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# Bioactive Potential of Apicultural Products in Dairy Science: A Critical and Comprehensive Review on Rumen Modulation and Functional Food Development

**Vittorio Lo Presti**

Veterinary Sciences Department, University of Messina, Viale Palatucci, 98168 Messina, Italy; vittorio.lopresti@unime.it; Tel.: +39-090-6766546

**Abstract**

The dairy industry is increasingly seeking natural alternatives to synthetic additives to meet the growing demand for clean-label and functional foods. Bee-derived products (BDPs), including propolis, honey, bee pollen, bee bread, and royal jelly, represent a promising class of bioactive ingredients due to their antimicrobial, antioxidant, and immunomodulatory properties. This review critically examines their integration across the dairy value chain, adopting a farm-to-product perspective. At the farm level, BDPs can modulate rumen fermentation, influence microbial populations, and contribute to improved feed efficiency and reduced enteric methane emissions. These effects may translate into modifications in milk composition and functional properties. At the processing and product levels, the incorporation of BDPs into dairy matrices such as yogurt, cheese, and fermented milk enables the development of functional foods enriched with bioactive compounds and supports probiotic viability in synbiotic systems. However, their application is associated with technological and sensory challenges, including variability in chemical composition, dose-dependent antimicrobial effects, and potential impacts on texture and flavour. By bridging animal and food science, this review highlights the multifunctional role of BDPs in enhancing sustainability, safety, and nutritional value in dairy systems, while identifying current limitations and future research directions for their effective industrial implementation.

**Keywords:** bee-derived products; propolis; rumen modulation; dairy systems; functional dairy products; dairy processing; shelf life; sustainability

## 1. Introduction

The global dairy sector is undergoing a profound transformation driven by increasing consumer demand for safe, natural, and sustainably produced foods. The transition toward clean-label products and the progressive reduction of synthetic additives and antibiotics have become central priorities in both research and industrial practice. In this context, the identification of natural bioactive compounds capable of improving both animal performance and product quality has emerged as a key research priority.

Among the various natural resources currently being investigated to address these challenges, BDPs have attracted increasing attention due to their unique combination of antimicrobial, antioxidant, anti-inflammatory, and functional properties. Unlike conventional feed additives or synthetic preservatives, these products offer the potential to simultaneously influence animal performance, product quality, and preservation, making them particularly attractive for integrated dairy production systems. Figure 1 provides a

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schematic overview of the role of BDPs along the dairy production chain, highlighting their dual function as feed additives and functional ingredients. It illustrates the connection between rumen modulation, animal performance, and the enhancement of quality and stability in dairy products.

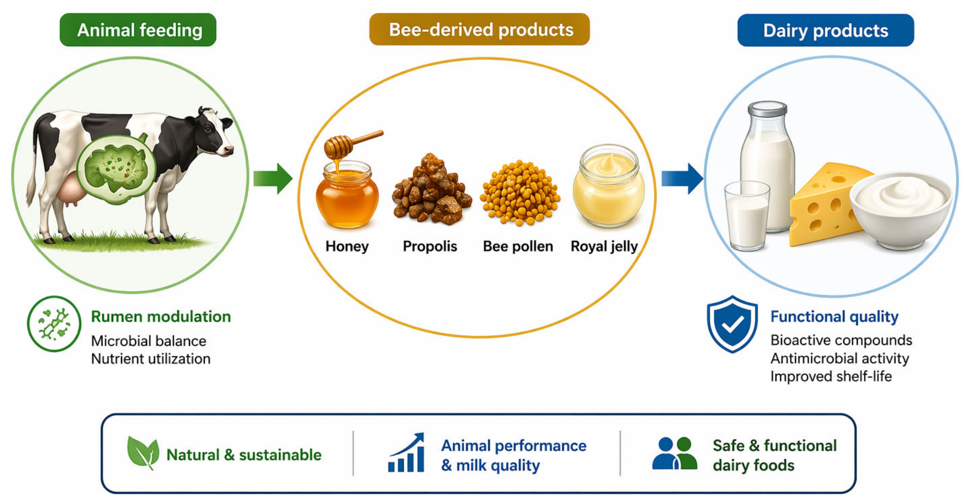


**Figure 1.** Schematic overview of the application of BDPs in dairy systems, illustrating their role in rumen modulation, animal performance, and the enhancement of quality and functionality of dairy products. Created by the author based on the studies included in this review.

As illustrated in Figure 1, the role of BDPs in dairy systems is inherently multidimensional, spanning from animal nutrition to product processing and preservation. This dual functionality requires a clear distinction between mechanisms operating at the rumen level and those affecting the physicochemical and microbiological properties of dairy products. At the same time, it highlights the need for an integrated approach capable of linking feed strategies with product quality and shelf-life outcomes.

The shift toward natural additives is further supported by international outlooks emphasizing the need for sustainable intensification and improved efficiency in dairy production systems [1]. In this framework, dairy products—particularly cheese and fermented milk—remain highly susceptible to microbial spoilage and oxidative deterioration, posing persistent challenges for food safety, shelf-life extension, and product standardization [2,3].

However, the application of natural additives in dairy systems cannot be approached as a uniform strategy. BDPs—including propolis, bee pollen, royal jelly, and honey—represent chemically and functionally heterogeneous matrices, characterized by substantial differences in composition, bioactivity, and technological applicability. Their antimicrobial, antioxidant, and immunomodulatory properties are largely attributed to complex mixtures of polyphenols, flavonoids, phenolic acids, and terpenoids, whose composition is strongly influenced by botanical and geographical origin [4]. While this variability provides opportunities for functional differentiation, it also constitutes a major limitation for reproducibility, standardization, and large-scale industrial implementation. Among bee products, propolis has been the most extensively investigated, particularly due to its well-documented antimicrobial activity and its potential applications in both animal nutrition and food preservation.

From a zootechnical perspective, BDPs have been explored as phytogenic feed additives with the potential to modulate rumen fermentation and improve nutrient utilization. Experimental evidence suggests that propolis supplementation can influence ruminal microbial populations and fermentation pathways, including modifications in volatile fatty acid profiles and reductions in undesirable fermentation products, although most of these findings derive from in vitro studies or controlled experimental conditions [5]. Subsequent in vivo investigations have reported improvements in diet digestibility, microbial balance, and metabolic efficiency in ruminants, including dairy cows and small ruminants, although results remain heterogeneous and context-dependent [6,7]. These effects are particularly relevant for sustainable dairy production, where improving feed efficiency and reducing environmental impact are key objectives, but their consistency under commercial farming conditions still requires further validation.

Beyond rumen modulation, BDPs have also been associated with improvements in animal health and immune response. Their antimicrobial and anti-inflammatory properties have been investigated in mastitis control, suggesting a potential role as natural alternatives to conventional antibiotics [8]. This aspect is especially relevant in the context of antimicrobial resistance, which has intensified the search for sustainable therapeutic strategies in livestock production [9]. Nevertheless, the available evidence remains limited, often derived from experimental models or small-scale trials, and does not yet provide robust conclusions for large-scale application.

At the product level, the incorporation of BDPs into dairy matrices such as yogurt, fermented milk, and cheese has been investigated for two distinct but complementary purposes: the enhancement of technological and functional properties, and the extension of product shelf life. In terms of technological functionality, their addition has been shown to influence microbial activity, fermentation kinetics, physicochemical characteristics, and the enrichment of dairy products with bioactive compounds [10–12]. However, these effects are often accompanied by sensory challenges, as the strong flavor and aroma of certain products—particularly propolis—may negatively affect consumer acceptance, especially at higher inclusion levels.

In parallel, a rapidly expanding research area concerns the use of BDPs as natural preservation agents. Their incorporation into edible coatings, bioactive films, and active packaging systems has demonstrated antimicrobial and antifungal efficacy, contributing to shelf-life extension and improved microbial safety [3,13–15]. These approaches respond to increasing demand for sustainable preservation technologies and environmentally friendly packaging solutions. However, several technological challenges remain unresolved, including compound stability, controlled release mechanisms, and interactions with complex food matrices, which may limit their effectiveness under real processing and storage conditions [16].

Despite the growing body of research, the application of BDPs in dairy systems remains fragmented and poorly standardized. Existing studies are often focused on isolated aspects—such as rumen fermentation, antimicrobial activity, or food preservation—without adopting an integrated approach across the dairy value chain. Moreover, much of the available evidence is derived from in vitro experiments or small-scale studies, limiting its transferability to commercial production systems [5]. The intrinsic variability of BDPs, combined with the lack of standardized methodologies, further complicates data comparison and hinders the development of clear and reproducible application guidelines. In addition, economic feasibility and cost–benefit considerations remain underexplored, representing a significant barrier to industrial adoption.

In this context, this review aims to provide a critical and integrative evaluation of the bioactive potential of BDPs in dairy science, explicitly bridging animal nutrition, dairy technology, and food preservation. Specifically, it addresses their role in (i) modulating rumen fermentation and improving animal performance, (ii) enhancing milk quality and functional properties, (iii) supporting dairy processing and product development, and (iv) extending shelf life through natural preservation strategies. By integrating evidence across these domains, the review seeks to move beyond a fragmented perspective and to identify current limitations, methodological constraints, and research gaps, while outlining future directions for the effective, scalable, and sustainable use of BDPs in dairy systems.

## 2. Methodological Approach

### 2.1. Review Design and Rationale

This review was designed as a structured narrative review supported by a transparent literature identification, screening, and synthesis workflow to critically evaluate the bioactive potential of BDPs in dairy systems. The adopted approach was selected because the available evidence encompasses heterogeneous experimental designs, including in vitro rumen fermentation studies, in vivo animal trials, and technological investigations addressing dairy processing, product quality, and shelf-life extension. Such methodological diversity limits the applicability of formal meta-analytic procedures while supporting a comprehensive and integrative synthesis of the available literature.

The primary objective was not only to summarize existing evidence but also to critically examine the translational relevance of BDPs across the dairy production chain, from rumen modulation and animal performance to milk quality, dairy processing, and functional product development. Particular attention was devoted to identifying knowledge gaps, methodological limitations, and opportunities for future research and industrial implementation.

### 2.2. Search Strategy and Eligibility

A comprehensive literature search was conducted using Scopus, Web of Science, PubMed, and Google Scholar, covering studies published between 2000 and 2026, with the final search update performed in March 2026. The selected time frame was intended to capture both pioneering investigations and recent advances concerning the use of BDPs in ruminant nutrition and dairy technology.

