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INNOVATIVE TECHNOLOGIES FOR PRODUCING FISH FEED IN MODERN AQUACULTURE CONDITIONS

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Modern aquaculture is experiencing rapid technological innovation, and feed production plays a key role. With growing demand for fish and seafood, the development of sustainable, cost-effective, and environmentally friendly feeds is becoming a pressing challenge. Innovative feed production technologies include the use of alternative protein sources, biotechnological techniques, probiotic components, and digital automated feeding control systems.

According to the FAO (2024), global fish and seafood production has reached record levels of over 185 million tonnes, of which approximately 52% comes from aquaculture. However, this growth is accompanied by an increasing demand for high-quality feed, which accounts for up to 60–70% of production costs [1].

The traditional use of fishmeal and fish oil is becoming economically and environmentally unsustainable, spurring a shift to alternative ingredients and innovative feed production technologies.

Alternative protein sources in fish feed are innovative components using instead of traditional fishmeal. These include insect proteins *(Hermetia illucens, Tenebrio molitor)*, which are characterized by a high crude protein content (from 40 to 65%), a balanced amino acid composition, the presence of fatty acids, minerals and biologically active peptides that improve the immune response of fish, microalgae *(Spirulina platensis, Chlorella vulgaris)*, single-cell proteins (yeast, bacteria, methanotrophs) [1].

These organisms are rich in proteins, carotenoids, vitamins, omega-3 and omega-6 fatty acids, as well as antioxidants, making them not only a source of nutrients but also a functional additive that improves fish quality and stress resistance.

Single-cell proteins (SCPs) - products of microbiological synthesis from yeast *(Candida, Saccharomyces)*, bacteria (methanotrophs, methylotrophs), and microscopic fungi - are generating significant interest. They have a high growth rate, do not require fertile soil, and can be produced on organic substrates, including agricultural and food industry waste, making the technology economically and environmentally feasible [1].

In producing the compound feed, considerable attention is paid to using plant protein concentrates – soy, pea, sunflower and rapeseed. The main problem with their use is the presence of anti-nutrients, but modern fermentation and enzymatic processing methods can significantly improve the digestibility of plant proteins and enhance their absorption by fish [1].

Alternative protein sources not only address the problem of fishmeal shortages but also contribute to the sustainable development of aquaculture, reducing the burden on marine ecosystems and creating the basis for environmentally friendly and cost-effective production of next-generation feeds.

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Modern feed technologies increasingly utilize biotechnological processes, such as: fermentation of plant substrates, which increases protein bioavailability and reduces phytate and antinutrient levels; enzymatic modification of protein and carbohydrate components, which increases feed digestibility by 10–15%; and encapsulation of biologically active substances (vitamins, probiotics, fatty acids), which extends shelf life and improves digestibility [1, 2].

Furthermore, biotechnological lines for the deep processing of organic waste are actively developing, resulting in feeds with a minimal carbon footprint.

The use of probiotics, prebiotics, enzymes, and phytobiotics improves feed digestibility, stimulates immunity, and modifies the intestinal microbiota.

The researches show that feed containing insect meal and probiotics positively influences the composition of the gut microbiota in freshwater and marine species, improving growth and disease resistance.

Modern approaches to aquaculture nutrition are focused not only on ensuring growth and productivity, but also on maintaining fish health and immune status, reducing disease incidence, and increasing stress resistance. In this regard, functional feed additives capable of performing bioregulatory, antioxidant, and immune-stimulating functions are becoming increasingly important. Their use is considered as an alternative to the prophylactic use of antibiotics and chemotherapeutic agents, which is especially important in the context of sustainable and environmentally friendly fish farming [4].

Probiotic supplements, including strains of *Lactobacillus* spp., *Bacillus subtilis*, *Enterococcus faecium*, and others, have a positive effect on the composition of the gut microbiota, improve digestion and nutrient absorption, and enhance the body resistance to pathogens [1].

Prebiotics stimulate the growth of beneficial microorganisms and normalize the intestinal microbial balance. The combined use of probiotics and prebiotics (synbiotics) demonstrates a synergistic effect, improving the immune response and the growth rate of fish.

Phytobiotics are natural plant-based compounds with antimicrobial, anti-inflammatory, and antioxidant properties.

The use of enzyme supplements is aimed at increasing feed digestibility, especially when using plant-based ingredients containing antinutrients. Enzymes such as phytase, xylanase, β-glucanase, and protease break down complex polysaccharides and phytates, increasing the availability of phosphorus, nitrogen, and amino acids. This helps to increase the feed conversion ratio (FCR) and reduce water pollution by reducing the amount of undigested residues [1, 4].

Functional feed additives play a key role in the sustainable development of aquaculture, reducing antibiotic use and improving fish health without harming the environment. Their integration into feed technologies improves physiological functions, immune status, and the quality of final products. The creation of multifunctional and species-specific feed additives that provide a complex effect on the metabolism and intestinal microbiota of fish is a promising direction for further research in Ukraine.

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Innovative feed production technologies are a strategic direction for the development of sustainable aquaculture. The integration of biotechnology, functional additives, and digital solutions is creating a new paradigm in fish nutrition management.

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