Ann. Anim. Sci., Vol. 24, No. 1 (2024) 13–25 *DOI: 10.2478/aoas-2023-0034*

sciendo

AN OVERVIEW OF MODERN BIOTECHNOLOGICAL TOOLS IN AQUATIC FOOD PRODUCTION – A REVIEW

Vikash Kumar[#], Satya Narayan Parida[#], Suvra Roy, Souvik Dhar, Kampan Bisai, B.K. Behera[♦], Basanta Kumar Das[♦]

Aquatic Environmental Biotechnology and Nanotechnology Division, ICAR-Central Inland Fisheries Research Institute, Barrackpore, Kolkata-700120, West Bengal
[♦]Corresponding authors: beherabk18@yahoo.co.in, basantakumard@gmail.com
[#]Shared equal authorship

Abstract

Aquatic food production system raises aquatic organisms including fish, shellfish and seaweeds for human consumption and associated value chains. Moreover, as the global human population continues to expand at a high rate and is expected to reach over 9 billion by 2030, developing a cost-efficient production method is a significant challenge in the future development of the aquatic food production industry to provide food and nutritional security with high-quality animal protein. Recent advancements in biotechnological tools and approaches provided a new toolset that can be used to design and optimize the existing processes such as food preservation, fermentation, packaging, quality control and setting proper guidelines to manufacture and process genetically modified fish. At the same time, with the refinement of technology, these are becoming easier applicable and transferable to several other aquatic species production systems. These trends have resulted in exploiting new and unconventional microbial systems with sophisticated properties, which render promising results in the production industry. Here, we highlight the recent advances in the newly emerging biotechnological technology in the production of fish and fish products and discuss the potential of these tools as a sustainable platform for centuries to come with a significant impact on the aquatic food production industry.

Key words: biotechnological tools, aquatic food production, microbial systems, cost-efficient, sustainable platform

Aquatic food has a major role in sustainably feeding and nourishing the world of 800 million people (including both women and men) (Kumar et al., 2016; FAO, 2018; Roy et al., 2019, 2020; Ngasotter et al., 2020). Also, it has a significant effect on livelihoods and nutritional security and meeting the current/future demands for quality animal protein (FAO, 2014; Roy et al., 2018; Kumar et al., 2021 a, 2022 a). However, problems like climate change bring a cascade of threats to the agro-ecosystems affecting both the quantity and quality of production and global food security (Robert and Jancovich, 2016; Soltani et al., 2019; Maulu et al., 2021). It influences the physical condition and physiology of aquatic animals, modifies the ecosystem structure, inputs supplies and prices of products (cost of fish oil and fish meal), primary and secondary productivity of water bodies and other services and goods required for sustainable production (Kumari et al., 2021; Kumar et al., 2022 c, d). Biotechnology offers a sustainable solution in aquatic food production through genetic engineering approaches to enhance food quality by microorganisms, animals or plants, microbial fermentation processes for manufacturing innovative food, enzyme and additives, introducing new technologies for food packaging and preservation. It can also enhance food consistency, edibility and shelf life by inhibiting the growth of undesirable toxin-releasing microorganisms that may contaminate or are naturally present in foods and producing antimicrobial agents against unwanted putrefactive microbes (Ranjha et al., 2020; Cabrera-Barjas et al., 2022).

A walk through a supermarket starkly demonstrates how processed foodstuffs have evolved over the previous decades. The food production industry has responded to rising customer knowledge and concern about food safety, quality, nutrition and convenience by developing and marketing goods that match consumer desires and needs and meet consumer demands while ensuring food quality and safety. Novel and efficient technologies like biotechnology will be essential (Venugopal et al., 2009; Kumar et al., 2023 a). According to Convention on Biological Diversity (CBD), biotechnology is defined as any technological application that employs a biological system (plant, animal and microorganism) or any derivative thereof to manufacture or alter goods or processes for a specialized purpose (Tramper and Zhu, 2011). Biotechnology in food production may substantially impact the quality, composition and functioning of food products by offering tools for product stabilization, modification, preservation, quality control, characterization and safety.

Furthermore, the fermentation process and separation as well as waste management and recycling can help to enhance food production efficiency (Knorr and Sinskey, 1985). The introduction of genetic engineering in the

last 20 years, which permits the interchange of genetic information across related and unrelated species, separates the more traditional old biotechnology from new biotechnology (Hulse, 2004). Other techniques that are covered under biotechnology include fermentation technology, plant and animal cell culture, enzyme and protein engineering, bioengineering, hybridoma technology and DNA probe technology (Harlander, 1989). In addition to removing undesired components from food production, biotechnology is often used to produce affordable supplements that boost the nutrition value of the consumed product and along with it enhance textures, appearance and flavor (Najafi and Lee, 2014; Kumar et al., 2022 b).

Fish is consumed as a significant source of animal protein by billions of people. Biotechnology provides give and take management system in which biotechnology tools are responsible for sustainable extraction and conservation of aquatic resources (Vijayan et al., 2013). Food security will be one of humanity's most pressing concerns as we approach the millennium. It is hoped that the world population will stabilize at 11 billion by 2050 (Vijayan et al., 2013). The agricultural sector's challenge is to double food production output by 2025 and triple it by 2050, using less land per capita with fewer water resources and under more difficult environmental circumstances (Vasil, 1998; Freire et al., 2022; Kumar et al., 2022 b). The application of modern biotechnology to increase aquatic species production has the potential not only to meet demand but also to improve fish in aquaculture. Genetic modification and biotechnology also have enormous potential to increase the quantity and quality of fish farmed in aquaculture (Ayoola and Idowu, 2008; Kumar et al., 2022 c; Roy et al., 2022 a). In aquaculture, biotechnology involves improving feed composition and source, transgenics, controlling reproductive cycles using hormone treatment, developing novel vaccines, preserving genetic resources, developing disease resistance in fish, strengthening unique biological models and improving growth rate in fish (FAO, 2002). Many coastal nations like China, Norway, Chile and India have developed active aquaculture projects in recent decades with outstanding outcomes. Although biotechnology applications address a variety of bottleneck difficulties associated with ethical guidelines, aquatic and marine biotechnology represents the best promise for making agricultural and food production more efficient and cost-effective (Hew and Fletcher, 2001). It is anticipated that the advancement and implementation of new technology and farming technology will speed up development and enhance output in the near future.

Application of biotechnology in aquatic food production

The recombinant enzyme in aquatic food processing

Combining recombinant DNA technology and protein engineering with commonly used microbial sources make them suitable, comfortable and adaptable for large-scale industrial usage (Mahaliket al., 2014, 2018). The methodology to produce a recombinant enzyme follows a series of processes, starting with identifying the appropriate gene by using gene-specific primer and genomic DNA as the template for an enzyme of interest and cloning the gene of interest in a suitable host (yeast, filamentous fungi, *E. coli*), expressing this gene of interest in this host and purification of the particular enzyme protein (Muthusamy et al., 2022). The method for producing recombinant variants is diagrammatically represented in Figure 1. Fermented fish products typically have a niche market due to their ability to deliver a distinct feature, particularly texture, flavor and scent. This is due to the action of microbes or enzymes found in fish muscle tissue during the fermentation process converting organic molecules into simpler chemicals (Hutkins, 2006). The enzymatic activity of the raw material and the metabolic activity of microorganisms throughout the fermentation process can alter the nutritional and bioactive properties of fish matrices and generate beneficial impacts on human health (Xu et al., 2021). Because of the probiotic characteristics and fermentation activities, lactic acid bacteria (LAB) are frequently employed in the food business and dominate traditional fish fermentation techniques (Ngasotter et al., 2021). Enzymes are the most important contributors to taste creation and textural alterations in fermented fish products. Aside from enzymes, microorganisms that contribute to the fermentation process also aid in developing fragrance and flavor (Giyatmi and Irianto, 2017). One of the major challenges in the aquatic industry is to descale a large amount of fishes within a stipulated period. It was traditionally done mechanically, but it was time-consuming when the fish had many scales. With the fermentation process by using a new enzymatic method to remove the scale, the descaling of a large amount of fish was streamlined. During the procedure the fish was incubated in a specially built incubation tank filled with a slightly acidified water solution of the descaling protease enzyme, collagenase. Following the treatment, the fish is removed from the incubation liquid and thoroughly cleaned. The technology can deskin at a rate of 1.3 metric tons per hour (Fernandes, 2016). Similarly, in fish sauce production, using exogenous enzymes like papain, ficin, bromelain and commercially produced Protex 51FP and Neutrase boosts fish fermentation and nutraceuticals (Aquerreta et al., 2002; Gildberg et al., 2007). Furthermore, in the ripening process of salted fish like cod, salmon, herring and anchovy the degradation of muscle protein with an endogenous enzyme like chymotrypsin, trypsin and cathepsins are typically more significant (Østli et al., 2006). The use of transglutaminase (TGAs) like protein glutamine γ-glutamyl transferases (EC 2.3.2.13) promotes acyl transfer reaction where the γ-carboxamide group of a peptide-bound glutamine residue as acyl donor and primary amines as acyl acceptor (Zilda, 2014). Recently transglutaminase from microbes like MTGase was used for modification of the seafood product and therefore used for the restructuration of raw meats and production of surimi (Kieliszek and Misiewicz, 2014). Along with that MTGase is also used in the modification of finfish

texture, formation of collagen and gelatin bond, production of shark fin, formulations of fish meat mince and reduction of drip after freezing (Fernandes, 2016). Similarly, lipases, like triacylglycerol acyl hydrolases (EC 3.1.1.3) hydrolyze long chain mono, di and triglycerides to glycerol and fatty acids in the presence of excess water. In fish production, this enzyme is used as an agent to isolate fats and oil from the seafood byproducts along with the preparation of ω-3-polyunsaturated fatty acids and enriched marine oil (McClements and Rao, 2011; Walker et al., 2015). Lipases also facilitate the removal of fats from fish bone (Sharma et al., 2016; Mehta et al., 2021). Several proteolytic enzymes like papain, pepsin, alcalase, pancreatin and trypsin are used widely to remove protein from chitin (Singh and Benjakul, 2018). A recent study by Loan et al. (Loan et al., 2022) shows that the bacterial strain *C. necator* H16 with waste fish oil as a substrate can be used to make PHP (poly 3-hydroxybutyrate) as a fermented product, which has certain valuable qualities such as the production of recyclable plastic. The recent use of microbes and enzymes in the production of fish products is mentioned in Table 1.