Search strings combined bee-derived product descriptors (“propolis”, “bee pollen”, “bee bread”, “royal jelly”, “honey”, and “beeswax”) with dairy- and ruminant-related terms (“ruminant”, “dairy cow”, “sheep”, “goat”, “milk”, “mastitis”, “rumen fermentation”, “cheese”, “yogurt”, and “shelf life”) using Boolean operators. Searches conducted in Web of Science, PubMed, and Google Scholar were used to complement the evidence base, identify additional relevant studies, and verify literature coverage. Detailed export records were available for the documented Scopus searches, which constituted the primary source of bibliographic records used for screening and selection.

Bibliographic records were exported into working reference libraries and screened for duplicate entries prior to eligibility assessment. Across the documented Scopus exports, 593 records were identified. Following duplicate removal, 152 records were excluded, resulting in 441 unique records retained for subsequent relevance screening.

Peer-reviewed studies investigating BDPs in ruminant nutrition, milk production, animal health, dairy processing, product quality, shelf-life extension, or functional dairy product development were considered eligible. Both experimental studies and relevant review articles were included when they provided information directly relevant to the objectives of the present review. Conference abstracts, studies lacking sufficient methodological detail, and publications unrelated to dairy production systems were excluded.

### 2.3. Selection Process and Evidence Assessment

Screening, eligibility assessment, evidence classification, and data extraction were performed by the author. Studies retained after duplicate removal underwent title, abstract, and thematic relevance assessment, followed by full-text evaluation when considered pertinent to the scope of the review.

Additional studies were identified through backward citation tracking and manual examination of reference lists of highly relevant publications, yielding 32 supplementary records that contributed to the final evidence base.

Due to the narrative and integrative nature of the review, detailed exclusion logs and formal PRISMA exclusion counts were not prospectively recorded. Nevertheless, duplicate removal, thematic screening, and full-text relevance assessment were systematically conducted before inclusion in the final synthesis.

An implicit evidence hierarchy guided the critical appraisal of the literature. Greater weight was assigned to in vivo studies evaluating animal performance, health, and production outcomes, followed by in vitro investigations providing mechanistic insights into rumen fermentation and microbial modulation. Technological studies addressing dairy processing, preservation strategies, physicochemical quality, sensory characteristics, and functional product development were evaluated according to experimental design, reproducibility, applicability to real dairy systems, and translational relevance.

The final qualitative synthesis included 111 studies considered directly relevant to the objectives of the review. These studies collectively covered rumen fermentation, nutrient utilization, animal performance, milk quality, dairy processing, shelf-life extension, and functional dairy product development.

### 2.4. Synthesis Framework

The narrative synthesis was organized according to a progressive dairy-oriented framework linking the chemical composition and bioactive profile of BDPs with their functional implications across the dairy production chain. The framework encompasses: (i) characterization of BDPs and their bioactive constituents; (ii) modulation of rumen fermentation and nutrient utilization; (iii) effects on animal performance, health, and milk quality; (iv) applications in dairy processing systems; and (v) development of functional dairy products and shelf-life enhancement strategies.

This integrative structure enables a comprehensive evaluation of the biological, technological, and functional roles of BDPs while facilitating identification of translational opportunities and remaining knowledge gaps relevant to sustainable dairy production.

The literature identification and selection procedure adopted in the present review is summarized in Figure 2. A structured workflow was implemented to enhance methodological transparency and ensure the systematic organization of the available evidence. Bibliographic records were retrieved from multiple scientific databases, screened for relevance, evaluated through full-text assessment, and complemented by backward citation tracking. This approach enabled the integration of evidence spanning ruminant nutrition, milk quality, dairy processing, and functional dairy product development, ultimately resulting in a qualitative synthesis of studies directly relevant to the objectives of the review.

A comparative synthesis of the available evidence across different BDPs is presented in Table 1, providing a structured overview of their functional relevance along the dairy production chain and highlighting key translational gaps.

**Table 1.** Comparative evidence grading of BDPs across the dairy production chain ($n$ = 111 studies, 2000–2026).

| BDP | Rumen/Farm Level (VFA, $CH_4$, N Efficiency) | Milk Quality/Health (Yield, Mastitis) | Processing/Product (Fermentation, Shelf Life) | Overall Strength | Key Limitation(s) |
|---|---|---|---|---|---|
| Propolis | ●●● | ●●○ | ●●● | Most consistent and extensive evidence across all levels | High compositional variability; dose–response effects |

**Table 1.** *Cont.*

| BDP | Rumen/Farm Level (VFA, $CH_4$, N Efficiency) | Milk Quality/Health (Yield, Mastitis) | Processing/Product (Fermentation, Shelf Life) | Overall Strength | Key Limitation(s) |
|---|---|---|---|---|---|
| Bee Pollen | ●○○ | ●○○ | ●●○ | Moderate evidence mainly at product level | Heterogeneity; limited bioavailability |
| Bee Bread | ●○○ | ○○○ | ●●○ | Emerging evidence, mostly preliminary | Limited number of studies |
| Royal Jelly | ●○○ | ●○○ | ●●○ | Moderate but fragmented evidence | Small-scale and in vitro-dominated data |
| Honey | ○○○ | ●○○ | ●●○ | Established technological role, limited biological effects | Low functional potency |
| Beeswax | ○○○ | ○○○ | ●●● | Strong technological application (coatings/packaging) | Physical functionality only (non-bioactive) |

Note: Table 1 represents an author-generated comparative synthesis based on the qualitative evaluation of the literature dataset included in the present review ($n$ = 111 studies). The evidence levels were assigned according to the number, consistency, and type of studies available for each bee-derived product across the dairy production chain. The grading system is intended to highlight general literature trends and the relative strength of the available evidence rather than to provide precise quantitative estimates. ●●● = strong evidence (consistent findings supported by multiple in vivo studies); ●●○ = moderate evidence (mixed or context-dependent results); ●○○= limited evidence (few studies or predominantly in vitro studies); ○○○ = no available evidence. Abbreviations: VFA, volatile fatty acid; $CH_4$, Methane.

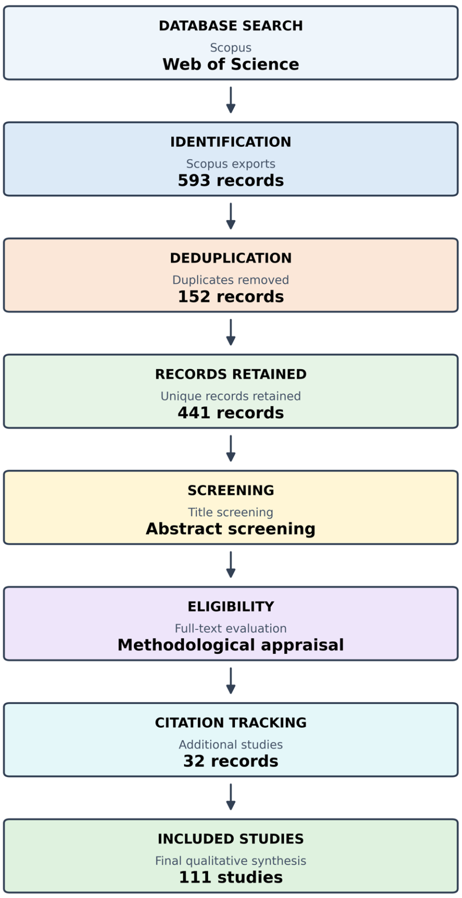


**Figure 2.** PRISMA-inspired workflow illustrating the literature identification, screening, selection, and qualitative synthesis procedures adopted in this review. Created by the author based on the studies included in this review.

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## 3. Chemical and Functional Fingerprint of Bee-Derived Products

BDPs represent highly complex natural matrices characterized by a broad diversity of primary nutrients and bioactive compounds. Their composition is strongly influenced by botanical origin, geographical conditions, bee species, and seasonal variability, resulting in substantial heterogeneity across samples. Rather than being a limitation confined to compositional description, this variability represents a key determinant of their functional behaviour, directly influencing antioxidant capacity, antimicrobial efficacy, and interactions with microbial ecosystems.

From a dairy science perspective, this intrinsic variability has important implications. It not only explains the wide range of biological activities reported in the literature but also contributes to inconsistencies among experimental results and poses significant challenges for standardization and industrial application. Therefore, understanding the chemical fingerprint of BDPs is essential to interpret their functional performance and to assess their reliability in dairy-oriented systems.

### *3.1. Major Bioactive Compounds in Bee-Derived Products*

#### 3.1.1. Propolis

Propolis is a resinous material collected by bees from plant exudates and subsequently modified through enzymatic activity. It represents the most chemically complex bee-derived product and is characterized by a high content of secondary metabolites, including flavonoids, phenolic acids and their esters, terpenes, and aromatic compounds [17,18].

A defining feature of propolis is the strong dependence of its chemical profile on botanical and geographical origin. This results in marked qualitative and quantitative variability, as exemplified by Brazilian propolis, which is particularly rich in prenylated phenolics such as artepillin C, whereas other types may contain higher proportions of flavonoids or isoflavonoids [17]. Metabolomic and chemometric analyses have further demonstrated that propolis consists of highly complex mixtures, including triterpenoids, sesquiterpenes, steroids, hydrocarbons, and phenolic compounds, with clear associations between chemical composition and biological activity [19,20].

Importantly, the biological activity of propolis cannot be attributed to individual compounds alone but arises from synergistic interactions among multiple constituents. This aspect is particularly relevant for interpreting its behaviour in biological systems and dairy applications, where matrix interactions and dose-dependent effects may significantly influence outcomes. Consequently, compositional variability is directly linked to differences in functional performance, contributing to the heterogeneous results observed in animal feeding and dairy studies [21–23].

#### 3.1.2. Bee Pollen and Bee Bread

Bee pollen is a nutritionally dense matrix consisting of flower pollen grains agglutinated with nectar and salivary secretions. It combines macronutrients—such as proteins, carbohydrates, and lipids—with a wide range of bioactive compounds, including phenolic acids and flavonoids [24,25].

Proteins represent a major component, typically accounting for 15–25% of its composition, and provide a balanced amino acid profile [4,24]. In addition, compounds such as quercetin, kaempferol, and rutin contribute significantly to its antioxidant activity [24,25]. However, as observed for other BDPs, its composition is highly dependent on botanical origin, leading to substantial variability in nutritional and functional properties [4,24].

