilized for its medicinal properties. Recent research has revealed that encapsulating honey can heighten its antibacterial effects. Mandal and Mandal's research indicated that encapsulated honey exhibited more potent antibacterial action against both Gram-positive and Gram-negative bacteria when compared to free honey (Ranneh et al., 2021). In contrast to salt encapsulation, a recent study by a new research team discovered that encapsulated honey increases the longevity of Bifidobacterium strains, well-known probiotics, in gastrointestinal simulation (Favarin 2015). Similarly, Albaridi found that encapsulation techniques like freeze-drying and spray-drying may significantly enhance honey's antibacterial qualities by shielding its bioactive components during transportation and storage (Yupanqui Mieles et., 2022). The previously discussed studies provide important insights into the enhanced antibacterial effectiveness of encapsulated honey. They also highlight the potential benefits of using encapsulation techniques to preserve and enhance honey's antimicrobial properties.

Table 1. Overview of encapsulation methods of bee products, including wall materials, key findings, and references.
Tablo 1. Duvar malzemeleri, temel bulgular ve referanslar da dahil olmak üzere arı ürünlerinin kapsülleme yöntemlerine genel bakış.

Encapsulated Product	Encapsulation Method	Wall-Materials	Findings	References
Propolis	Spray drying	Whey protein isolate and maltodextrin	With the rise in inlet air temperature and the fall in output air temperature, the moisture content and water activity of the products increased, leading to encapsulation efficiency varying between 29.79% and 99.73%	(Baysan et al., 2019)
Propolis	Emulsion	Poly (lactic-co-glycolic acid)	The nanoparticle demonstrated antimicrobial potential, with a MIC of 15.6 to 125 µg/mL.	(de Mélo Silva et al., 2020)
Propolis	Liposomes	Liposomes	The liposome's MIC values varied from 512 to 128 µg/mL for bacteria and 256 to 128 µg/mL for fungi.	(Aytekin et al., 2020)
Propolis	Hot solvent diffusion method	Soy lecithin (Lipoid S75®) and ethanol	All propolis nanoparticles demonstrated antimicrobial activity against *Staphylococcus aureus*, with a MIC ranging from 156 to 310 µg/mL. The total phenolic content encapsulation efficiency ranged from 73% to 91%.	(Pinheiro Machado et al., 2019)
Propolis	Ionic gelation	Chitosan	The nanoformulation completes bacterial growth eradication of *K. pneumoniae* within 2 hours, and the MIC is 6.25 µg/mL.	(Elnaggar et al. 2020)
Propolis	Complex coacervation	Soy protein and pectin	The microencapsulated propolis showed inhibitory effects on *S. aureus* at a concentration of 200-400 µg/mL. Free propolis also exhibited inhibitory activity against *S. aureus* at around 50-100 µg/mL concentrations.	(Nori et al., 2011)
Propolis	Spray drying	Chitosan nanoparticles	The MIC value of PM-CH for *E. coli* was 12.8 µg/mL The MIC values for *S. aureus, S. epidermidis,* and *L. monocytognes* were 2, 2.8 and 5.38 g/mL, respectively.	(Vaseghi et al., 2024)
Propolis	Ionic gelation method with modification	Chitosan nanoparticles	The solution prevented the formation of *E. faecalis* biofilm and decreased the bacteria in the biofilm by approximately 90% at a concentration of 200 µg/mL. When used on existing biofilms, the solution reduced the bacterial count by about 40% and 75% at 200 µg/mL and 300 µg/mL, respectively.	(Ong et al., 2017)
Propolis	Electrospraying method	Polyvinyl alcohol nanoparticles	PVA-NPs demonstrated strong inhibitory effects on *S. aureus* at low concentrations by broth dilution method. However, it did not show any inhibitory effects against *E. coli* O157:H7.	(Subaşı-Zarbaliyev et al., 2023)
Pollen	Freeze-drying	Chitosan	After extracting the pollen with alcohol, the total polyphenol content rose from 21.4 mg/g to 26.6 mg/g. The strongest antibacterial activity was seen for *Listeria monocytogenes.* With encapsulated compounds, 1134, 707, 314, and 616 mm^2 inhibition zones were achieved against *Salmonella, E. coli, S. aureus, and Listeria monocytogenes.*	(Baysal et al., 2022)
Honey - *Bifidobacterium*	Freeze-drying	Sodium alginate 3%	The protective effect of suspending free cells of both strains of *Bifidobacterium* in honey solutions was the same as that of simple microencapsulation with 3% sodium alginate. It is determined that *Bifidobacterium*'s *in vitro* tolerance of gastrointestinal conditions was enhanced by microencapsulation and the addition of honey. In the presence of honey, both strains of *Bifidobacterium* showed a substantial increase in cell survival under simulated gastrointestinal circumstances	(Favarin et., 2015)
Omega 3	Nanoencapsulation	Beeswax	As a result, nanoparticles demonstrated excellent stability in the face of adversity, acting as a suitable carrier with a reasonable loading capacity-all critical for using sensitive nutrients	(Shakeri et al., 2024)
Flurbiprofen	Emulsion congealing technique	Beeswax	Flurbiprofen was shown to have a high loading encapsulating efficiency ranging from 8 to 94%. According to this study, beeswax microspheres loaded with flurbiprofen can distribute drugs continuously.	(Ranjha et al., 2020)

5. Conclusion

In summary, encapsulating bee products has demonstrated a notable enhancement in their antimicrobial properties, opening new opportunities for their utilization in medicine, cosmetics, and food preservation. Encapsulation techniques ensure bioactive components' stability and controlled release, leading to increased resistance against microbial spoilage. This comprehensive review emphasizes the significance of further exploration and advancement in leveraging the antimicrobial potential of encapsulated bee products to address the challenge of antimicrobial resistance and contribute to the progression of public health standards.

As consumer interest in health-boosting foods continues to grow, bee-collected pollen and bee bread promise to serve as functional foods with significant nutritional benefits. However, a more thorough investigation is still required before concrete data backs up health claims and uses of bee bread and bee-collected pollen as sources of antimicrobials in clinical practice. As a result, the encapsulation of bee products is an area that merits further research and development. These endeavors can expand the use of bee products in healthcare and enable us to harness their healing properties more effectively.

6. Conflict of Interest

The authors do not declare any conflicts of interest.

7. References

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