The expansion of food production is achieved by the effective use of enzymes in food industries for production, manufacturing and improvement, along with those other components like taste, color, fragrance, appearance, shelf life, texture and nutritional quantity (Neidleman, 1984). Food enzymes may be derived from various sources, but microbial sources are the most promising and prospective. Previous study shows that cunner fish trypsin was cloned in the yeast (*Pichia pastoris*) as the microbial host to produce cold-adapted fish trypsin, which exhibits the characteristic of a high degree of activity at a lower temperature (Macouzet et al., 2005). This higher catalytic activity makes this recombinant trypsin an efficient protease enzyme with wide application in biotechnology and food production. Previously an attempt was done to produce cold-adapted fish trypsin by using the widely used expression vector *E. coli* which results in the overexpression of recombinant trypsin and the formation of inclusion bodies (Yee and Blanch, 1993). Similarly, Atlantic cod trypsin was effectively produced by taking the *E. coli* His-Patch Thio Fusion expression system as a vector (Jónsdóttir et al., 2004). Recently a study was focused on developing a method to immobilize lipase isolated from recombinant *Bacillus subtilis* on magnetic nanoparticles for hydrolysis of fish oil to concentrate omega-3 fatty acid EHP (eicosapentaenoic acid) and DHA (docosahexaenoic acid) from anchovy fish oil for the production of omega-3 concentrates for a nutritional supplement (Verma et al., 2019).

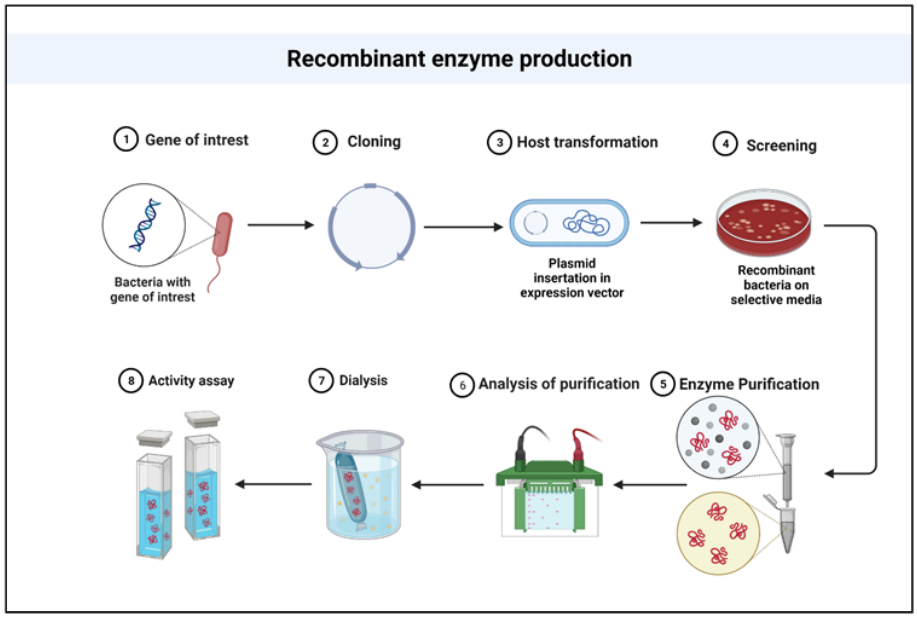


Figure 1. Systematic diagram on recombinant enzyme production

Table 1. Microbes and enzymes used for making fish products

Sl No.	Enzyme or microbes used	Product	Reference
1	*S. piscifermentans*, *S. piscifermentans*	Utonga-kupsu	(Singh et al., 2018)
2	*Psychrobacter*, *Tetragenococcus*	Prohok	(LeGrand et al., 2020)
3	Collagenase	Fish scale remover	(Anokhova et al., 2020; Likhar and Chudasama, 2021)
4	*Lactobacillus plantarum* CCRC 10069, *Lactococcus lactis* CCRC 12315, *Lactobacillus helveticus* CCRC 14092	Fermented fish	(Xu et al., 2021)
5	Protease	Anchovy sauce	(Zhu et al., 2021)
6	*Saccharomyces cerevisiae*, *Lactobacillus reuteri*	Aquafeed	(Tropea et al., 2021)
7	Neutral protease, papain, β-cyclodextrin	Improved umami flavor of soy sauce	(Ruan et al., 2022)

Functional health management

To minimize the losses due to the infectious disease in aquaculture, every health issue should address scientifically proven methods to enhance the efficiency of processed food (Assefa and Abunna, 2018; Kumar et al., 2021 a; Roy et al., 2022 b). The application of recombinant technology was utilized to immunize the fishes against widely available fish pathogenic bacteria by using the outer membrane protein A (OmpA) by incorporating the outer membrane protein inside the vector-like *Escherichia coli* M 15 cells and generating the desired protein to use as a vaccine. The isolated protein is highly immunogenic in fish, so the fish will be resistant to a particular bacterial pathogen like *Edwardsiella tarda* (Sun et al., 2010; Maiti et al., 2011). The immunization in fish against rock bream iridovirus was archived by expressing a recombinant major capsid protein (rMCP) of rock bream iridovirus in transgenic rice callus and the fishes were immunized orally by feed supplemented with lyophilized rice callus powder. The fishes were successfully induced for the production of antibodies against iridovirus and other marine viral diseases (Shin et al., 2013). Similarly, the outer membrane protein of *Aeromonas hydrophila* (Aha1), introduced into the recombinant vector pPG1 and pPG2, containing 1366 bp of DNA fragment electroporated into *Lactobacillus casei* CC16, results in the production of recombinant bacteria *L. casei*-pPG1-Aha1 and *L. casei*-pPG2-Aha1. The probiotic bacteria were orally administered to the common carps resulting in the high induction of immunogenicity and an increase in the survivability of fish with *Aeromonas hydrophila* infection (Zhao et al., 2022). The work done by Chukwu-Osazuwa et al. (2022) revealed the use of polyvalent or universal vaccines by screening the bacterial proteomes of most Gram-negative bacterial pathogens and identifying the common epitopes and antigens on the various Gram-negative bacteria like *A. salmonicida*, *P. salmonis*, *V. anguillarum*, *Y. ruckeri*, *M. viscosa*. Later, the vaccine efficacy was checked by their interaction with the major histocompatibility complex class II (MHC class II). The epitopes provide a library for developing a universal vaccine against bacterial pathogens (Chukwu-Osazuwa et al., 2022). The advancement in genetic engineering has aided in manufacturing live-attenuated vaccines, which are often manufactured by deleting, disrupting, or inserting the metabolic pathway or virulence gene that causes pathogen attenuation (Meeusen et al., 2007). The mutant pathogens that develop act as avirulent pathogens eliciting a protective immune response in the host while causing no infection (Bedekar et al., 2020). Similarly, DNA vaccination involves delivering a plasmid DNA encoding a vaccine antigen protein to the host, which then expresses inside the recipient under the eukaryotic promoters (Ghaffarifar, 2018). The antigenic proteins expressed are recognized by the host immune system, inducing intense and long-lasting humoral and cell-mediated immune responses without the possibility of unintended infection (Dávila et al., 2020). Different modes of vaccine production and their use in fish were presented in Figure 2. However, the regular monitoring of disease outbreaks due to any pathogen through surveillance programs using advanced diagnostic techniques was also conducted from time to time to monitor and minimize the losses in the aquaculture sector (Kuri et al., 2022).

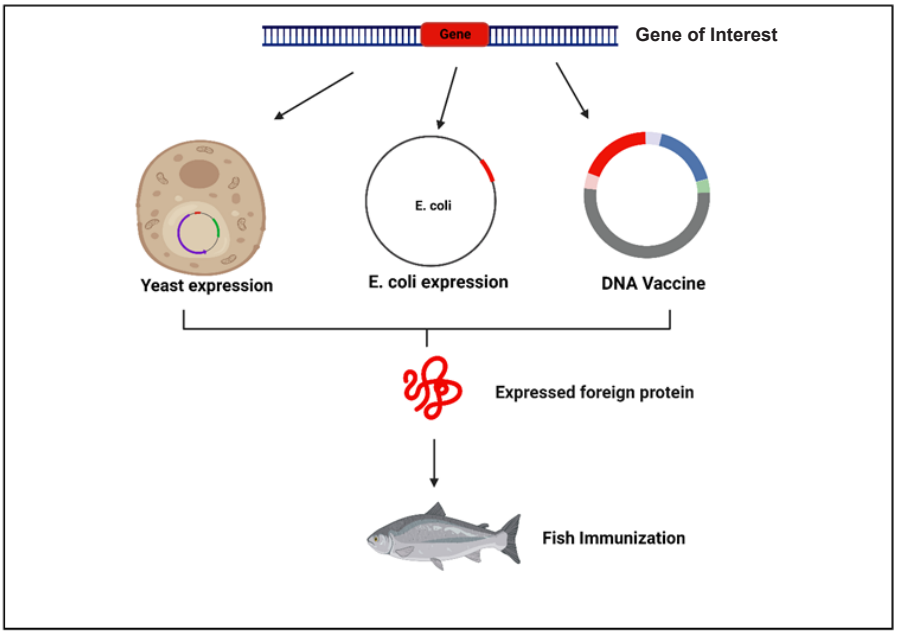


Figure 2. Systematic diagram on production of vaccine by different methods

Recently nanotechnology has provided a comprehensive application for health management in fish (Dar et al., 2019). These are nano-based drug delivery systems, nano-vaccine delivery, nanomedicine and nanoparticle-based gene therapy (Sarkar et al., 2022). Before the application of nanotechnology, the vaccine application of fish was used through the injection method, which was labor-intensive and injecting specific fish sizes was usually seen as a restriction to the vaccine delivery. To increase the efficacy of the new oral delivery system, the nano-delivery produced from nanoclay, halloysite nanotubes (HNTs) and its modified form where the HNTs loaded with killed vaccines will release the vaccine when the particle reaches the digestive system of the fish (Karewicz et al., 2021). The efficacy of this nano-delivery of vaccine was studied by the amount of antibody generation and disease prevention in *Oreochromis niloticus* (Pumchan et al., 2022).