Bee bread, obtained through microbial fermentation of pollen within the hive, represents a functionally distinct matrix. During this process, lactic acid bacteria (LAB) and yeasts transform the original pollen structure, increasing nutrient bioavailability and generating organic acids and additional bioactive compounds [4,25]. Compared with bee pollen, bee bread exhibits improved digestibility, enhanced microbial content, and a modified chemical profile.

This transformation is particularly relevant for dairy-oriented contexts, as bee bread represents a natural interface between bioactive matrices and microbial ecosystems. Its fermentation-derived composition may support microbial modulation and influence fermentation processes, making it especially promising for applications involving starter cultures and functional fermented products.

#### 3.1.3. Royal Jelly

Royal jelly is a secretion produced by the hypopharyngeal and mandibular glands of worker bees and serves as the exclusive diet of queen larvae and adult queens. It is characterized by high moisture content (60–70%) and a complex composition including proteins, lipids, carbohydrates, vitamins, and minerals [26,27].

Proteins account for approximately 50–60% of its dry matter, with major royal jelly proteins representing the dominant fraction [26,28]. Its lipid fraction is particularly distinctive, being rich in medium-chain fatty acids, especially 10-hydroxy-2-decenoic acid (10-HDA), which serves as a biomarker of authenticity and is closely associated with its biological properties [27–29].

In contrast to propolis, the bioactivity of royal jelly is more strongly associated with specific compounds and protein fractions rather than complex polyphenolic mixtures. This difference may influence its mode of action in biological systems, particularly in relation to immunomodulatory and metabolic effects. However, its composition remains sensitive to environmental conditions, harvesting practices, and potential adulteration, which may significantly affect its functional properties [29,30].

#### 3.1.4. Honey

Honey is primarily composed of carbohydrates, mainly fructose and glucose, which account for more than 80% of its composition, along with water, organic acids, enzymes, amino acids, vitamins, minerals, and minor bioactive compounds [25,31].

Although often considered primarily an energy source, honey also contains phenolic acids and flavonoids—such as caffeic acid, gallic acid, quercetin, and chrysin—that contribute to its antioxidant and functional properties [31,32]. However, its bioactivity is generally lower than that of propolis due to the lower concentration of phenolic compounds.

Its composition is highly variable and influenced by floral source, geographical origin, environmental conditions, and processing, which in turn affect its physicochemical characteristics, sensory attributes, and biological activity [32,33]. Advanced analytical techniques, including High-Performance Liquid Chromatography and Gas Chromatography–Mass Spectrometry, spectroscopic, and sensor-based approaches, are widely used to characterize its composition and verify authenticity [34,35].

From a dairy perspective, honey plays a dual role: as a natural sweetener and as a functional ingredient capable of modulating microbial activity and contributing to product stability, although its effects are strongly matrix- and dose-dependent. The antimicrobial activity of honey is mainly associated with its high sugar content, low water availability, acidity, hydrogen peroxide generation, and phenolic compounds, which may act synergistically to inhibit spoilage and pathogenic microorganisms [31,32]. However, these effects may be attenuated after dilution and in complex food matrices, while higher inclusion levels may increase antimicrobial efficacy but also affect fermentation dynamics and sensory properties [32].

#### 3.1.5. Beeswax

Beeswax is a lipid-based material composed mainly of long-chain aliphatic compounds, including esters, hydrocarbons, free fatty acids, and alcohols, which confer hydrophobicity and structural stability [25,30].

Unlike other BDPs, beeswax does not primarily act through biochemical bioactivity but through its physical and technological properties. Its hydrophobic nature makes it particularly suitable for use in edible coatings and packaging systems, where it functions as an effective barrier against moisture loss and oxygen permeability.

In dairy applications, beeswax-based coatings can contribute to shelf-life extension by limiting water loss, reducing oxygen exposure, and indirectly inhibiting microbial growth. When combined with bioactive compounds such as propolis or chitosan, beeswax-based systems can further enhance antimicrobial and antioxidant performance, providing a platform for multifunctional preservation strategies [3,13].

### *3.2. Functional Relevance in Dairy-Oriented Contexts*

#### 3.2.1. Antioxidant Potential

The antioxidant activity of BDPs is among their most extensively documented biological properties and is primarily associated with phenolic compounds, including flavonoids, phenolic acids, and related secondary metabolites [18,24,25,31]. These compounds can neutralize reactive oxygen species, chelate pro-oxidant metal ions, and inhibit lipid peroxidation processes, thereby contributing to the protection of both biological systems and food matrices from oxidative deterioration [18,36].

Among the various BDPs, propolis generally exhibits the highest antioxidant potential due to its elevated concentration of polyphenolic compounds, whereas bee pollen provides additional antioxidant activity through its complex mixture of flavonoids, carotenoids, vitamins, and other bioactive constituents [18,24,25]. Royal jelly also contributes to antioxidant protection through specific peptides, proteins, and lipid-derived compounds, including 10-HDA, which has been associated with several biological activities [26–28].

From a dairy-oriented perspective, antioxidant activity is particularly relevant because oxidative processes can negatively affect both animal physiology and product quality. Oxidative deterioration may influence the stability of lipids and other sensitive components, potentially affecting sensory characteristics, nutritional quality, and storage stability of dairy products. Consequently, the antioxidant properties of BDPs provide a biological rationale for their growing interest as natural functional ingredients in dairy production systems and value-added dairy foods [18,31,36].

#### 3.2.2. Antimicrobial Potential

BDPs exhibit broad-spectrum antimicrobial activity against bacteria, yeasts, and moulds, although the magnitude of this effect varies according to product type, botanical origin, chemical composition, and target microorganism [18,31]. Antimicrobial activity is mainly attributed to phenolic compounds, bioactive peptides, terpenoids, and other secondary metabolites capable of interfering with microbial growth and survival.

Propolis is the most extensively investigated antimicrobial bee product and generally demonstrates greater efficacy against Gram-positive bacteria, likely due to differences in cell wall structure and permeability [18]. Proposed mechanisms include membrane disruption, inhibition of enzymatic systems, interference with nucleic acid synthesis, and impairment of microbial metabolic processes [18]. Royal jelly contributes through antimicrobial peptides such as defensin-1 and other biologically active compounds, while honey and bee pollen combine multiple inhibitory factors, including acidity, osmotic pressure, hydrogen peroxide generation, and phenolic constituents [26,31].

The relevance of these antimicrobial properties extends beyond direct microbial inhibition. Within dairy systems, natural antimicrobial compounds are increasingly attracting interest as potential tools for improving microbial stability and supporting clean-label preservation strategies. Their activity against spoilage microorganisms and selected pathogens may contribute to the development of dairy products with enhanced shelf life and improved microbiological quality, although the balance between antimicrobial efficacy and the preservation of desirable fermentation microbiota remains an important consideration [18,31,36].

#### 3.2.3. Microbiological and Fermentation Relevance

Beyond their antioxidant and antimicrobial properties, several BDPs may interact with microbial ecosystems and fermentation processes, representing an important functional link between animal nutrition, dairy fermentations, and functional food development.

Bee pollen and particularly bee bread are of special interest in this regard. Bee bread is produced through the natural fermentation of pollen by LAB and yeasts, a process that enhances nutrient bioavailability and promotes the accumulation of organic acids and bioactive metabolites [25,36]. As a result, bee bread represents a biologically transformed matrix in which fermentation contributes to both nutritional enrichment and functional diversification.

The interaction between BDPs and beneficial microorganisms may also have implications for fermentation-based dairy applications. Fermentation-derived metabolites, organic acids, and bioactive compounds may support microbial activity and contribute to the stability of fermentation processes [25,36]. Furthermore, royal jelly has been reported to stimulate probiotic growth and metabolic activity under specific experimental conditions, suggesting potential applications in the development of functional fermented foods [26,27].

Collectively, these microbiological and fermentation-related properties highlight the potential of BDPs as multifunctional ingredients capable of linking bioactive composition, microbial ecology, and food functionality. Although current evidence remains heterogeneous and product standardization is still limited, the available literature suggests that BDPs may represent promising components for future dairy innovations, particularly in the area of functional and fermented dairy products [25–27,36,37].

BDPs exhibit distinct chemical profiles that determine their functional roles [23]. Propolis is characterized by a high content of phenolic compounds and represents the most bioactive matrix, particularly in terms of antioxidant and antimicrobial properties. Bee pollen combines nutritional value with bioactive potential, while royal jelly is a biologically specialized secretion with unique protein and lipid components. Beeswax, in contrast, plays a predominantly structural and technological role.

These differences highlight the importance of considering each product as a distinct functional entity. Their complementary properties support diverse applications in dairy systems, including nutritional enhancement, microbial modulation, product preservation, and technological innovation. An overview of their main chemical and functional characteristics is provided in Table 2.

**Table 2.** Chemical composition, key bioactive compounds, biological activities of BDPs.

| Bee Product | Main Components | Key Bioactive Compounds | Biological Activities (Mechanisms) | References |
|---|---|---|---|---|
| Propolis | Resins (~50%), wax (~30%), essential oils (~10%), pollen fractions | Flavonoids, phenolic acids, CAPE, terpenoids | ROS scavenging, lipid peroxidation inhibition, membrane disruption, enzyme inhibition, anti-inflammatory, immunomodulatory | [17,18,21–23,38] |

**Table 2.** *Cont.*

| Bee Product | Main Components | Key Bioactive Compounds | Biological Activities (Mechanisms) | References |
|---|---|---|---|---|
| Bee Pollen | Proteins (15–25%), carbohydrates, lipids, fibre, vitamins, minerals | Polyphenols, flavonoids, carotenoids | Antioxidant, antimicrobial, nutritional support | [4,24,25] |
| Bee Bread | Fermented pollen, organic acids, enzymes | LAB, peptides, organic acids | Enhanced bioavailability, antioxidant, probiotic-like activity | [36] |
| Royal Jelly | Proteins (MRJPs), lipids, sugars, vitamins, minerals | 10-HDA, MRJPs, antimicrobial peptides | Antimicrobial, immunomodulatory, metabolic regulation, antioxidant | [26–29,39] |
| Honey | Sugars (glucose, fructose), organic acids, enzymes | Phenolics, oligosaccharides | Antioxidant activity, antimicrobial effects (osmotic pressure, acidity), mild prebiotic activity | [12,32] |
| Beeswax | Hydrocarbons, esters, fatty acids, alcohols | Minor phenolics | Physical barrier effect (moisture and oxygen), limited antimicrobial activity | [2,16,38] |

Note: Values and compositional data are intended to provide a general overview of the typical characteristics of each bee-derived product and may vary according to botanical origin, geographical source, seasonal conditions, processing methods, and analytical procedures. Biological activities are based on the predominant mechanisms reported in the literature and should be interpreted as indicative rather than absolute. Abbreviations: CAPE, caffeic acid phenethyl ester; LAB, lactic acid bacteria; MRJPs, major royal jelly proteins; 10-HDA, 10-hydroxy-2-decenoic acid; ROS, reactive oxygen species.

