2. Традиційні методи аналізу потребують модернізації та інтеграції з цифровими технологіями, що підвищує ефективність виявлення та прогнозування загроз.

3. Інноваційні методи – системний підхід, цифрові платформи, експертні оцінки та моделі прогнозування – дозволяють підприємствам своєчасно реагувати на ризики та підвищувати рівень економічної безпеки.

4. Використання сучасних методів діагностики має практичне значення для підвищення конкурентоспроможності підприємств та забезпечення стійкості їх розвитку в умовах глобальної економіки.

5. Перспективи досліджень полягають у розробці інтегрованих систем діагностики, що поєднуватимуть фінансові, операційні та інформаційні аспекти економічної безпеки підприємств із застосуванням аналітичних та інноваційних технологій.

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INNOVATIVE APPROACHES TO THE USE OF BEE-DERIVED BIOACTIVE SUBSTANCES IN FUNCTIONAL FOODS

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Abstract. The article explores innovative approaches to the use of bioactive substances of bee origin in the development of functional food products. Special attention is given to honey, propolis, royal jelly, bee pollen, and bee bread as valuable sources of biologically active compounds with antioxidant, anti-inflammatory,

antimicrobial, and immunomodulatory properties. The paper analyzes current technological challenges related to the stability, standardization, and sensory characteristics of these ingredients. Modern solutions such as encapsulation, micro- and nanoemulsion technologies, and synergistic combinations with probiotics and plant extracts are discussed. The study emphasizes the potential of bee-derived substances to enhance the nutritional value, biological activity, and market competitiveness of functional foods.

Keywords: bee products, bioactive compounds, functional foods, encapsulation technologies, antioxidant activity, nutritional innovation

In the modern world, there is a rapidly growing interest in functional food products that not only satisfy basic human nutritional needs but also contribute to health maintenance, prevention of chronic diseases, and improvement of physiological functions of the body. Among natural sources of bioactive compounds, bee products such as honey, propolis, royal jelly, pollen, and bee bread occupy a special place. They contain a wide range of biologically active substances, including phenolic compounds, flavonoids, peptides, vitamins, trace elements, and fatty acids, which exhibit antioxidant, anti-inflammatory, antimicrobial, and immunomodulatory activities. This makes them promising components for the development of functional foods and dietary supplements.

Modern scientific studies confirm that regular consumption of bee products can have a positive effect on the immune system, improve metabolic processes, reduce oxidative stress, and contribute to the maintenance of overall health. The incorporation of such products into food matrices enables the creation of innovative functional foods that meet consumer demand for natural, environmentally friendly, and safe products.

At the same time, the integration of bee products into functional foods faces a number of technological challenges. First, the bioactive compounds of these products are often unstable to high temperatures, oxygen, and light, which can lead to a decrease in their biological activity during production and storage. Second, the presence of specific taste and aroma characteristics, such as the bitter taste of propolis, may affect the sensory acceptability of the final product. Third, the variability in the composition of bee products depending on botanical origin, harvesting season, and geographical conditions complicates standardization and quality control.

To overcome these challenges, modern food science offers a number of innovative approaches. These include the use of encapsulation technologies and micro- and nanoemulsions, which protect bioactive components from degradation, enable their controlled release during digestion, and increase bioavailability. Other approaches involve synergistic combinations of bee products with other functional ingredients such as probiotics, prebiotics, and plant extracts, which enhance product efficacy and improve organoleptic properties. In addition, innovative formulation solutions make it possible to create targeted functional foods aimed at supporting specific aspects of health, such as blood glucose control, immune system strengthening, or maintenance of a healthy gut microbiota.

Thus, the modern food industry has significant potential for incorporating bee products into functional foods, ensuring a simultaneous increase in nutritional value, biological activity, and market competitiveness. However, for the effective use of these resources, systematic research of their chemical composition, physicochemical properties, stability during technological processing, and impact on human health is required.

The aim of the article is to investigate modern innovative approaches to the use of bee-derived bioactive substances in functional food products and to evaluate their effectiveness in enhancing the biological activity and nutritional value of foods.

Bee products are known for their high content of bioactive components and a wide range of functional properties. Honey, as one of the main bee products, contains more than 200 different compounds, among which monosaccharides, organic acids, enzymes, and phenolic compounds play a major role. These components determine the antioxidant, antimicrobial, and anti-inflammatory activity of honey, making it a promising ingredient for functional foods (Bogdanov, 2016).

Propolis is characterized by a high content of flavonoids, aromatic acids, and essential oils, which ensure its anti-inflammatory, antioxidant, and immunomodulatory activity. These properties of propolis are widely used in the development of dietary supplements and functional products (Alvarez-Suarez et al., 2014). Royal jelly, rich in unique proteins known as Major Royal Jelly Proteins (MRJP), fatty acids, and vitamins, exhibits antioxidant, anti-inflammatory, and adaptogenic activity, making it a valuable component for increasing the functional value of food products (Maitra & Ghosh, 2024; Strant, Yücel, Topal, & Puscasu, 2019).

Bee pollen and bee bread are sources of proteins, amino acids, carotenoids, vitamins, and minerals. Bee bread, unlike fresh pollen, undergoes fermentation in the honeycomb, which increases the bioavailability of nutrients and bioactive compounds. This makes it a promising ingredient for the development of functional foods with enhanced biological activity (Giannenas et al., 2021).

Modern technologies for integrating bee products into food matrices are developing towards increasing stability, bioavailability, and sensory attractiveness. One of the key approaches is the encapsulation of bioactive components. Micro- and nanoemulsions protect phenolic compounds, proteins, and peptides from degradation during heat treatment, exposure to oxygen, and light, and ensure controlled release of components during digestion (Ribeiro et al., 2019).