Genetic modification in fish

Using gene transfer technology, it is now possible to introduce any foreign gene of interest into the genome of animals. When the gene is inserted, inherited and successfully expressed, the organism gains a novel genotype and phenotype depending on the inserted gene and the intensity and specificity of the promotor regulating the expression. In the case of fish, the technology can be used to (1) enhance food consumption by modifying biochemical or metabolic processes, (2) adapt to harsh conditions, such as freeze/cold resistance, (3) modify the biochemical properties of the meat to improve its nutritional value, (4) increase the fish's growth rate, (5) increase survival by boosting disease resistance to pathogens, (6) control sex differentiation, sexual maturation and sterility (Hew and Fletcher, 2001). Traditional biotechnology deals with the induced diploid gynogenesis and polyploid formation produced by manipulating chromosomal sets. The objective of producing gynogenetic fish is to create a female stock and extremely inbred animals by genetically inactivated sperm (Purdom, 1983; Behera, 2021). It should be noted that meiosis is stopped during the first phase of the normal cleavage of the nucleus, during which the first polar body is generated and later degenerates into an egg cell. Following the end of the second meiotic phase, the activated egg only possesses a haploid pair of chromosomes due to the destruction of chromosomes in sperm. The haploid eggs develop into a gynogenetic embryo (Purdom, 1983; Refstie and Gjedrem, 2005). The gynogenesis has already been established in *Cyprinus carpio* (Nagy et al., 1978) and in European sea bass (Felip and Piferrer, 2018). Similarly, in androgenesis, genome manipulation was done by inactivating the eggs by gamma or X-ray and fertilizing the egg with normal sperm, resulting in paternal character in offspring having YY genotype in modified fishes (Hussain, 1996). A recent report on inducing androgenesis in *Oncorhynchus mykiss* is achieved (Polonis et al., 2019). Polyploidy is another approach to modifying the genome organization by introducing an extra set (s) of chromosomes by suppressing the second meiotic division shortly after fertilization of eggs or disrupting the first mitotic division prior to the formation of the first cleavage (Hussain, 1996; Samad and Ghani, 2021). The polyploidy was archived earlier in salmonids using cytochalasin B (Refstie et al., 1977) and in European sea bass (Felip and Piferrer, 2018).

Table 2. Transgenic fish variety with their enhanced character

Sl No.	Fish variety	Transgene	Enhanced character	Reference
1	*Salmo salar* (salmon)	Growth-hormone gene from *Oncorhynchus tshawytscha* and genetic regulatory elements from *Zoarces americanus*	Faster growth rate	(Waltz, 2017)
2	*Danio rerio* (zebrafish)	Hepcidin (AN-hepc)	Enhanced immunity against *Aeromonas hydrophila* and *Streptococcus iniae*	(Tseng et al., 2020)
3	*Oreochromis niloticus* (Nile tilapia)	Delta-5 and delta-6 desaturase from salmon	Disease resistant against *Vibrio vulnificus*	(Chiang et al., 2020)
4	*Clarias gariepinus* (Mutiara catfish)	Over expression of CgGH	Enhanced protein and amino acid content	(Buwono et al., 2021)
5	*Danio rerio* (zebrafish)	Over expression of *asip1*-Tg	High egg-laying capacity and linear growth	(Navarro et al., 2021)
6	*Ictalurus punctatus* (channel catfish)	Δ5-desaturase (D5D) from salmon	Faster growth, disease resistance, higher protein and moisture	(Huang et al., 2021)
7	*Ictalurus punctatus* (channel catfish)	*Elovl2* from salmon	High omega-3 (n-3) fatty acids production	(Xing et al., 2022)
8	*Ictalurus punctatus* (channel catfish)	Cecropin B from the moth *Hyalophora cecropia*	Disease resistance against *Edwardsiella ictaluri*	(Abass et al., 2022)

The different gene delivery techniques through which transgenesis are archived like microinjection of the desired gene into one cell embryo, delivery of DNA through electroporation, the introduction of DNA into the fertilized egg by using a viral vector and recombinant sperm mediate transfer into the unfertilized egg (Wang et al., 2021). Following the first successful transfer of a foreign gene into the fertilized eggs of a goldfish, *Carassius auratus* by Zhu et al. (1985), the production of many transgenic fish varieties surged. The discovery of antifreeze proteins (AFPs) during the 1970s and 80s gives researcher access to develop transgenic fish that can allow normal fish to survive in freezing water (Davies, 2022). Winter flounder is a freeze-resistant variety of fish due to the presence of antifreeze proteins that circulate inside their blood. Whereas, in fish like salmon where this protein is absent mass culture in sea pens is almost impossible (Khanna and Daggard, 2008). The transgenic variety of the salmon is produced by transferring the AFP gene from winter flounder to salmon by microinjection of the fertilized eggs (Fletcher et al., 1992). Further, the recombinant variety is produced by incorporating the disease-resistant genes into the genetically modified fish to reduce cost, increase productivity without causing drug resistance and improve the poor trait (Lo et al., 2014). CRISPR/Cas9 was applied to produce the recombinant *Ictalurus punctatus* (Coogan et al., 2022) by knockout of the myostatin (*mstn*) gene that regulates the growth of skeletal muscle. As a result, the recombinant MSTN mutant was 88% larger, along with resistance against *Edwardsiella ictaluri,* which causes enteric septicemia. CRISPR/Cascan also become a game changer in the future fisheries sector (Roy et al., 2022 b). A 90-day observation was carried out by Guo et al. (2022) to study the toxicity of transgenic triploid carp (GH-ttc) on Wistar rats, suggesting no toxic effect on rats. Recently the transgenic fish called 'Aqu Advantage' salmon having a high growth rate, got approved by the US Food and Drug Administration (FDA) (Ledford, 2015) as safe to eat. The genetically modified fish variety with their enhanced character and the transgene involved in producing the fish variety are mentioned in Table 2.

Biotechnology in aquatic waste management

The application of biotechnology is widely available to manage waste products from the fishing industry (Kumar et al., 2023 b). The waste material can be utilized as a high-value raw material source for producing bio compounds (Mohanty et al., 2018; Kumar et al., 2021 b). The fish-derived materials like scales, fins, skin and eyeballs have suitable viscosity, tensile strength and flexibility as a protective matrix (Wankhade, 2020). Recently the leading market player used fish-derived biopolymer to manufacture everyday necessities like paper bags, food packaging material, bottles and fabrics (Singh et al., 2022). Among the various byproducts of fish, collagen is used in the food and beverage industry and cosmetics. Collagen is partially hydrolyzed and thermally denatured to form gelatin, which is employed as a significant molecule in medicines, nutraceutical biomaterials and the food industry (Je et al., 2004). Similarly, several peptides are derived from fish hydrolysates used as antioxidants, antihypertensive, antimicrobial and neuroprotective activities (Urakova et al., 2013). A large amount of crustacean shell is wasted every year, which can be used to produce chitin converted to chitosan as a natural food preservative and used for bone and tissue engineering (Kara et al., 2019; Santos et al., 2020). Furthermore, the shrimp shell waste valorization was also utilized to produce valuable materials such as carotene proteins, colloidal chitin, microcrystalline chitin and nanochitin (Dayakar et al., 2021, 2022; Ngasotter et al., 2022; Sampath et al., 2022 a, b). The production of fish oil from waste fish manure can be utilized in feed and nutraceutical applications along with biofuel production (Kara et al., 2018). Figure 3 displays the flow diagram of producing fish oil from fish manure. Among the others, fish waste can be utilized to produce fish calcium that is used for pharmaceutical purposes, fish glue that is made from the fish head and skin and Isinglass that is used as a clarifying agent for beer, wine, vinegar and production of FAA (fish amino acid) (Windsor and Barlow, 1981; Uma and Jeevan, 2022). The establishment of a sustainable fish waste management system is critical because it is directly tied to the waste framework directive, which strives to reduce waste output as much as possible by employing innovative applications of biotechnology and to use waste created as a resource for recovery, reuse and recycling (Coppola et al., 2021).