## 4. Bee-Derived Products in Ruminant Nutrition: Rumen Metabolism and Efficiency

BDPs have gained increasing attention as natural feed additives in ruminant nutrition due to their complex composition and multifunctional biological activities. Rich in phenolic compounds, flavonoids, peptides, and other bioactive molecules, these products have been investigated for their ability to modulate rumen fermentation, improve nutrient utilization, and influence animal performance [7,21,40]. However, their effects are strongly dependent on botanical origin, chemical composition, dosage, and dietary context, resulting in variable responses across experimental conditions [22,36].

Within ruminant systems, the rumen represents the primary site of Bee-derived product (BDP) activity. Through selective interactions with microbial populations, these compounds can alter fermentation pathways, including volatile fatty acid (VFA) production, hydrogen utilization, and methanogenesis [21,40]. These changes are particularly relevant for improving feed efficiency and reducing enteric methane emissions, a key objective in sustainable livestock production [21,41]. At the same time, shifts in microbial dynamics may affect nitrogen metabolism, with potential implications for microbial protein synthesis and nitrogen retention [22,42].

Beyond rumen-level effects, modulation of fermentation processes may translate into changes in digestibility, feed efficiency, and metabolic responses. These effects can ultimately influence milk yield, composition, and quality, although their magnitude and consistency remain variable [43,44]. In addition, the antimicrobial and antioxidant properties of BDPs suggest a potential role in supporting animal health, including the control of subclinical conditions such as mastitis [8,45].

To provide an integrated overview of these mechanisms, Figure 3 presents a schematic representation of the role of BDPs in ruminant nutrition and dairy systems. The figure summarizes the main pathways through which BDPs influence rumen metabolism, nutrient utilization, and downstream productive and health-related responses, highlighting both their potential benefits and the complexity of their biological effects.

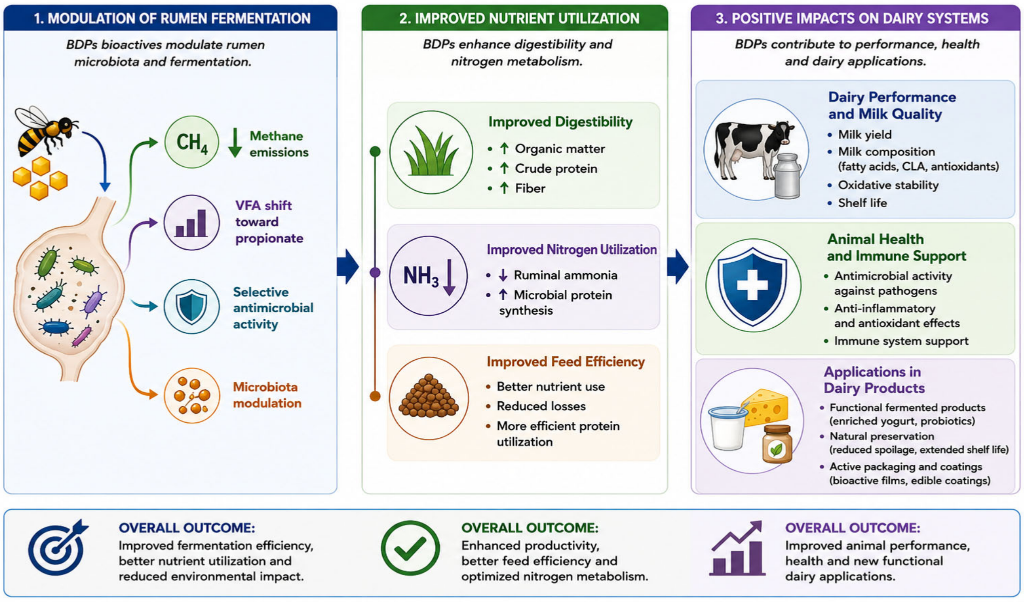


**Figure 3.** Integration of BDPs into dairy production systems and their potential effects on rumen function, milk composition, and dairy product quality. Created by the author based on the studies included in this review.

### 4.1. Modulation of Rumen Fermentation: Volatile Fatty Acid Profiles and Methane Mitigation (In Vitro vs. In Vivo Evidence)

Among BDPs, propolis is the most extensively investigated natural additive for modulating rumen fermentation. Its biological activity is mainly attributed to flavonoids, phenolic acids, and other secondary metabolites capable of selectively affecting rumen microbial populations and fermentation pathways [7,21,40].

In vitro studies consistently indicate that propolis can reduce methane production while modifying VFA profiles toward more energetically efficient patterns. Santos et al. [21] reported reduced methane emissions associated with changes in ruminal fermentation, while Ozturk et al. [40] observed alterations in microbial activity and fermentation end-products, including reduced ammonia-N concentrations. These findings are consistent with broader evidence on phytogenic additives, which mitigate enteric methane through hydrogen redirection and inhibition of methanogenic pathways [46].

From a mechanistic perspective, propolis appears to partially mimic ionophore-like activity by increasing propionate production and reducing the acetate-to-propionate ratio, thereby limiting hydrogen availability for methanogenesis [47]. This effect is supported by its selective antimicrobial activity. De Aguiar et al. [42] reported a higher susceptibility of hyper-ammonia-producing bacteria, indicating a targeted modulation of nitrogen metabolism rather than a broad inhibition of rumen microbiota.

Further evidence confirms that propolis influences ruminal nitrogen dynamics and microbial ecology. De Aguiar et al. [48] demonstrated differential bacterial tolerance to propolis and a reduction in ammonia-N concentration, suggesting improved nitrogen utilization efficiency. Similarly, propolis supplementation has been shown to reduce ruminal ammonia-N under in vitro conditions, although these effects are not always associated with increased total VFA production or overall fermentation efficiency [40].

In vivo studies generally support these mechanisms, although responses are more variable. Morsy et al. [6] reported improved digestibility, nitrogen retention, microbial protein synthesis, and reduced methane emission in ewes. In calves, Gaafar et al. [44] observed increased total VFA and key fermentation products such as acetate and propionate, together with reduced ammonia-N concentrations, indicating a shift toward more efficient rumen fermentation. Similar effects were observed in suckling Friesian calves, where propolis supplementation enhanced fermentation patterns and reduced ruminal pH [44].

However, results are not always consistent. Valero et al. [49] reported no significant effects of propolis on rumen parameters or animal performance under certain conditions, highlighting the strong influence of dosage, diet composition, and extract variability. This variability remains a major limitation for the standardization of propolis use in ruminant nutrition.

Additional in vitro evidence suggests that the response to propolis is also substrate-dependent. Coşkuntuna et al. [41] showed that propolis supplementation in sorghum-based systems increased gas production and organic matter digestibility while reducing methane production in specific cultivars, indicating interactions between propolis bioactives and plant secondary compounds.

Enteric methane production is closely linked to ruminal hydrogen metabolism. The balance among VFA plays a central role, as acetate and butyrate formation release hydrogen, whereas propionate formation acts as a competitive hydrogen sink, thereby reducing methanogenesis [50]. In this context, propolis has been shown to modulate fermentation patterns and reduce ammonia-N concentration, although its anti-methanogenic efficacy remains dependent on botanical origin and requires further in vivo validation [50].

Dose-dependent effects have also been reported. De Araujo et al. [51] observed a quadratic response to propolis inclusion, with reduced gas production and rapid fermentation fractions at intermediate levels, suggesting partial inhibition of microbial activity. At higher concentrations, this effect may limit overall digestibility, highlighting the importance of dosage optimization.

Similarly, Ehtesham et al. [52] demonstrated that increasing propolis concentrations reduced methane production, ammonia-N levels, and methanogen populations, while altering bacterial communities. Interestingly, higher inclusion levels were associated with increased total gas production, suggesting a shift in fermentation pathways rather than a simple suppression of microbial activity.

In vivo evidence also indicates that the effects of propolis may be influenced by interactions with other dietary components. Yoshimura et al. [53] reported no significant effects on rumen fermentation, digestibility, or microbial populations in dairy cows fed flaxseed oil, although an increase in conjugated linoleic acid in milk was observed, suggesting a stronger impact on milk quality than on rumen fermentation.

Additional evidence in buffaloes showed that propolis supplementation reduced *Entodinium* protozoa and modified fermentation patterns, including a quadratic increase in acetate production and a tendency toward improved microbial protein synthesis, without negatively affecting digestibility [54].

Overall, propolis supplementation consistently demonstrates the ability to modulate rumen fermentation through selective microbial interactions, particularly affecting methanogenesis and nitrogen metabolism. However, the magnitude and direction of these effects are highly variable and depend on multiple factors, including dosage, botanical origin, dietary composition, and experimental conditions, highlighting the need for standardized approaches and further in vivo validation.

### *4.2. Impact on Nutrient Digestibility and Nitrogen Balance: Bee-Derived Products as Natural Alternatives to Ionophores*

The modulation of rumen fermentation by propolis has direct implications for nutrient digestibility and nitrogen utilization. Improved nitrogen efficiency is particularly relevant in dairy systems, where it contributes to enhanced feed efficiency and reduced nitrogen excretion.

Several studies report that propolis supplementation can improve digestibility and nitrogen metabolism. Morsy et al. [6] observed increased organic matter and crude protein digestibility, higher nitrogen retention, and enhanced microbial protein synthesis in ewes. Similarly, Gaafar et al. [44] reported improvements in nutrient digestibility, rumen fermentation, and metabolic status in suckling calves, including increased total VFA, reduced ruminal ammonia-N, enhanced immunoglobulin levels, and improved growth performance. In line with these findings, green propolis extract has been shown to effectively replace ionophores such as salinomycin without negatively affecting feed intake while supporting nitrogen utilization efficiency in sheep [55].

However, responses are not consistent across studies. A recent meta-analysis reported increased average daily gain in beef cattle but no significant effects on dry matter intake or feed efficiency, highlighting the context dependency of propolis supplementation [56]. Similarly, not all improvements in nutrient utilization translate into enhanced productive performance, as also observed for other bioactive additives such as mannan oligosaccharides [57].