An important aspect is also the use of synergistic combinations. Combining bee products with probiotics, prebiotics, or plant extracts increases product effectiveness and improves organoleptic properties (El Ghouizi et al., 2023). Such approaches allow the development of targeted functional foods aimed at glycemic control, gut health support, or immune system strengthening.

A number of studies demonstrate that the use of microencapsulated propolis in dairy products increases antioxidant activity without impairing taste (Pascoal et al., 2014). Similarly, royal jelly incorporated into energy bars or dry mixes for athletes

has a positive effect on the immune system and antioxidant defense levels (Strant et al., 2019). The addition of pollen or bee bread to cereal products increases protein content, polyunsaturated fatty acids, and trace elements, thereby enhancing the nutritional value and functionality of the final product (Yücel, Topal, & Puscasu, 2017).

Equally important is the issue of standardization and quality control. Bioactive components of bee products show significant variability in composition depending on botanical and geographical origin, which complicates the prediction of their functional activity in food products (Bogdanov, 2016). Modern research is aimed at developing standardization methods, including the identification of key activity biomarkers and optimization of technological processes to preserve the functional value of bee products (Belščak-Cvitanović et al., 2023).

Thus, the literature review demonstrates that bee products are a valuable source of bioactive components for functional foods. Their integration into food matrices requires the application of innovative technologies such as encapsulation and synergistic combinations, standardization, and assessment of bioavailability, which ensures product effectiveness and market competitiveness.

Based on the analysis of scientific sources and modern technological approaches to the integration of bee-derived bioactive substances into functional foods, it is advisable to formulate a number of practical and scientifically grounded recommendations aimed at increasing the efficiency of their use, stability, and consumer attractiveness.

First of all, when developing functional foods using bee products, it is necessary to clearly define the target functional orientation of the product. This may include immune system support, antioxidant protection, normalization of metabolic processes, regulation of the glycemic index, or support of the gut microbiota. According to the chosen goal, a justified selection of a specific bee product or their combination should be made, taking into account the specificity of their bioactive composition and mechanisms of action.

An important recommendation concerns the optimization of technological processing, particularly minimizing thermal load. Since a significant portion of bioactive compounds in honey, propolis, royal jelly, and bee bread are thermolabile, it is advisable to use gentle pasteurization regimes or alternative preservation methods such as high hydrostatic pressure, ultrasound processing, or cold extrusion. This allows preservation of functional properties without compromising product safety.

Special attention should be paid to encapsulation technologies, which are currently among the most promising tools for preserving bioactive components of bee products. The use of microencapsulation with food-grade biopolymers such as alginates, pectins, and protein matrices is recommended, as they provide protection against oxidation, light, and the acidic environment of the stomach. This approach not only increases stability but also enables controlled release of bioactive compounds in the intestine, enhancing their bioavailability.

Considering sensory limitations, including the specific aroma and taste of propolis or royal jelly, the application of synergistic formulation solutions is advisable. Combining bee products with fruit, berry, or plant extracts, as well as probiotic cultures, helps balance organoleptic properties, increase consumer acceptability, and simultaneously enhance functional effects through the synergy of bioactive components.

Another important recommendation is the need for raw material standardization. Given the significant variability in the composition of bee products depending on botanical and geographical origin, it is advisable to implement quality control systems based on the determination of marker bioactive compounds such as phenolic profiles, flavonoids, and specific proteins. This ensures reproducibility of functional properties and increases consumer trust.

From a practical perspective, manufacturers of functional foods are encouraged to focus on the development of everyday-consumption products such as yogurts, beverages, cereal bars, and bakery products enriched with bee products in physiologically justified doses. This approach promotes regular intake of bioactive substances without the need for pharmaceutical supplements.

The analysis confirms that bee products are an extremely promising source of bioactive substances for the development of functional foods. Their unique chemical composition, including phenolic compounds, flavonoids, proteins, peptides, fatty acids, vitamins, and minerals, provides a wide range of biological activities, particularly antioxidant, anti-inflammatory, antimicrobial, and immunomodulatory effects.

Modern research demonstrates that integrating bee products into food matrices significantly enhances nutritional and functional value, provided that appropriate technological approaches are applied. Innovative methods such as encapsulation, micro- and nanoemulsions, and synergistic combinations with other functional ingredients have proven to be particularly effective.

At the same time, the main limiting factors remain sensitivity to technological impacts, sensory characteristics, and compositional variability. Overcoming these challenges is possible through standardized quality control approaches, formulation optimization, and the use of advanced technologies for protecting bioactive components.

Thus, the aim of the study has been achieved: modern innovative approaches to the use of bee-derived bioactive substances in functional foods have been analyzed and their effectiveness in enhancing biological activity and nutritional value has been evaluated. The obtained results confirm the feasibility and перспективність of further development of this field in food science and industry.

Future research in the field of using bee products in functional foods should focus on several key areas. First, in-depth investigation of the bioavailability and bioefficacy of bioactive compounds after their integration into various food matrices is needed, taking into account digestion and metabolic processes in the human body. Second, the development of personalized functional foods enriched with bee products, considering age, physiological, and metabolic characteristics of consumers, is a promising direction aligned with modern trends in nutrition science. Third,

comprehensive studies aimed at harmonizing quality and safety standards for bee products used in the food industry and developing unified criteria for evaluating their functional activity are required. Overall, bee products have significant potential as natural, safe, and effective ingredients for functional foods, and further scientific and technological advances in this field will contribute to the creation of innovative products focused on health preservation and improvement of quality of life.

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