Food packaging and preservation

Fish and seafood are nutritionally essential foods widely valued and consumed globally. However, due to the extreme perishability of these products, a variety of preservation, production and analytical approaches have been developed (Ravishankar, 2019). Food packaging guarantees product safety against chemical, biological or external physical impacts and extends product shelf life (Robertson, 2009). The usage of plastic as a food packaging material has created a global environmental issue which can be tackled by using biodegradable protein-based polymers made from soy protein isolate (a by-product of the soybean oil industry) (Wu et al., 2021), zein (storage protein in corn endosperm) (Aytac et al., 2020), gelatin (hydrolyzed collagen from bone and skin) (Zhao et al., 2020) and whey protein (a by-product of cheese and casein manufacturing) (Çağrı Mehmetoğlu et al., 2021; Zhen et al., 2022). The application of biotechnology was applied to produce a biodegradable packaging material like bacterial cellulose membrane (BCM) made up of raw bacteriocins that were isolated from lactic acid bacteria with the ability to show antimicrobial activity against *E. coli*, *Bacillus subtilis* and *Staphylococcus aureus* (Nhu et al., 2019). The use of edible coating and films for the packaging can form a layer and dissolve in a safe solvent and is compatible with antioxidants, an-

timicrobial compounds and some specific plasticizers and is made from acylglycerol, fatty acid, polysaccharides and alginates (Tsironi and Taoukis, 2018). Incorporating nanofillers into biopolymers has recently improved features such as antibacterial, antioxidant and mechanical barriers and is utilized as an indication for monitoring the deterioration of packaged food products (Bhargava et al., 2020; Abelti et al., 2022; Zhang et al., 2022).

Due to their biological composition, aquatic products are very perishable and easily prone to contamination. Biotechnology involvement is unavoidable to improve adequate control over fish and fish products and get the most out of them (Dar et al., 2019). The use of nanotechnology has recently gained popularity due to its application in extending shelf life (Qiu et al., 2020). Recently, a study showed that 3% ZnO NPs in fish packaging film prevented most fungal species, increasing the shelf life of most fish species to more than 15 days (Ali, 2022). The wide applications of nanotechnology used in preservation include nanocomposites like cellulose microfibrils and carbon nanotubes due to their structural and biological characteristic to show antibacterial activity (Duan et al., 2008). The use of nanoemulsions stabilizes the protein content of packaged fish when extending the shelf-life of the product by lowering bacterial contamination (Meral et al., 2019). Nanoliposome have been utilized in the food industry to deliver flavor and aroma along with the ability as antimicrobials that help in the preservation of food against microbial contamination (Khorasani et al., 2018). Due to advancements in biotechnology, ozonated ice has been utilized for food preservation, particularly for the suppression of surface foodborne microorganisms on fish skin (Shin et al., 2004). Another approach to preserve fish and fish product is to use bacteriophage as a potential inhibitor for spoilage caused by the bacteria like *Listeria monocytogenes*. Compared to traditional antibiotics, phages offer distinct advantages for use as alternative antimicrobial agents, including no harmful effect on human or animal cells, lower development and production costs than innovative antibiotics and the ability to self-dose (Axelsson et al., 2020; Lee et al., 2022). In 2006 the US Food and Drug Administration (FDA) approved the use of 6 individually purified bacteriophages (LMP-120) in packaged fish and meat as an antimicrobial agent against *Listeria monocytogenes* (Lang, 2006). The mode of action of bacteriophage on the bacteria as host is displayed in Figure 4.

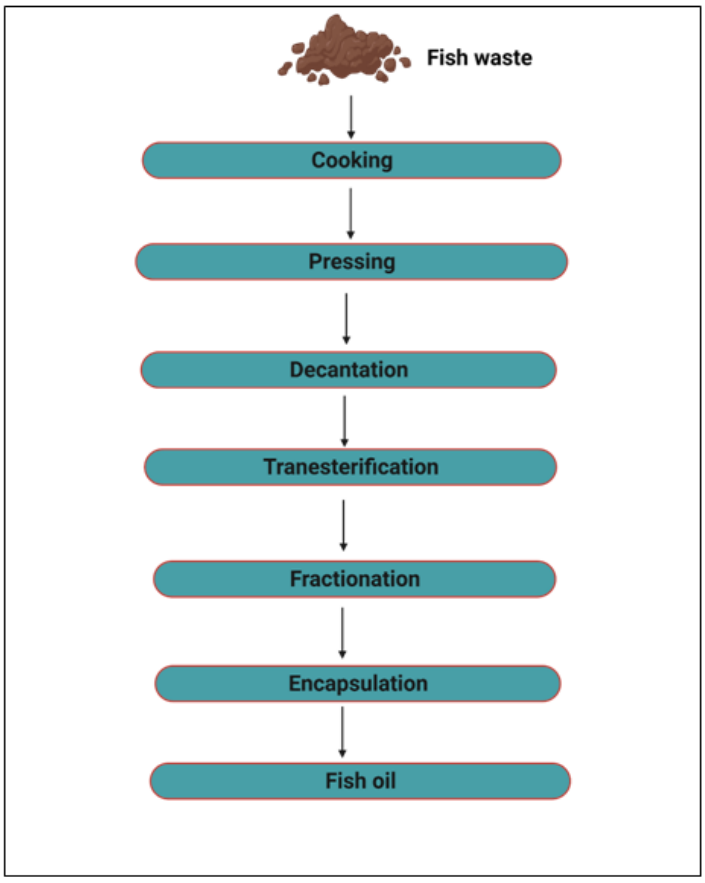


Figure 3. Schematic representation of a typical process from fish waste to final products

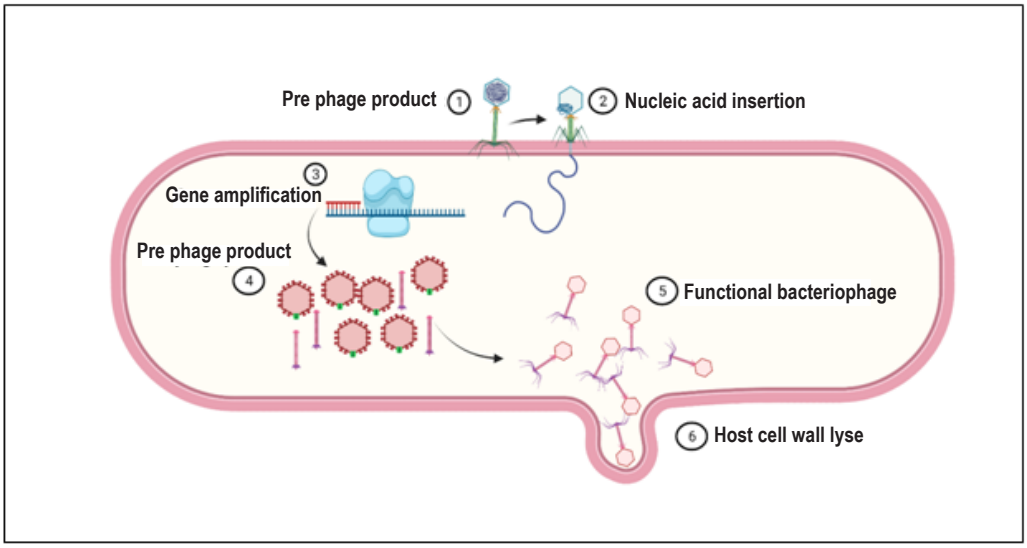


Figure 4. The life cycle of bacteriophage inside the bacteria to limiting the bacterial population

Biotechnology in quality assurance

After being captured from its source, fish quality declines due to the invasion of bacteria, chemical oxidation, enzyme autolysis and mechanical damage (Tahsin et al., 2017). Fish deterioration can have a negative impact on customers and differ from the traditional market value (Putriantini et al., 2022). As a result, food industries worldwide are attempting to find techniques to ensure the freshness of fish. The strategies being developed are based on the physical and chemical changes that occur in the fish after capture (Nie et al., 2022). However, immunodiagnostic is a potential for rapid detection of the pathogen in aquatic food products. A new dimension in fish health management is provided by multiplex testing systems such as Luminex technology, which allow for the simultaneous detection of multiple pathogens or immune response molecules, such as lysozyme, cytokines and IgM. Additionally, the possibility for epitope mapping and subsequent vaccine development is provided by Luminex technology (Adams and Thompson, 2006). Biotechnology intervention to assure quality and freshness is currently emerging through the development of biosensor-based detection (Thakur and Ragavan, 2013). A biosensor is a quantitative analytical instrument that combines a biological detection element (microbe, enzyme, receptor and antibody) with a chemical or physical transducer (Wagner and Schmid, 1990). Transducers are responsible for turning certain biological reactions into electrical impulses that may be analyzed by an automated system or software (Faradilla et al., 2021; Freitas et al., 2021). Food freshness, in the case of fish, refers to newly caught or sliced and kept frozen. The biosensor is being examined for food freshness assessment and has been chosen to detect target metabolites released during food spoilage. The spoilage induced by microbes and pH fluctuations determines the freshness of fish, which changes drastically if spoiling occurs. This pH-indicating biosensor, when combined with fish and meat packaging, has the potential to test food integrity by monitoring the pH levels of packed meat and fish. This sensor device is rapid and sensitive and its reaction directly proportional to spoiled food's pH (Kuswandi et al., 2011). Similarly, the biosensor was developed by immobilization with xanthine to assess xanthanin levels in meat. Xanthanin is a primary biomarker generated in animal tissues after adenine nucleotide breakdown. This biosensor device detects protein degradation during fish packaging (Devi et al., 2013; Sobhan et al., 2021). Histamine is a biomarker for food spoilage and may be used as a freshness measure in this kind of analysis of fish.