At the microbial level, these effects are largely associated with the inhibition of hyper-ammonia-producing bacteria, resulting in lower ammonia-N concentrations and more efficient nitrogen incorporation into microbial biomass [42]. This mechanism is functionally comparable to that of ionophores, which improve feed efficiency through targeted modulation of rumen microbial populations. Supporting this analogy, propolis supplementation has been shown to reduce lactic acid accumulation and stabilize ruminal pH under acidosis conditions [58].

Propolis has therefore been proposed as a natural alternative to antibiotic growth promoters, supported by its antimicrobial, antiprotozoal, and immunomodulatory properties [59–61]. Recent in vivo evidence further supports this role, showing that green propolis extract can effectively replace ionophore additives such as salinomycin without negatively affecting feed intake, while maintaining nutrient digestibility and improving nitrogen retention in sheep [62,63]. Its phenolic compounds can modulate rumen microbial populations, reduce ammonia-N production, and improve nutrient utilization efficiency [61]. Comparative studies suggest that its effects may partially resemble those of monensin, although generally with lower magnitude and consistency [63].

Recent in vivo evidence further supports this comparison. In lambs, propolis supplementation improved body weight, average daily gain, and feed efficiency compared to monensin-treated animals [64]. However, these improvements were not always associated with increased fermentation end-products, as lower short-chain fatty acid concentrations and higher ruminal pH were observed, suggesting a distinct mode of action. Similarly, propolis maintained nutrient utilization while avoiding the negative effects on digestibility and nitrogen retention observed with salinomycin [55].

Evidence from dairy cows indicates that propolis can modulate nitrogen metabolism and rumen microbial populations, reducing ruminal ammonia-N without affecting pH, and inducing changes in milk composition, including increased fat and lactose content, despite no effects on milk yield [65]. In transition cows, supplementation with propolis-containing bioactive mixtures improved metabolic and inflammatory status, reducing serum non-esterified fatty acids and haptoglobin concentrations and improving energy balance during early lactation [66].

These metabolic responses are closely linked to the physiological adaptation of dairy cows to stress conditions. Activation of neuroendocrine pathways, particularly the hypothalamic–pituitary–adrenal axis, can negatively affect feed intake, nutrient utilization, and immune function, while behavioral changes further influence metabolic efficiency [56,67].

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Despite these positive findings, several studies report limited or inconsistent effects. Valero et al. [49] found no improvements in digestibility or performance in bulls, while in feedlot cattle propolis supplementation did not significantly affect intake, growth, or feed efficiency and, at higher doses, even reduced performance [68]. Similarly, in neonatal lambs, no significant changes in most hematological and biochemical parameters were observed, although no adverse effects were detected [69]. These findings highlight the dose-dependent and context-specific nature of propolis responses.

Other BDPs, such as bee pollen and royal jelly, remain less investigated in ruminants. Current evidence does not yet support a well-defined role in rumen efficiency modulation [25,39]. However, emerging in vivo studies suggest that bee pollen supplementation can improve growth performance, feed conversion, and metabolic parameters in calves and heifers [70], indicating potential as a natural growth-promoting additive.

Beyond nutritional effects, propolis also exhibits relevant antimicrobial and therapeutic properties in dairy systems. In mastitic cows, intramammary propolis formulations reduced bacterial load and somatic cell count, in some cases outperforming conventional antibiotics [71]. Additional evidence highlights its antiparasitic activity, including efficacy against protozoan pathogens and helminths [72,73], as well as its clinical effectiveness in mastitis treatment [74].

Overall, BDPs—particularly propolis—modulate rumen fermentation and nitrogen metabolism through selective microbial interactions. However, their effects are often moderate and highly variable, depending on dosage, animal category, diet, and experimental conditions. Consequently, propolis should be considered a promising natural alternative to ionophores, but not yet a fully equivalent substitute. The resulting modulation of the feed–rumen–milk axis may influence not only feed efficiency but also the transfer of bioactive compounds into milk, with implications for dairy product quality and functionality.

### *4.3. Effects on Milk Yield, Composition, and Mammary Health*

Compared with rumen-related outcomes, the effects of BDPs on milk production are more variable and often indirect. Propolis does not consistently increase milk yield but can influence milk composition, oxidative stability, and animal health.

In small ruminants, Shedeed et al. [75] reported increased milk yield, milk fat, and total solids in ewes supplemented with propolis, together with improved antioxidant status and immune response. The increase in milk fat can be partially explained by changes in rumen fermentation (Section 4.1), particularly increased acetate availability, which provides key precursors for *de novo* fatty acid synthesis in the mammary gland.

In dairy cows, responses are more nuanced. Aguiar et al. [43] found no significant effects on milk yield or feed efficiency but reported modifications in milk fatty acid composition and antioxidant capacity. Similarly, Santos et al. [21] observed improved antioxidant status when propolis was combined with vitamin E, particularly under diets rich in unsaturated fatty acids.

In young animals, propolis appears to exert stronger effects on health than on growth performance. Slanzon et al. [76] reported no improvements in weight gain in preweaned calves but observed a significant reduction in diarrhea incidence and veterinary treatments. In contrast, Gaafar et al. [44] reported improvements in growth performance and feed efficiency, confirming that responses depend on management conditions and supplementation strategies.

A key aspect in dairy systems is the effect of propolis on udder health. Its antimicrobial activity against mastitis pathogens, including *Staphylococcus* spp., has been demonstrated in vitro [77]. In vivo applications, such as the intramammary formulation Apimast®, have shown increased antioxidant activity in milk [78], while more recent studies report reductions in bacterial load and improvements in immune response in subclinical mastitis [8,45].

Additional in vivo studies confirm the potential of propolis-based formulations in udder health management. Topical applications, including post-dipping formulations containing green propolis and *Aloe vera*, significantly reduced somatic cell count in dairy cows over 56 days [79]. Similarly, propolis-based emulgels showed reductions in somatic cell count, although without significant differences compared with conventional treatments, indicating moderate but promising efficacy [80]. However, limited sample size and the lack of pathogen-specific analyses highlight the need for further controlled studies under field conditions.

Beyond direct antimicrobial effects, propolis supplementation has been associated with improved oxidative status and immune response, particularly under stress conditions. Reductions in reactive oxygen species and lipid peroxidation, together with increased antioxidant enzyme activity, may indirectly support animal performance and milk quality [81].

The inclusion of BDPs in dairy diets may also influence milk composition through the transfer of bioactive compounds or their metabolites from feed to milk. This feed–milk relationship is particularly relevant for phenolic compounds, which undergo extensive ruminal transformation before absorption. Although transfer efficiency is generally low, dietary polyphenols can enhance milk antioxidant capacity and oxidative stability [82]. However, bioavailability remains highly variable and depends on factors such as chemical structure, rumen metabolism, inclusion level, and animal physiology, limiting the consistency of functional enrichment strategies [82].

In line with these observations, dietary propolis supplementation has been associated with improved fatty acid profiles and enhanced antioxidant capacity of milk [83]. Supporting evidence from dairy cows shows increased antioxidant activity, higher concentrations of phenolic compounds and flavonoids, and reduced lipid oxidation products such as propanal and hexanal [84].

More broadly, dietary modulation can influence the phytochemical and sensory profile of milk. Clarke et al. [85] demonstrated that feeding systems significantly affect volatile compounds, isoflavone content, and sensory attributes, highlighting the role of diet-derived metabolites and rumen processes in shaping milk quality.

Consistent with these findings, supplementation with other polyphenol-rich feed additives, such as citrus peel extract, has been shown to enhance antioxidant status and modify milk lipid profiles, including reductions in saturated fatty acids and increases in monounsaturated fatty acids and conjugated linoleic acid [86]. These patterns are comparable to those observed with propolis supplementation, supporting a common mechanism related to polyphenol-mediated modulation of milk composition.

Despite these promising effects, propolis supplementation does not consistently improve productive performance. For example, no significant effects on growth performance were observed in some studies, although improvements in product quality parameters, such as meat color stability, were reported [68].

Overall, BDPs, particularly propolis, can influence milk composition, oxidative stability, and animal health more consistently than milk yield. Their effects are largely mediated through rumen metabolism, systemic antioxidant responses, and the partial transfer of bioactive compounds into milk. However, high variability in responses, limited transfer efficiency, and differences in experimental conditions remain key constraints, requiring further research to optimize their application in dairy systems.

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## 5. Applications of Bee-Derived Products in Dairy Processing Systems

Following their evaluation as feed additives and modulators of rumen metabolism and animal performance, BDPs have gained increasing interest at the processing level. In dairy systems, their role extends beyond on-farm applications to their use as multifunctional ingredients capable of influencing both the nutritional profile and the technological properties of dairy products.

In particular, the incorporation of BDPs into dairy matrices—especially fermented products such as yogurt and cultured milk—creates complex interactions between bioactive compounds and microbial ecosystems. Phenolic compounds, peptides, and other secondary metabolites may affect starter cultures by modulating fermentation kinetics, acidification patterns, and microbial viability. These effects are often dose-dependent and may be either beneficial or inhibitory, highlighting the importance of optimized formulation strategies.

In addition to microbial interactions, the integration of BDPs involves relevant physicochemical and structural aspects, including interactions with milk proteins, effects on matrix stability, and modifications of texture and consistency. The intrinsic variability of BDP composition further complicates their technological application, requiring tailored approaches to ensure reproducibility and consistent product quality.

This section therefore focuses on the integration of BDPs into dairy processing systems, with particular emphasis on their effects on fermentation processes, starter cultures, and technological performance. The aim is to critically evaluate how these natural bioactive compounds can be incorporated into dairy manufacturing while maintaining process efficiency and product quality.

### *5.1. Incorporation of Bee-Derived Products into Dairy Matrices*

The incorporation of BDPs into dairy matrices represents a critical step in their technological application and largely determines their functional performance during processing. Different approaches have been explored, ranging from the direct addition of raw materials or extracts to more advanced formulation strategies aimed at improving stability, dispersibility, and bioavailability.

In liquid and semi-liquid systems, such as yogurt, fermented milk, and dairy beverages, BDPs are typically added as ethanolic or aqueous extracts, powders, or blended ingredients [10–12]. In these matrices, dispersion is generally homogeneous, and the main challenges relate to interactions between bioactive compounds and the protein gel network formed during fermentation. In contrast, in solid or semi-solid matrices such as cheese, incorporation is more complex, as BDPs may partition unevenly between curd and whey during coagulation. This distribution depends on compound hydrophobicity, affinity for milk proteins, and matrix structure, which differs substantially from acid-induced gels [2].