The histamine content exceeding 200 ppm causes histamine poisoning and danger to the consumer's health. Colourimetric biosensor-based histamine detection was proposed using magnetic DAO (diamine oxidase) as a biosensing element and etched AuNRs (gold nanorods) as signal converters. Figure 5 shows the different components of biosensor devices to detect any harmful components. The reusable magnetic DAO is prepared by immobilizing DAO on MGO (magnetic graphene oxide) through an adsorption method with a detection limit of 1.23 µM – 160 µM (Xu et al., 2022). Devarayan et al. (2020) created a halochromic thin film sensor by combining halochromic dye with polyvinyl alcohol, cellulose acetate and starch/potato dextrose agar and characterizing it by Fourier-transform infrared spectroscopy. This sensor can detect the spoiling of packaged fish by displaying color variations in proportion to the rotting of the packed seer fish. Similarly, by adding alizarin dye into zein electrospun nanofibers, a protein-based halochromic electrospun nanosensor for measuring the freshness of trout fish was developed to measure the freshness depending on the color change in real time (Aghaei et al., 2020).

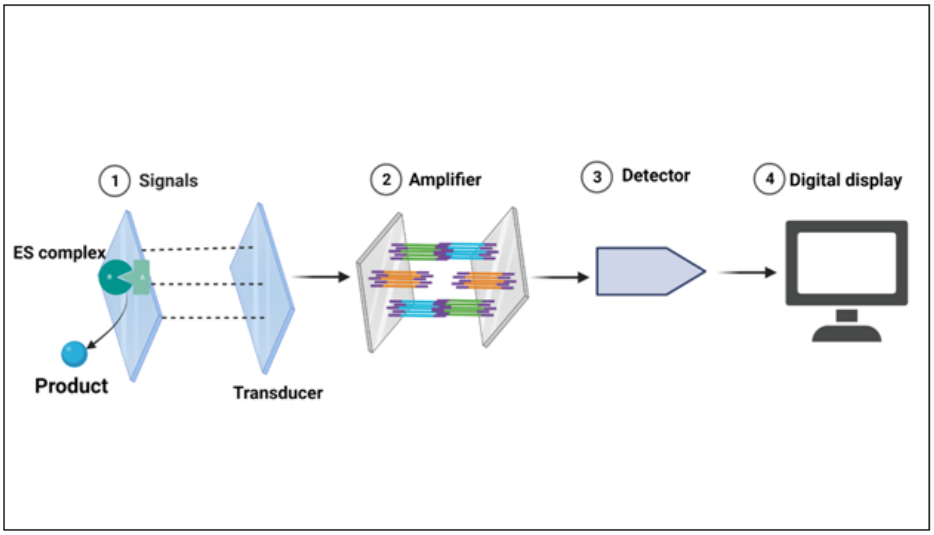


Figure 5. Schematic illustration of biosensor components involved in detection

Future potential application of biotechnology in the aquatic food production

Future research is required to resolve the numerous unanswered concerns about the use of biotechnology in fish production. This review work indicated the following future directions:

a) Fish waste may include substances relevant to the pharmaceutical or food industries. This is a good approach for monetizing fish waste, which benefits both economically and environmentally and contributes to the long-term viability of the fishery's output by supporting clean energy utilization.

b) Process optimization, computational tools, engineering and advances in molecular biology and related domains have contributed considerably to the manufacture of commercial fish production. However, issues and bottlenecks persist, such as a general lack of adequate screening of genetic variations arising from random mutagenesis.

c) Greater transparency between fish producers and consumers, as well as the implementation of honest labeling, would help to improve public perception of genetically altered fish. The food safety authority should require accurate labeling of genetically altered foods. This would provide buyers with information on the origin and perhaps the genetic composition of the fish they are purchasing.

d) Increased public money should be dedicated toward agricultural biotechnology on production-based research in the future. Increased government financing for other agricultural technology, such as the development of a genetically modified organism and their application, is also required.

Conclusion

In the interest of a sustainable food supply for the accelerated global population, biotechnology has emerged as a robust tool for upgrading and increasing aquatic food production and bioprocessing. Using biotechnology approaches, nonedible and perishable food items can be transformed into safe, palatable food with an extended shelf-life and significantly improved quality (e.g., nutritional values, sensory and physicochemical attributes). It has the potential to minimize the use of agrochemicals while also increasing the productivity, efficiency and profitability of food production. It also keeps our environment safe and clean for the use of future generations. The use of biotechnology in the fishing industry is a relatively new activity. Nonetheless, it is a suitable option for increasing fish production. The use of biological systems capabilities is fast increasing in a wide range of food applications, resulting in the development of several novel food sources, methods and products. This paper briefly highlights the current progress in fish and fish-related product production by utilizing biotechnology as a helpful tool.

Acknowledgements

The authors are thankful to ICAR – Central Inland Fisheries Research Institute (ICAR-CIFRI) for the financial and technical assistance in the study.

Conflicts of interest

The authors declare no conflict of interest.

References

Abass N.Y., Simora R.M.C., Wang J., Li S., Xing D., Coogan M., Johnson A., Creamer D., Wang X., Dunham R.A. (2022). Response of cecropin transgenesis to challenge with *Edwardsiella ictaluri* in channel catfish *Ictalurus punctatus*. Fish Shellfish Immunol., 126: 311–317.

Abelti A.L., Teka T.A., Fikreyesus Forsedo S., Tamiru M., Bultosa G., Alkhtib A., Burton E. (2022). Bio-based smart materials for fish product packaging: a review. Int. J. Food Prop., 25: 857–871.

Adams A., Thompson K.D. (2006). Biotechnology offers revolution to fish health management. Trends Biotechnol., 24, 201–205.

Aghaei Z., Ghorani B., Emadzadeh B., Kadkhodaee R., Tucker N. (2020). Protein-based halochromic electrospun nanosensor for monitoring trout fish freshness. Food Control., 111: 107065.

Ali A. (2022). New technique for improving fish packaging hygiene and prolonged shelf life. Afr. J. Biotechnol., 21: 237–251.

Anokhova V.D., Chupakhin E.G., Pershina N.A., Storublevtsev S.A., Antipova L.V., Matskova L.V., Antipov S.S. (2020). Sensitivity of different collagens to proteolytic enzyme treatment. Proc. Int. Conf.: "Health and wellbeing in modern society" (ICHW 2020), Atlantis Press, pp. 44–49.

Aquerreta Y., Astiasarn I., Bello J. (2002). Use of exogenous enzymes to elaborate the Roman fish sauce 'garum'. J. Sci. Food Agric., 82: 107–112.

Assefa A., Abunna F. (2018). Maintenance of fish health in aquaculture: review of epidemiological approaches for prevention and control of infectious disease of fish. Vet. Med. Int., 2018: 5432497.

Axelsson L., Bjerke G.A., McLeod A., Berget I., Holck A.L. (2020). Growth behavior of *Listeria monocytogenes* in a traditional Norwegian fermented fish product (Rakfisk) and its inhibition through bacteriophage addition. Foods, 9: 119.

Ayoola S.O., Idowu A.A. (2008). Biotechnology and species development in aquaculture. Afr. J. Biotechnol., 7: 4722–4725.

Aytac Z., Huang R., Vaze N., Xu T., Eitzer B.D., Krol W., MacQueen L.A., Chang H., Bousfield D.W., Chan-Park M.B., Ng K.W., Parker K.K., White J.C., Demokritou P. (2020). Development of biodegradable and antimicrobial electrospun zein fibers for food packaging. ACS Sustain. Chem. Eng., 8: 15354–15365.

Bedekar M.K., Kole S., Tripathi G. (2020). Biotechnological approaches to fish vaccine. In: Genomics and biotechnological advances in veterinary, poultry and fisheries. Academic Press, pp. 407–419.

Behera B.K. (2021). Nutritional biotechnology to augment aquaculture production. In: Advances in fisheries biotechnology. Springer Nature Singapore, pp. 231–243.

Bhargava N., Sharanagat V.S., Mor R.S., Kumar K. (2020). Active and intelligent biodegradable packaging films using food and food waste-derived bioactive compounds: a review. Trends Food Sci. Technol., 105: 385–401.

Buwono I.D., Iskandar I., Grandiosa R. (2021). Growth hormone transgenesis and feed composition influence growth and protein and amino acid content in transgenic G3 mutiara catfish (*Clarias gariepinus*). Aquac. Int., 29: 431–451.

Cabrera-Barjas G., Banerjee A., Valdes O., Moncada M., Sirajunnisa A.R., Surendhiran D., Ramakrishnan G., Rani N.S., Hamidi M., Kozani P.S., Kozani P.S. (2022). Food biotechnology: innovations and challenges. In: Future foods. Academic Press, pp. 697–719.

Çağrı Mehmetoğlu A., Sezer E., Erol S. (2021). Development of antimicrobial whey protein-based film containing silver nanoparticles biosynthesised by *Aspergillus niger*. Int. J. Food Sci. Technol., 56: 965–973.

Chiang K.Y., Lin W.C., Tsai T.Y., Lin C.W., Huang S.J., Huang C.Y., Wu S.H., Ken C.F., Gong H.Y., Chen J.Y., Wu J.L. (2020). Dual expression of transgenic delta-5 and delta-6 desaturase in tilapia alters gut microbiota and enhances resistance to *Vibrio vulnificus* infection. PLoS One, 15: e0236601.

Chukwu-Osazuwa J., Cao T., Vasquez I., Gnanagobal H., Hossain A., Machimbirike V.I., Santander J. (2022). Comparative reverse vaccinology of *Piscirickettsia salmonis*, *Aeromonas salmonicida*, *Yersinia ruckeri*, *Vibrio anguillarum* and *Moritellaviscosa*, frequent pathogens of Atlantic salmon and lumpfish aquaculture. Vaccines, 10: 473.