Among BDPs, propolis has been the most extensively investigated due to its high phenolic content. Its incorporation into yogurt has been associated with increased total phenolic content and antioxidant activity, while maintaining acceptable rheological properties and syneresis at optimized concentrations [80,87,88]. However, these effects are strongly dependent on dosage, extraction method, and matrix interactions.

From a physicochemical perspective, polyphenols in propolis and other BDPs interact with milk proteins, particularly caseins, leading to the formation of protein–polyphenol complexes. These interactions can influence structural and functional properties, including gel strength, viscosity, and water-holding capacity. At moderate levels, they may reinforce the protein network, whereas at higher concentrations they can disrupt gel formation [89]. In addition, these interactions may reduce the bioavailability of phenolic compounds, affecting the functional value of the final product.

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Other BDPs, such as honey, bee pollen, and royal jelly, play different technological roles. Honey acts primarily as a natural sweetener and fermentable substrate, supporting microbial activity and improving palatability, while bee pollen contributes nutrients and royal jelly provides bioactive peptides and lipid-derived compounds [10,12,90]. Compared with propolis, these products generally exhibit lower antimicrobial activity and therefore pose fewer constraints during fermentation.

The choice of incorporation strategy is a key factor influencing technological performance. Direct addition, although simple, may lead to limited solubility, heterogeneous distribution, and rapid interactions with microbial cells. To overcome these limitations, carrier systems and structuring agents, such as hydrocolloids, have been investigated to improve dispersion and matrix compatibility while preserving functional properties [87].

Encapsulation techniques represent a promising approach for optimizing BDP integration into dairy systems. Microencapsulation can protect bioactive compounds from degradation, modulate their interaction with the matrix, and enable controlled release during processing. This is particularly relevant for propolis, whose antimicrobial activity may interfere with fermentation. By regulating the availability of bioactive compounds, encapsulation can also influence fermentation dynamics and microbial growth [91,92].

Overall, the incorporation of BDPs into dairy matrices requires a balance between technological feasibility and functional efficacy. Appropriate formulation strategies are essential to ensure homogeneous distribution, controlled interactions with milk components, and compatibility with fermentation processes, which are discussed in the following section.

The main physicochemical interactions governing BDP incorporation into dairy matrices are schematically illustrated in Figure 4.

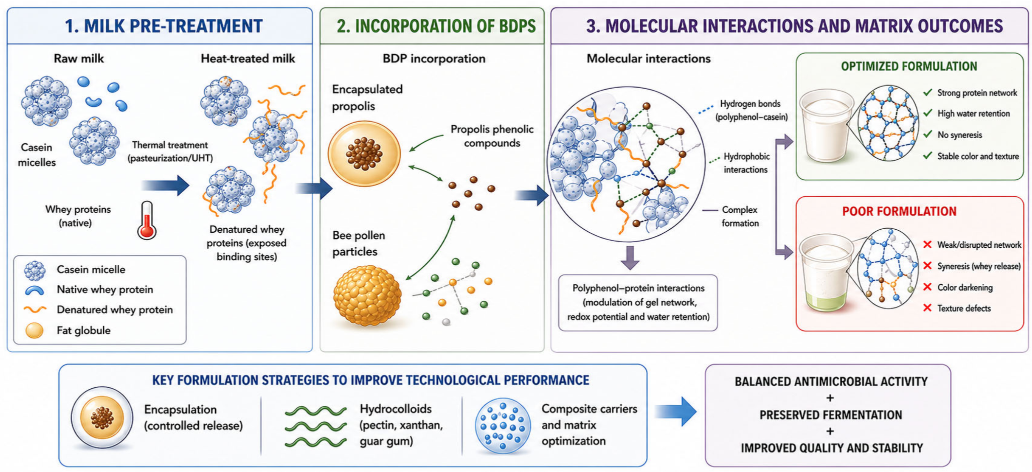


**Figure 4.** Schematic representation of the incorporation of BDPs into dairy matrices and their interactions with milk proteins, influencing gel structure, water retention, and product quality. Created by the author based on the studies included in this review.

*5.2. Effects on Fermentation Kinetics and Starter Cultures*

The interaction between BDPs and microbial cultures is a key determinant of their technological applicability in dairy processing. In fermented dairy systems, the activity of starter cultures—primarily LAB—is essential for acidification, texture development, and product stability. The addition of BDPs can significantly affect fermentation kinetics, microbial growth, and metabolic activity.

Among BDPs, propolis has been the most extensively studied due to its antimicrobial properties. Its phenolic compounds can exert selective inhibitory effects on microbial populations, directly influencing fermentation performance. In yogurt systems, propolis supplementation has been associated with reduced LAB growth and delayed acidification, leading to longer fermentation times [87]. These effects are likely related to alterations in membrane permeability, enzymatic activity, and redox balance, which collectively influence microbial metabolism. However, the response is strongly dose-dependent and reflects the balance between antimicrobial activity and microbial functionality.

The antimicrobial efficacy of propolis is also highly dependent on botanical and geographical origin, resulting in variability in phenolic composition and bioactivity. Consequently, propolis extracts from different sources may exert markedly different effects on LAB, influencing fermentation kinetics in a matrix-dependent manner. This variability highlights the need for careful selection and characterization of raw materials.

Despite its inhibitory potential, propolis does not necessarily compromise fermentation when applied at controlled concentrations. Under optimized conditions, LAB viability can be maintained during both fermentation and storage. Probiotic yogurt enriched with propolis has shown stable microbial populations over time [80], and synbiotic systems combining propolis with probiotic strains such as *Lactobacillus casei* have demonstrated sustained microbial survival depending on formulation and dosage [93].

The response of starter cultures is strain-dependent. Differential sensitivity among LAB species has been reported, with some strains exhibiting greater tolerance to phenolic compounds. This variability influences fermentation kinetics and final product characteristics, emphasizing the importance of strain selection in BDP-enriched systems [94].

In contrast to propolis, other BDPs generally show more favorable interactions with microbial cultures. Honey, due to its high content of fermentable sugars, promotes microbial growth and improves palatability. Bee pollen provides micronutrients and bioactive compounds that may stimulate microbial metabolism, while royal jelly has been associated with enhanced probiotic viability and activity [12,90,92]. These findings indicate that, unlike propolis, these products tend to support rather than inhibit fermentation.

Technological strategies are essential to modulate these interactions. Encapsulation, in particular, can reduce the direct exposure of microbial cells to bioactive compounds, enabling controlled release and mitigating inhibitory effects. Microencapsulated propolis has shown improved compatibility with starter cultures, preserving microbial viability while maintaining functional properties [91,92].

Similarly, composite formulations combining BDPs with hydrocolloids or plant-derived ingredients can reduce inhibitory effects on LAB and improve fermentation performance [87,94].

In cheese systems, BDPs are less frequently involved in fermentation and are more often applied at the product level, for example through surface treatments or edible coatings. In these cases, their antimicrobial activity primarily targets spoilage and pathogenic microorganisms rather than starter cultures, reflecting a different technological role that will be discussed in the following section.

Overall, the effects of BDPs on fermentation kinetics and starter cultures depend on a complex interplay among bioactive compound concentration, microbial strain sensitivity, and formulation strategy. Achieving a balance between antimicrobial activity and microbial functionality is essential to ensure efficient fermentation and the successful development of BDP-enriched dairy products.

### *5.3. Technological Interactions and Formulation Strategies*

The successful integration of BDPs into dairy processing systems is strongly influenced by their physicochemical interactions with milk components and by the formulation strategies adopted to ensure technological compatibility. Unlike conventional dairy ingredients, BDPs are complex matrices rich in polyphenols, peptides, sugars, and lipid-derived compounds, whose behavior in milk systems depends on solubility, polarity, and affinity for proteins and fat globules [36,89].

Processing conditions, particularly thermal treatments applied prior to BDP incorporation, play a key role in defining these interactions. Heat-induced modifications of milk proteins can promote interactions with phenolic compounds, leading to the formation of protein–polyphenol complexes and influencing the structural organization of the dairy matrix [89]. These interactions may affect colloidal stability and contribute to the retention and distribution of bioactive compounds within the system, as observed in propolis-enriched yogurt formulations [95].

A key aspect concerns the interaction between polyphenols—particularly abundant in propolis—and milk proteins. Caseins can bind phenolic compounds through hydrophobic interactions and hydrogen bonding, leading to the formation of protein–polyphenol complexes. These interactions can affect both the stability of bioactive compounds and the structural properties of the matrix. In fermented systems, they may modify gelation behavior, influencing viscosity, firmness, and water-holding capacity. Depending on concentration and processing conditions, polyphenols may either reinforce the protein network or interfere with its formation, leading to changes in product consistency [89].

The distribution of BDPs within dairy systems is also governed by solubility and partitioning behavior. Hydrophobic compounds, such as certain flavonoids and aromatic constituents of propolis, tend to associate with the fat phase or protein aggregates, whereas more polar compounds remain in the aqueous phase [89]. This partitioning affects both matrix homogeneity and the accessibility of bioactive compounds during processing, as observed in propolis-enriched dairy systems [95]. In cheese systems, it may result in uneven distribution between curd and whey, complicating formulation and process control [2].

Another critical factor is the stability of the protein network and water retention. The incorporation of particulate materials such as raw bee pollen may increase syneresis due to competition for water with the protein gel network, negatively affecting texture and visual quality [88,96]. The use of hydrocolloids and stabilizers can mitigate these effects by improving water-holding capacity and reinforcing gel structure [93].

Color stability represents an additional technological challenge. BDPs contain pigments such as carotenoids (bee pollen) and dark phenolic compounds (propolis), which may induce color changes and oxidative darkening during processing and storage, potentially affecting consumer acceptance [36,95]. Controlling pigment dispersion and oxidation is therefore essential.

Encapsulation is one of the most promising strategies for optimizing BDP integration. By entrapping bioactive compounds within protective matrices—such as proteins or polysaccharides—encapsulation improves stability, controls release, and modulates interactions with both the dairy matrix and microbial populations. This is particularly relevant for propolis, where controlled release can limit antimicrobial interference during fermentation while preserving functionality [91,92].

Beyond encapsulation, composite formulations combining BDPs with other functional ingredients offer additional opportunities. The combination of propolis with plant-derived compounds or structuring agents can reduce its inhibitory effects on fermentation and improve compatibility with dairy systems [87]. Similarly, blending BDPs with ingredients that enhance emulsification or gel stability may facilitate their incorporation into complex matrices.

From a sensory and industrial perspective, further constraints must be considered. Propolis is characterized by a bitter and astringent taste, often associated with phenolic compounds and their interactions with proteins, which may reduce consumer acceptance [12,36]. Bee pollen, if not properly micronized, can introduce a granular texture and negatively affect mouthfeel [96]. In addition, viscous or resinous extracts such as propolis may present challenges at industrial scale, particularly in terms of dosing accuracy and processing compatibility [2,95].

Despite these limitations, the rational design of formulation strategies—integrating physicochemical knowledge with technological optimization—offers significant potential to improve the incorporation of BDPs into dairy systems. A comprehensive understanding of these interactions is essential to ensure process stability and maximize the functional potential of these bioactive ingredients.

A summary of the main effects of BDPs on starter cultures, probiotic viability, and fermentation performance in dairy systems is presented in Table 3.

**Table 3.** Technological Challenges and Formulation Strategies for the Incorporation of BDPs in Dairy Processing Systems.

| Challenge | BDP Involved | Formulation/ Technological Strategy | Impact on Processing and Matrix Properties | References |
|---|---|---|---|---|
| Poor solubility and dispersion in aqueous dairy matrices | Propolis | Encapsulation; caseinate-based carriers | Improved dispersion, increased solubility, enhanced stability of phenolic compounds; reduced phase separation | [22] |
| Antimicrobial interference with starter cultures (LAB inhibition) | Propolis | Controlled dosage; microencapsulation; gradual release systems | Stabilized fermentation kinetics; maintained LAB viability; reduced delay in acidification | [93] |
| Protein–polyphenol interactions affecting gel structure | Propolis | Protein-based carriers; optimization of phenolic concentration | Formation of reversible casein–polyphenol complexes; modulation of gel strength, viscosity, and water-holding capacity | [22] |
| Gel structure destabilization at high inclusion levels | Propolis | Use of stabilizers; optimization of inclusion levels | Improved gel integrity; controlled viscosity and reduced structural weakening | [93] |
| Increased syneresis and water competition | Bee pollen | Hydrocolloids; particle size reduction | Improved water-holding capacity; reduced whey separation; enhanced texture stability | [96] |
| Variability in fermentation performance | Propolis, honey, pollen, royal jelly | Matrix-specific formulation; strain selection | Modulation of microbial growth and metabolic activity; improved fermentation control | [36] |
| Controlled release of bioactive compounds | Propolis | Micro/nano-encapsulation systems | Reduced direct antimicrobial stress on LAB; improved compatibility with fermentation processes | [22] |

**Table 3.** *Cont.*

| Challenge | BDP Involved | Formulation/ Technological Strategy | Impact on Processing and Matrix Properties | References |
|---|---|---|---|---|
| Thermal instability and interaction with denatured proteins | Propolis | Post-pasteurization addition; protective carriers | Improved retention of bioactive compounds; reduced degradation during heat treatment | [22] |
| Color changes and oxidative darkening | Propolis, bee pollen | Controlled dosage; antioxidant stabilization | Improved color stability; reduced pigment oxidation during storage | [36] |

Note: The technological challenges and formulation strategies reported in this table represent the main trends identified in the literature and may vary according to product formulation, processing conditions, starter culture composition, and dairy matrix characteristics. Abbreviations: BDP, bee-derived product; LAB, lactic acid bacteria.

## 6. Effects of Bee-Derived Products on Dairy Product Quality, Functionality and Shelf Life

At the product level, the incorporation of BDPs extends their role beyond processing, directly influencing the quality, stability, and functional properties of dairy products. Owing to their rich content of bioactive compounds, including phenolics, peptides, and micronutrients, BDPs can enhance microbial safety, delay spoilage, and contribute to the development of functional foods.

These effects are expressed within the final matrix, where BDPs interact with microbial populations and physicochemical components, influencing shelf life, texture, sensory attributes, and nutritional value. However, their performance is strongly matrix-dependent and requires careful optimization to balance technological benefits with potential impacts on product acceptability.

This section critically examines the product-level effects of BDPs, focusing on microbial safety, shelf-life extension, physicochemical and sensory properties, and functional enhancement in dairy systems.

Figure 5 summarizes the integration of BDPs into dairy systems and their resulting benefits. BDPs enhance functional properties of dairy products—such as antioxidant activity, microbial stability, and nutritional value—while contributing to improved food safety, shelf life, sensory quality, and consumer-oriented attributes, including health, sustainability, and clean-label appeal.

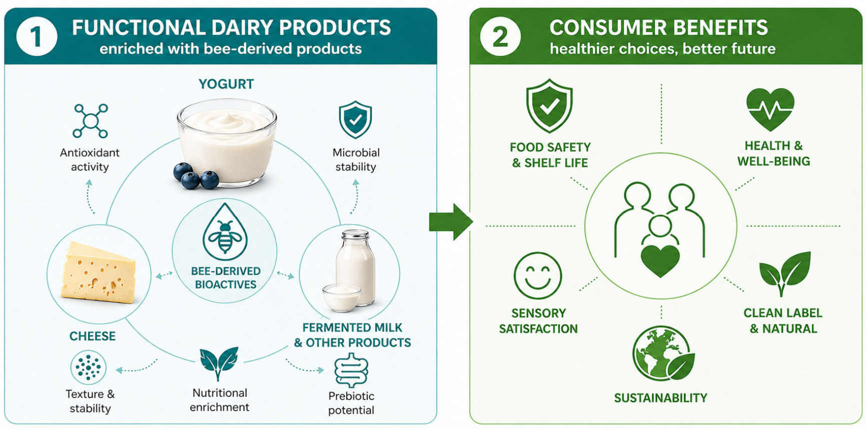


**Figure 5.** Schematic representation of the incorporation of BDPs into dairy matrices and their effects on product quality, functionality, and consumer benefits. Created by the author based on the studies included in this review.

### 6.1. Antimicrobial Activity and Shelf-Life Extension in Dairy Systems

The increasing demand for clean-label dairy products has intensified interest in natural preservatives capable of enhancing microbial safety and extending shelf life without compromising product quality. Among BDPs, propolis is the most extensively investigated due to its high content of flavonoids and phenolic acids, which underpin its broad-spectrum antimicrobial activity [36].

In liquid milk systems, propolis extracts inhibit microbial proliferation and delay spoilage, reducing total bacterial counts, coliforms, yeasts, and molds, while stabilizing physicochemical parameters such as pH during storage. These effects translate into extended shelf life compared with untreated controls. In particular, delayed coagulation and reduced acidification in raw milk indicate effective inhibition of spoilage microbiota [97].

The antimicrobial efficacy of propolis is especially relevant in fresh and minimally processed dairy products, where contamination risks are high. In whey cheese systems, propolis extracts inhibit foodborne pathogens such as *Listeria monocytogenes*, with sustained reductions in microbial counts during refrigerated storage [98].

These antimicrobial properties are further supported by in vivo veterinary evidence, where propolis and other BDPs have been successfully applied in the treatment of infections and inflammatory conditions [99].

Beyond antibacterial effects, propolis exhibits strong antifungal activity, which is critical for cheese preservation. Propolis-enriched edible films and coatings inhibit spoilage molds and yeasts and, in some cases, completely suppress fungal growth, significantly extending shelf life [13,100]. Similarly, the incorporation of red propolis into probiotic yogurt has been shown to ensure microbiological stability for up to 28 days without altering physicochemical parameters or fatty acid composition, while enhancing antioxidant activity and preserving LAB viability [95]. This dual role—as both additive and packaging component—represents a key technological advantage.

Further evidence confirms the effectiveness of propolis-based coatings. Tumbarski et al. [101] demonstrated that carboxymethyl cellulose films enriched with 1% propolis inhibited fungal growth on Kashkaval cheese for up to 56 days without negatively affecting LAB or yeasts.

In fermented systems such as yogurt, propolis reduces spoilage indicators, including total bacterial load, yeasts, molds, and coliforms [102]. However, its antimicrobial activity may also inhibit LAB depending on concentration and formulation, requiring careful optimization to preserve fermentation performance [94].

Other BDPs, including honey, bee pollen, and royal jelly, exhibit antimicrobial activity, although generally weaker and more variable. Honey acts partly through hydrogen peroxide production, but its efficacy decreases in diluted systems such as milk, while pollen and royal jelly show inconsistent preservative effects [12].

Overall, antimicrobial effects are consistently demonstrated under experimental conditions, but their magnitude and persistence are highly dependent on matrix composition, dosage, and storage conditions, limiting direct translation to industrial systems.

### 6.2. Edible Coatings and Active Packaging Systems

Following their demonstrated antimicrobial activity, BDPs—particularly propolis—have been increasingly incorporated into edible coatings and active packaging systems. In these applications, BDPs act not only as bioactive agents but also as components of delivery systems designed to improve stability and control the release of antimicrobial compounds.

Edible coatings based on alginate, chitosan, cellulose derivatives, and hydroxypropyl methylcellulose (HPMC) form protective layers on dairy products, particularly cheeses, reducing moisture loss, oxygen penetration, and microbial contamination while enabling controlled release of bioactive compounds.

Chitosan-based systems are particularly effective due to their intrinsic antimicrobial activity and synergistic interaction with propolis. Electrostatic interactions and hydrogen bonding enhance film strength and barrier properties, while potentially creating localized modified atmospheres at the product surface [3,15].

Similarly, cellulose- and HPMC- based films enriched with propolis improve oxygen and moisture barrier properties, contributing to physicochemical stability and microbial control [16,103,104].

Beeswax-based coatings play a complementary role by reducing water vapor transfer due to their hydrophobic nature, thereby limiting dehydration and structural defects in ripened cheeses [105]. In composite systems, beeswax enhances mechanical resistance and barrier performance [38].

A key advantage of these systems is the localization of antimicrobial activity at the product surface, where contamination is most likely. Propolis-enriched coatings effectively inhibit fungal growth and extend shelf life [13].

The effectiveness of these systems is strongly influenced by release kinetics and application methods. Direct coatings provide rapid antimicrobial effects, whereas incorporation into packaging materials allows more controlled and prolonged release [14].