Coogan M., Alston V., Su B., Khalil K., Elaswad A., Khan M., Simora R.M.C., Johnson A., Xing D., Li S., Wang J., Lu C., Wang W., Hettiarachchi D., Hasin T., Terhune J., Butts I.A.E., Dunham R.A. (2022). CRISPR/Cas-9 induced knockout of myostatin gene improves growth and disease resistance in channel catfish (*Ictalurus punctatus*). Aquaculture, 557: 738290.

Coppola D., Lauritano C., Palma Esposito F., Riccio G., Rizzo C., De Pascale D. (2021). Fish waste: from problem to valuable resource. Mar. Drugs., 19: 116.

Dar A.H., Rashid N., Majid I., Hussain S., Dar M.A. (2019). Nanotechnology interventions in aquaculture and seafood preservation. Crit. Rev. Food Sci. Nutr., 60: 1912–1921.

Davies P.L. (2022). Reflections on antifreeze proteins and their evolution. Biochem. Cell Biol., 100: 282–291.

Dávila M.S., Latimer M.F., Dixon B. (2020). Enhancing immune function and fish health in aquaculture. Fish Physiol., 38: 123–161.

Dayakar B., Xavier K.A.M., Das O., Porayil L., Balange A.K., Nayak B.B. (2021). Application of extreme halophilic archaea as biocatalyst for chitin isolation from shrimp shell waste. Carbohydr. Polym. Technol. Appl., 2: 100093.

Dayakar B., Xavier K.A.M., Ngasotter S., Layana P., Balange A.K., Priyadarshini B., Nayak B.B. (2022). Characterization of spray-dried carotenoprotein powder from Pacific white shrimp (*Litopenaeus vannamei*) shells and head waste extracted using papain: antioxidant, spectroscopic and microstructural properties. LWT, 159: 113188.

Devarayan K., Pandiyan P., Nagaraju K.S., Anjappan H. (2020). Halochromic sensors for real-time monitoring of spoilage of packed seer fish. Mater. Today: Proc., 33: 3961–3966.

Devi R., Yadav S., Nehra R., Yadav S., Pundir C.S. (2013). Electrochemical biosensor based on gold coated iron nanoparticles/chitosan composite bound xanthine oxidase for detection of xanthine in fish meat. J. Food Eng., 115: 207–214.

Duan X., Zhang M., Li X., Mujumdar A.S. (2008). Microwave freeze drying of sea cucumber coated with nanoscale silver. Drying Technol., 26: 413–419.

FAO (2002). The state of food insecurity in the world. Rome, Italy, pp. 1–36.

FAO (2014). The state of world fisheries and aquaculture, Food and Agriculture Organization of the United Nations. Rome, Italy, pp. 1–230.

FAO (2018). State of fisheries and aquaculture in the world. Rome, Italy, pp. 332–333.

Faradilla W.E., Khalid W., Izzatul N., Jais A. (2021). A mini review on sensor and biosensor for food freshness detection. Malaysian J. Anal. Sci., 25: 153–164.

Felip A., Piferrer F. (2018). The induction of polyploidy, gynogenesis and androgenesis in the European sea bass. Sex Cont. Aquac., pp. 347–358.

Fernandes P. (2016). Enzymes in fish and seafood processing. Front. Bioeng. Biotechnol., 4: 59.

Fletcher G.L., Davies P.L., Hew C.L. (1992). Genetic engineering of freeze-resistant Atlantic salmon. Transgenic Fish, pp. 190–208.

Freire D.G., Fernández-Gómez R., Reyes-Salinas A., Castro G.M., Dorca-Fornell C., Proaño K. (2022). The colors of biotechnology in Ecuador: a general overview. CABI Reviews, 2022.

Freitas J., Vaz-Pires P., Câmara J.S. (2021). Quality index method for fish quality control: understanding the applications, the appointed limits and the upcoming trends. Trends Food Sci. Technol., 111: 333–345.

Ghaffarifar F. (2018). Plasmid DNA vaccines: where are we now. Drug. Today, 54: 315–33.

Gildberg A., Wichaphon J., Lertsiri S., Assavanig A., Sørensen N.K., Thongthai C. (2007). Chemical and organoleptic comparison of fish sauce made from cold water species and typical Thai fish sauce. J. Aquat. Food Prod. Technol., 16: 31–42.

Giyatmi G., Irianto H.E. (2017). Enzymes in fermented fish. Adv. Food Nutr. Res., 80: 199–216.

Guo J., Li Y., Wang Y., Chen B., Hu Y., Musha Y., He X., Tong T., Huang K. (2022). A 90-day subchronic toxicity study of consumption of GH-transgenic triploid carp in Wistar rats. Fishes, 7: 10.

Harlander S.K. 1(989). Food biotechnology: yesterday, today and tomorrow. Food Technol., 49: 196–206.

Hew C.L., Fletcher G.L. (2001). The role of aquatic biotechnology in aquaculture. Reprod. Biotechnol. Finfish Aquac., pp. 191–204.

Huang Y., Bugg W., Bangs M., Qin G., Drescher D., Backenstose N., Weng C.C., Zhang Y., Khalil K., Dong S., Elaswad A., Ye Z., Lu C., Vo K., Simora R.M., Ma X., Taylor Z., Yang Y., Zhou T., Guo J., Salze G., Qin Z., Wang Y., Dunham R.A. (2021). Direct and pleiotropic effects of the Masou Salmon Delta-5 Desaturase trans-