From a sustainability perspective, BDP-based coatings offer a biodegradable alternative to petroleum-based materials, aligning with clean-label and environmentally friendly strategies.

However, industrial implementation remains limited by variability in propolis composition, challenges in large-scale processing, and potential sensory impacts at higher concentrations, as well as regulatory constraints and consumer acceptance issues.

Recent developments, including beeswax-based wraps enriched with propolis [106] and superhydrophobic coatings [107], further highlight the potential of these systems, although antimicrobial efficacy remains formulation-dependent.

### 6.3. Physicochemical and Sensory Quality of Dairy Products

The practical application of BDPs ultimately depends on their effects on physicochemical properties and consumer acceptance. Their incorporation into dairy systems significantly influences structural, rheological, and sensory characteristics, particularly in fermented products.

As discussed in Section 5, phenolic compounds—especially from propolis—interact with milk proteins, forming protein–polyphenol complexes that can either reinforce or disrupt gel structure depending on concentration [89].

BDP-enriched systems typically exhibit pseudoplastic behavior due to modifications of the protein matrix and the presence of suspended particles. Particle size is a critical factor: coarse bee pollen induces a gritty texture, whereas micronization improves homogeneity and sensory perception [96].

Water-holding capacity and syneresis are also affected. Moderate propolis levels can improve gel stability and reduce syneresis, whereas bee pollen may increase serum separation unless stabilizing strategies are applied [88].

Color changes are another important aspect. Propolis reduces lightness ($L^*$) and induces darker tones, while bee pollen increases yellowness ($b^*$) due to carotenoids. These variations reflect both sensory perception and oxidative stability [93].

From a sensory perspective, propolis is associated with bitter and astringent notes that can limit acceptability at high concentrations. However, formulation strategies—such as the use of honey as a masking agent—can mitigate these effects [12]. Moderate inclusion levels generally improve sensory properties, whereas excessive concentrations lead to off-flavours [108,109].

This dose-dependent behavior is consistent across studies. Optimal levels have been identified at approximately 7.4% for honey and 0.42% for bee pollen, while propolis is generally acceptable between 1–2% [99,109]. At lower levels ($\leq$0.5%), propolis may even improve stability without compromising sensory quality [88].

Overall, physicochemical and sensory responses are highly formulation-dependent, and sensory acceptance remains the primary limiting factor for industrial application.

### 6.4. Functional and Nutritional Enhancement

Beyond technological and antimicrobial roles, BDPs represent promising ingredients for developing functional dairy foods with enhanced nutritional value. Their composition—rich in polyphenols, flavonoids, carotenoids, vitamins, and bioactive lipids—supports antioxidant, antimicrobial, and immunomodulatory functions.

Bee pollen provides essential nutrients and antioxidant compounds [36], propolis contributes strong antioxidant activity, and royal jelly supplies bioactive molecules capable of modulating microbial metabolism [110].

In dairy systems, these compounds increase viscosity, improve texture, and enhance antioxidant capacity, as demonstrated by increased DPPH and FRAP activity [93]. Similarly, bee pollen, bee bread, and royal jelly improve structural stability and physicochemical performance [12].

BDPs can also modulate microbial activity, stimulating LAB and enhancing fermentation-derived metabolites. Increased proteolysis may promote the release of bioactive peptides with antioxidant or antihypertensive properties.

The combination with probiotic cultures supports the development of synbiotic systems, with improved microbial viability and metabolic activity [110].

Microencapsulation further enhances functionality by improving stability and controlled release of bioactive compounds. In yogurt, microencapsulated propolis increases phenolic content and antioxidant activity without compromising fermentation or microbial viability [89]. Similar results have been observed in stirred yogurt systems [91,111].

From a nutritional perspective, BDPs contribute to the enrichment of dairy products with bioactive compounds and may reduce lipid oxidation [36].

However, the bioavailability of these compounds remains insufficiently characterized, and their functional efficacy in vivo is still uncertain, particularly due to interactions with the dairy matrix and digestive processes. In addition, sensory constraints—especially for propolis—require careful optimization (see Section 6.3).

Overall, BDPs offer significant potential for functional dairy development, but their industrial application requires better understanding of bioavailability, standardization, and long-term stability.

## 7. Limitations, Challenges, and Future Perspectives

Despite the growing body of evidence supporting the integration of BDPs into dairy systems, several technical, sensory, and regulatory constraints still limit their large-scale application and industrial adoption. At the same time, these challenges represent important drivers of innovation, guiding the transition from experimental findings to scalable and optimized dairy solutions.

A key limitation lies in the complexity of the feed–rumen–milk axis. As observed for dietary polyphenols, extensive microbial transformation in the rumen can generate bioactive metabolites while simultaneously reducing the transfer of native compounds to milk. Understanding and controlling these pathways is therefore essential to maximize the functional value of dairy products derived from animals supplemented with BDPs [82].

### *7.1. Variability, Standardization, and Dose-Dependent Effects*

A major constraint is the chemical heterogeneity of BDPs, particularly propolis and bee pollen. Their composition is strongly influenced by botanical origin, geographical conditions, seasonal variability, and extraction methods, resulting in inconsistent concentrations of key bioactive compounds such as galangin, caffeic acid phenethyl ester, and p-coumaric acid [36]. This variability limits reproducibility and standardization, although it also offers opportunities for functional differentiation. The development of standardized and titrated extracts with defined levels of bioactive markers is therefore essential. However, variability in composition and extraction methods remains a major limitation for practical application [83].

In addition, the biological activity of BDPs is strongly dose-dependent. Propolis, in particular, exhibits pronounced antimicrobial properties and can modulate microbial metabolism and fermentation pathways [21,40]. While beneficial at controlled levels, excessive concentrations may impair starter cultures and probiotic viability, affecting acidification kinetics and microbial growth [93]. These findings highlight the need for precise dose optimization and a deeper understanding of molecular interactions between bioactive compounds and microbial systems.

### *7.2. Technological and Sensory Constraints*

From a technological perspective, the incorporation of resinous and hydrophobic compounds into aqueous dairy matrices remains challenging. Poor solubility and dispersion may lead to phase separation and instability, while interactions between polyphenols and milk proteins can affect solubility, structural stability, and release behavior [89]. Processing conditions such as heat treatment and fermentation further influence the stability of bioactive compounds.

Sensory characteristics represent an additional critical limitation. High inclusion levels of propolis or bee pollen may impart bitterness, astringency, and persistent off-flavors, reducing consumer acceptance. Similar effects have been reported in pollen-enriched dairy beverages [96]. These constraints have driven the development of advanced formulation strategies, including encapsulation and controlled-release systems, as well as the use of complementary ingredients to improve flavor balance.

### *7.3. Application, Process Integration, and Sustainability Challenges*

The application of BDPs in edible coatings and active packaging systems represents an important technological opportunity but also introduces additional challenges. Propolis-based coatings have demonstrated effectiveness in improving microbial safety and extending shelf life [105], although they may also affect texture, microstructure, and sensory properties. More broadly, the direct incorporation of natural antimicrobials can alter physicochemical and sensory attributes if not properly formulated [2,16].

From an industrial perspective, scalability and process integration remain critical issues. The incorporation of BDPs requires compatibility with existing processing lines and consistent performance across batches. At the same time, sustainability considerations—including the use of biodegradable materials and the valorization of natural resources—represent a strong driver for their adoption.

### *7.4. Regulatory, Economic, and Future Perspectives*

Economic and regulatory aspects represent critical determinants for the industrial feasibility of BDPs in dairy systems. The availability, cost, and compositional variability of high-quality BDPs—particularly propolis and royal jelly—may limit their large-scale application. In addition, the lack of fully harmonized regulatory frameworks governing their use in food products represents a further barrier to commercialization across different markets.

Safety considerations are also essential, as BDPs may contain contaminants such as pesticides, heavy metals, and antibiotic residues. These risks require strict quality control, traceability, and standardized characterization protocols, supported by advanced analytical techniques such as Liquid chromatography–tandem mass spectrometry to ensure compliance with maximum residue limits and food safety regulations.

From a technological and functional perspective, future research should prioritize improving the bioavailability and in vivo efficacy of bee-derived bioactive compounds. Although numerous studies demonstrate functional potential in vitro and in food systems, further validation through in vivo models and clinical studies is needed to confirm their effectiveness under real production and consumption conditions. For example, royal jelly has been shown to enhance probiotic growth and metabolic activity, including short-chain fatty acid production [110], highlighting its potential for functional dairy applications.

In parallel, the integration of BDPs into circular economy strategies—such as their use in the valorization of dairy by-products, including acid whey and buttermilk—offers additional opportunities to improve sustainability and resource efficiency within the dairy sector. However, the successful implementation of these approaches will depend on the alignment between technological feasibility, regulatory compliance, and economic sustainability, ensuring that BDP-based innovations can be effectively translated from experimental systems to industrial applications.

## 8. Conclusions

BDPs represent a promising yet highly heterogeneous class of natural ingredients for dairy systems, with applications spanning animal nutrition, milk quality, dairy processing, and product preservation. Among them, propolis remains the most extensively studied matrix, providing the strongest evidence for modulating rumen fermentation, supporting animal health, and enhancing the microbial stability of dairy products. In contrast, bee pollen, royal jelly, honey, and bee bread exhibit relevant functional properties, but their evidence base is more limited and often context-dependent.

At the farm level, BDPs can influence rumen microbial activity, nitrogen metabolism, and fermentation pathways, with potential implications for feed efficiency and enteric methane mitigation. However, these effects are strongly influenced by botanical origin, extraction method, inclusion level, and dietary composition, preventing their direct extrapolation across production systems. This intrinsic variability remains a major barrier to standardization and practical adoption.

At the product level, BDPs support the development of clean-label and functional dairy foods by enhancing antioxidant capacity, promoting probiotic viability, and extending shelf life through antimicrobial and antifungal activity. These effects are particularly relevant in fermented milk, yogurt, cheese, and active packaging systems. Nevertheless, sensory acceptance, matrix compatibility, and controlled release remain critical technological constraints, especially in propolis-enriched formulations.

Overall, BDPs should not be considered interchangeable additives, but rather chemically distinct matrices requiring product-specific validation and formulation strategies. Future progress will depend on improved compositional standardization, robust in vivo validation, and a clearer definition of dose–response relationships, together with integrated approaches linking animal-level effects to product-level performance. In this context, the most promising industrial applications are those combining technological feasibility, sensory acceptability, and sustainability within a coherent farm-to-product framework.

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