gene in F1 channel catfish (*Ictalurus punctatus*). Transgenic Res., 30: 185–200.
Hulse J.H. (2004). Biotechnologies: past history, present state and future prospects. Trends Food Sci. Technol., 15: 3–18.
Hussain M.G. (1996). Advances in chromosome engineering research in fish: review of methods, achievements and applications. Asian Fish. Sci., 9: 45–60.
Hutkins R.W. (2006). Microbiology and technology of fermented foods. Blackwell Publishing. p. 457.
Je J.Y., Park P.J., Kwon J.Y., Kim S.K. (2004). A novel angiotensin I converting enzyme inhibitory peptide from Alaska pollack (*Theragra chalcogramma*) frame protein hydrolysate. J. Agric. Food Chem., 52: 7842–7845.
Jónsdóttir G., Bjarnason J.B., Gudmundsdóttir Á. (2004). Recombinant cold-adapted trypsin I from Atlantic cod – expression, purification and identification. Protein Expr. Purif., 33: 110–122.
Kara A., Tamburaci S., Tihminlioglu F., Havitcioglu H. (2019). Bioactive fish scale incorporated chitosan biocomposite scaffolds for bone tissue engineering. Int. J. Biol. Macromol., 130: 266–279.
Kara K., Ouanji F., Lotfi E.M., El Mahi M., Kacimi M., Ziyad M. (2018). Biodiesel production from waste fish oil with high free fatty acid content from Moroccan fish-processing industries. Egypt. J. Pet., 27: 249–255.
Karewicz A., Machowska A., Kasprzyk M., Ledwójcik G. (2021). Application of halloysite nanotubes in cancer therapy – a review. Materials, 14: 2943.
Khanna H.K., Daggard G. (2008). Antifreeze proteins: a molecular approach for developing cold-tolerant rice. Adv. Rice Genet., 488–489.
Khorasani S., Danaei M., Mozafari M.R. (2018). Nanoliposome technology for the food and nutraceutical industries. Trends Food Sci. Technol., 79: 106–115.
Kieliszek M., Misiewicz A. (2014). Microbial transglutaminase and its application in the food industry – a review. Folia Microbiol., 59: 241–250.
Knorr D., Sinskey A.J. (1985). Biotechnology in food production and processing. Science, 229: 1224–1229.
Kumar V., Roy S., Meena D.K., Sarkar U.K. (2016). Application of probiotics in shrimp aquaculture: importance, mechanisms of action and methods of administration. Rev. Fish. Sci. Aquac., 24: 342–368.
Kumar V., Roy S., Behera B.K., Bossier P., Das B.K. (2021 a). Acute hepatopancreatic necrosis disease (AHPND): virulence, pathogenesis and mitigation strategies in shrimp aquaculture. Toxins, 13: 524.
Kumar V., Roy S., Behera B.K., Das B.K. (2021 b). Disease diagnostic tools for health management in aquaculture. In: Advances in fisheries biotechnology. Springer Nature Singapore, pp. 363–382.
Kumar V., Das B.K., Swain H.S., Chowdhury H., Roy S., Bera A.K., Das R., Parida S.N., Dhar S., Jana A.K., Behera B.K. (2022 a). Outbreak of *Ichthyophthirius multifiliis* associated with *Aeromonas hydrophila* in *Pangasianodon hypophthalmus*: the role of turmeric oil in enhancing immunity and inducing resistance against co-infection. Front. Immunol., 13: 4811.
Kumar V., Roy S., Behera B.K., Das B.K. (2022 b). Heat shock proteins (Hsps) in cellular homeostasis: a promising tool for health management in crustacean aquaculture. Life, 12: 1777.
Kumar V., Roy S., Behera B.K., Das B.K. (2022 c). RNA interference and its potential applications in aquatic animal health management. In: Biotechnological advances in aquaculture health management. Springer Nature Singapore, pp. 25–41.
Kumar V., Swain H.S., Roy S., Das B.K., Upadhyay A., Ramteke M.H., Kumar V., Kole R.K., Banerjee H. (2022 d). Integrated biomarker approach strongly explaining *in vivo* sub-lethal acute toxicity of butachlor on *Labeo rohita*. Comp. Biochem. Physiol. Part - C: Toxicol. Pharmacol., 261: 109427.
Kumar V., Das B.K., Swain H.S., Chowdhury H., Roy S., Bera A.K., Malick R.C., Behera B.K. (2023 a). Immunomodulatory potency of *Eclipta alba* (Bhringaraj) leaf extract in *Heteropneustes fossilis* against oomycete pathogen, *Aphanomyces invadans*. J. Fungi, 9: 142.
Kumar V., Bera T., Roy S., Vuong P., Jana C., Sarkar D.J., Devi M.S., Jana A.K., Rout A.K., Kaur P., Das B.K., Behera B.K. (2023 b). Investigating bio-remediation capabilities of a constructed wetland through spatial successional study of the sediment microbiome. NPJ Clean Water, 6: 8.
Kumari S., Sarkar U.K., Karnatak G., Mandhir S.K., Lianthuamluaia L., Kumar V., Panda D., Puthiyottil M., Das B.K. (2021). Food selectivity and reproductive biology of small indigenous fish Indian river shad, *Gudusia chapra* (Hamilton, 1822) in a large tropical reservoir. Environ. Sci. Pollut. Res., 28: 11040–11052.
Kuri K., Sokolović M., Drašner K., Petravić J., Kulaš M.M., Jakšić G. (2022). Health management of endemic and non-endemic fish in the Aquatika – Freshwater Aquarium Karlovac. Croat. J. Fish., 80: 141–150.
Kuswandi B., Wicaksono Y., Abdullah A., Heng L.Y., Ahmad M. (2011). Smart packaging: sensors for monitoring of food quality and safety. Sens. Instrum. Food Qual. Saf., 5: 137–146.
Lang L.H. (2006). FDA approves use of bacteriophages to be added to meat and poultry products. Gastroenterology, 131: 1370.
Ledford H. (2015). Salmon is first transgenic animal to win US approval for food. Nature, 19: 2015.
Lee C., Kim H., Ryu S. (2022). Bacteriophage and endolysin engineering for biocontrol of food pathogens/pathogens in the food: recent advances and future trends. Crit. Rev. Food Sci. Nutr., pp. 1–20.
LeGrand K., Borarin B., Young G.M. (2020). Tradition and fermentation science of prohok, an ethnic fermented fish product of Cambodia. J. Ethnic Foods, 7: 1–19.
Likhar V., Chudasama B.G. (2021). Seafood enzymes and their potential industrial applications. J. Entomol. Zool. Stud., 9: 1410–1417.
Lo J.H., Lin C.M., Chen M.J., Chen T.T. (2014). Altered gene expression patterns of innate and adaptive immunity pathways in transgenic rainbow trout harboring Cecropin P1 transgene. BMC Genom., 15: 1–13.
Loan T.T., Trang D.T.Q., Huy P.Q., Ninh P.X., Van Thuoc, D. (2022). A fermentation process for the production of poly (3-hydroxybutyrate) using waste cooking oil or waste fish oil as inexpensive carbon substrate. Biotechnol. Rep., 33: e00700.
Macouzet M., Simpson B.K., Lee B.H. (2005). Expression of a cold-adapted fish trypsin in *Pichia pastoris*. FEMS Yeast Res., 5: 851–857.
Mahalik S., Sharma A.K., Mukherjee K.J. (2014). Genome engineering for improved recombinant protein expression in *Escherichia coli*. Microb. Cell Fact., 13: 1–13.
Mahalik S., Mohapatra D., Kumar D. (2018). Cellulase production in *Lysinibacillus* sp. isolated from the estuaries of Odisha. Biosci. Biotechnol. Res. Commun., 11: 743–753.
Maiti B., Shetty M., Shekar M., Karunasagar I., Karunasagar I. (2011). Recombinant outer membrane protein A (OmpA) of *Edwardsiella tarda*, a potential vaccine candidate for fish, common carp. Microbiol. Res., 167: 1–7.
Maulu S., Hasimuna O.J., Haambiya L.H., Monde C., Musuka C.G., Makorwa T.H., Munganga B.P., Phiri K.J., Nsekanabo J.D. (2021). Climate change effects on aquaculture production: sustainability implications, mitigation and adaptations. Front. Sustainable Food Syst., 5: 609097.
McClements D.J., Rao J. (2011). Food-grade nanoemulsions: formulation, fabrication, properties, performance, biological fate and potential toxicity. Crit. Rev. Food. Sci. Nutr., 51: 285–330.
Meeusen E.N.T., Walker J., Peters A., Pastoret P.P., Jungersen G. (2007). Current status of veterinary vaccines. Clin. Microbiol. Rev., 20: 489–510.
Mehta A., Guleria S., Sharma R., Gupta R. (2021). The lipases and their applications with emphasis on food industry. In: Microbial biotechnology in food and health. Academic Press, pp. 143–164.
Meral R., Ceylan Z., Kose S. (2019). Limitation of microbial spoilage of rainbow trout fillets using characterized thyme oil antibacterial nanoemulsions. J. Food Saf., 39: e12644.
Mohanty B., Mohanty U., Pattanaik S.S., Panda A., Jena A.K. (2018). Future prospects and trends for effective utilization of fish processing wastes in India. Innovative Farming, 3: 1–5.
Muthusamy S., Ajit S., Nath A.V., Anupama Sekar J., Ramyaa Lakshmi T.S. (2022). Enzymes from genetically modified organisms

and their current applications in food development and food chain. In novel food grade enzymes: applications in food processing and preservation industries. Springer, pp. 357–382.
Nagy A., Rajki K., Horvárth L., Csárnyi V. (1978). Investigation on carp, *Cyprinus carpio* L. gynogenesis. J. Fish Biol., 13: 215–224.
Najafi M., Lee B. (2014). Biotechnology and its impact on food security and safety. Curr. Nutr. Food Sci., 10: 94–99.
Navarro S., Guillot R., Crespo D., Schulz R.W., Ge W., Rotllant J., Cerdá-Reverter J.M., Rocha A. (2021). Enhanced growth without accelerated puberty in fish: a role for the melanocortin system. Aquaculture, 540: 736721.
Neidleman S.L. (1984). Applications of biocatalysis to biotechnology. Biotechnol. Genet. Eng. Rev., 1: 1–38.
Ngasotter S., Panda S.P., Mohanty U., Akter S., Mukherjee S., Waikhom D., Devi L.S. (2020). Current scenario of fisheries and aquaculture in India with special reference to Odisha: a review on its status, issues and prospects for sustainable development. Int. J. Bio-Res. Stress Manag., 11: 370–380.
Ngasotter S., Waikhom D., Sharma S., Meitei M.M., Mangang Y.A., Irungbam S.K., Bhuneshwar Devi M.S., Singh A.S. (2021). Characteristics and mechanism of potential probiotics with special reference to lactic acid bacteria from traditional fermented fish products: a review. J. Exp. Biol. Agric. Sci., 9: 263–275.
Ngasotter S., Sampath L., Xavier K.A.M. (2022). Nanochitin: an update review on advances in preparation methods and food applications. Carbohydr. Polym., 291: 119627.
Nhu N.T.H., Nhu N.Q., Nhi N.T.Y., Phuong N.H.N. (2019). Biodegradable food packaging membrane from bacterial cellulose and bacteriocin for preserving raw food. Vietnam J. Food Control, 2: 114–120.
Nie X., Zhang R., Cheng L., Zhu W., Li S., Chen X. (2022). Mechanisms underlying the deterioration of fish quality after harvest and methods of preservation. Food Control, 135: 108805.
Østli J., Heide M., Carlehög M., Eilertsen G. (2006). The importance of bacalhau consumption in Portugal and a preliminary product consumer test in Lisboa. In: Seafood research from fish to dish: quality, safety and processing of wild and farmed fish. Wageningen Academic, pp. 241–249.
Polonis M., Jagiełło K., Dobosz S., Rożyński R., Kondraciuk P., Gurgul A., Szmatoła T., Ocalewicz K. (2019). Alterations in the rainbow trout (*Oncorhynchus mykiss*) eggs exposed to ionizing radiation during induced androgenesis. Reprod. Domest. Anim., 54: 712–718.
Pumchan A., Sae-Ueng U., Prasittichai C., Sirisuay S., Areechon N., Unajak S. (2022). A novel efficient piscine oral nano-vaccine delivery system: modified halloysite nanotubes (HNTs) preventing streptococcosis disease in tilapia (*Oreochromis* sp.). Vaccines, 10: 1180.
Purdom C.E. (1983). Genetic engineering by the manipulation of chromosomes. Aquaculture, 33: 287–300.
Putriantini I.N., Dityanawarman A., Inaiyah I., Rahman H. (2022). A model of fish consumption among Indonesian youth with the moderation on their perception of fish quality assurance. Jurnal Perikanan Universitas Gadjah Mada, 24: 11–19.
Qiu L., Zhang M., Bhandari B., Yang C. (2020). Shelf-life extension of aquatic products by applying nanotechnology: a review. Crit. Rev. Food Sci. Nutr., 62: 1521–1535.
Ranjha M.M.A.N., Irfan S., Nadeem M., Mahmood S. (2020). A comprehensive review on nutritional value, medicinal uses and processing of banana. Food Rev. Int., 38: 199–225.
Ravishankar C.N. (2019). Advances in processing and packaging of fish and fishery products. Adv. Agric. Res. Technol. J., 3: 168–181.
Refstie T., Gjedrem T. (2005). Chromosome engineering. In selection and breeding programs in aquaculture. Springer, pp. 287–299.
Refstie T., Vassvik V., Gjedrem T. (1977). Induction of polyploidy in salmonids by cytochalasin B. Aquaculture, 10: 65–74.
Robert J., Jancovich J.K. (2016). Recombinant ranaviruses for studying evolution of host–pathogen interactions in ectothermic vertebrates. Viruses, 8: 1–13.
Robertson G.L. (2009). Food packaging and shelf life: a practical guide. CRC Press, p. 404.
Roy S., Kumar V., Mitra A., Manna R.K., Suresh V.R., Homechaudhuri S. (2018). Amylase and protease activity in shrimps and prawn of Sundarbans, West Bengal, India. Indian J. Mar. Sci., 47: 53–59.
Roy S., Kumar V., Bossier P., Norouzitallab P., Vanrompay D. (2019). Phloroglucinol treatment induces transgenerational epigenetic inherited resistance against *Vibrio* infections and thermal stress in a brine shrimp (*Artemia franciscana*) model. Front. Immunol., 10: 2745.
Roy S., Bossier P., Norouzitallab P., Vanrompay D. (2020). Trained immunity and perspectives for shrimp aquaculture. Rev. Aquac., 12: 2351–2370.
Roy S., Kumar V., Behera B.K., Das B.K. (2022 a). Epigenetics: perspectives and potential in aquaculture. In: Advances in fisheries biotechnology. Springer Nature Singapore, pp. 133–150.
Roy S., Kumar V., Behera B.K., Parhi J., Mohapatra S., Chakraborty T., Das B.K. (2022 b). CRISPR/Cas genome editing – can it become a game changer in future fisheries sector? Front. Mar. Sci., 9: 924475.
Ruan L., Ju Y., Zhan C., Hou L. (2022). Improved umami flavor of soy sauce by adding enzymatic hydrolysate of low-value fish in the natural brewing process. LWT, 155: 112911.
Samad N.E.A., Ghani I.F.A. (2021). Techniques to produce polyploidy species in aquaculture: a review. AJLS, 1: 51–55.
Sampath L., Ngasotter S., Layana P., Balange A.K., Nayak B.B., Xavier K.A.M. (2022 a). Effect of chemical treatment duration on physicochemical, rheological and functional properties of colloidal chitin. Food Hydrocoll., 2: 100091.
Sampath L., Ngasotter S., Porayil L., Balange A.K., Nayak B.B., Eappen S., Xavier K.A.M. (2022 b). Impact of extended acid hydrolysis on polymeric, structural and thermal properties of microcrystalline chitin. Carbohydr. Polym. Technol. Appl., 4: 100252.
Santos V.P., Marques N.S., Maia P.C., Lima M.A.B.D., Franco L.D.O., Campos-Takaki G.M.D. (2020). Seafood waste as attractive source of chitin and chitosan production and their applications. Int. J. Mol. Sci., 21: 4290.
Sarkar B., Mahanty A., Gupta S.K., Choudhury A.R., Daware A., Bhattacharjee S. (2022). Nanotechnology: A next-generation tool for sustainable aquaculture. Aquaculture, 546: 737330.
Sharma A.K., Sharma V., Saxena J., Kuila A. (2016). Lipase production from a wild (LPF-5) and a mutant (HN1) strain of *Aspergillus niger*. Afr. J. Biotechnol., 15: 2292–2300.
Shin J.H., Chang S., Kang D.H. (2004). Application of antimicrobial ice for reduction of foodborne pathogens (*Escherichia coli* O157:H7, *Salmonella typhimurium*, *Listeria monocytogenes*) on the surface of fish. J. Appl. Microbiol., 97: 916–922.
Shin Y.J., Kwon T.H., Seo J.Y., Kim T.J. (2013). Oral immunization of fish against iridovirus infection using recombinant antigen produced from rice callus. Vaccine, 31: 5210–5215.
Singh A., Benjakul S. (2018). Proteolysis and its control using protease inhibitors in fish and fish products: a review. Compr. Rev. Food. Sci. Food. Saf., 17: 496–509.
Singh M., Unadkat K., Kapoor S., Enamala M.K., Parikh P., Chandrasekhar K. (2022). Potential applications of biopolymers in fisheries industry. In: Biopolymers: recent updates, challenges and opportunities. Cham: Springer International Publishing, pp. 199–221.
Singh S.S., De Mandal S., Mathipi V., Ghatak S., Kumar N.S. (2018). Traditional fermented fish harbors bacteria with potent probiotic and anticancer properties. Biocatal. Agric. Biotechnol., 15: 283–290.
Sobhan A., Muthukumarappan K., Wei L. (2021). Biosensors and biopolymer-based nanocomposites for smart food packaging: challenges and opportunities. Food Packag. Shelf Life., 30: 100745.
Soltani M., Ghosh K., Hoseinifar S.H., Kumar V., Lymbery A.J., Roy S., Ringø E. (2019). Genus bacillus, promising probiotics in aquaculture: aquatic animal origin, bio-active components, bioremediation and efficacy in fish and shellfish. Reviews Fish. Sci. Aquac., 27: 331–379.
Sun Y., Liu C.S., Sun L. (2010). Identification of an *Edwardsiella tarda* surface antigen and analysis of its immunoprotective potential as a purified recombinant subunit vaccine and a surface-anchored subunit vaccine expressed by a fish commensal strain. Vaccine, 28: 6603–6608.

Tahsin K.N., Soad A.R., Ali A.M., Moury I.J. (2017). A review on the techniques for quality assurance of fish and fish products. Int. J. Adv. Eng. Res. Sci., 4: 4190–4206.

Thakur M.S., Ragavan K.V. (2013). Biosensors in food processing. J. Food Sci. Technol., 50: 625–641.

Tramper J., Zhu Y. (2011). Modern Biotechnology: for Better or for Worse? In: Modern biotechnology. Wageningen Academic Publishers, pp. 273–274.

Tropea A., Potortì A.G., Lo Turco V., Russo E., Vadalà R., Rando R., Di Bella G. (2021). Aquafeed production from fermented fish waste and lemon peel. Fermentation, 7: 272.

Tseng C.C., Chu T.W., Danata R.H., Risjani Y., Shih H.T., Hu S.Y. (2020). Hepcidin-expressing fish eggs as a novel food supplement to modulate immunity against pathogenic infection in zebrafish (*Danio rerio*). Sustainability, 12: 4057.

Tsironi T.N., Taoukis P.S. (2018). Current practice and innovations in fish packaging. J. Aquat. Food Prod. Technol., 27: 1024–1047.

Uma S., Jeevan P. (2022). Production of organic manure "FAA"– Fish amino acid. In: Bioentrepreneurship in biosciences – recent approaches. Darshan Publishers, pp. 119–134.

Urakova I.N., Pozharitskaya O.N., Demchenko D.V., Shikov A.N., Makarov V.G. (2013). The biological activities of fish peptides and methods of their isolation. Russ. J. Mar. Biol., 38: 417–422.

Vasil I.K. (1998). Agriculture: biotechnology and food security for the 21st century: a real-world perspective. Nat. Biotechnol., 16: 399–400.

Venugopal V., Lakshmanan R., Doke S.N., Bongirwar D.R. (2009). Enzymes in fish processing, biosensors and quality control: a review. Food Biotechnol., 14: 21–77.

Verma M.L., Rao N.M., Tsuzuki T., Barrow C.J., Puri M. (2019). Suitability of recombinant lipase immobilised on functionalised magnetic nanoparticles for fish oil hydrolysis. Catalysts, 9: 420.

Vijayan K.K., Sukumaran S., Pradeep M.A., Sanil N.K., Vijayagopal P. (2013). Biotechnological approaches in fishery management. In: ICAR funded short course on "ICT– oriented strategic extension for responsible fisheries management. CMFRI, pp. 119–125.

Wagner G., Schmid R.D. (1990). Biosensors for food analysis. Food Biotechnol., 4: 215–240.

Walker R., Decker E.A., McClements D.J. (2015). Development of food-grade nanoemulsions and emulsions for delivery of omega-3 fatty acids: opportunities and obstacles in the food industry. Food Funct., 6: 42–55.

Waltz E. (2017). First genetically engineered salmon sold in Canada. Nature, 548: 148.

Wang Y., Hamid N., Jia P.P., Pei D.S. (2021). A comprehensive review on genetically modified fish: key techniques, applications and future prospects. Rev. Aquac., 13: 1635–1660.

Wankhade V. (2020). Animal-derived biopolymers in food and biomedical technology. In: Biopolymer-based formulations. Elsevier, pp. 139–152.

Windsor M., Barlow S. (1981). Introduction to fishery by-products. Fishing News Books Ltd., p. 187.

Wu H., Lu J., Xiao D., Yan Z., Li S., Li T., Wan X., Zhang Z., Liu Y., Shen G., Li S. (2021). Development and characterization of antimicrobial protein films based on soybean protein isolate incorporating diatomite/thymol complex. Food Hydrocoll., 110: 106138.

Xing D., Su B., Bangs M., Li S., Wang J., Bern L., Simora R.M.C., Wang W., Ma X., Coogan M., Johnson A., Wang Y., Qin Z., Dunham R. (2022). CRISPR/Cas9–mediated knock-in method can improve the expression and effect of transgene in P1 generation of channel catfish (*Ictalurus punctatus*). Aquaculture, 560: 738531.

Xu X., Wu X., Zhuang S., Zhang Y., Ding Y., Zhou X. (2022). Colorimetric biosensor based on magnetic enzyme and gold nanorods for visual detection of fish freshness. Biosensors, 12: 135.

Xu Y., Zang J., Regenstein J.M., Xia W. (2021). Technological roles of microorganisms in fish fermentation: a review. Crit. Rev. Food Sci. Nutr., 61: 1000–1012.

Yee L., Blanch H.W. (1993). Recombinant trypsin production in high cell density fed-batch cultures in *Escherichia coli*. Biotechnol. Bioeng., 41: 781–790.

Zhang Z., Sun Y., Sang S., Jia L., Ou C. (2022). Emerging approach for fish freshness evaluation: principle, application and challenges. Foods, 11: 1897.

Zhao J., Wei F., Xu W., Han X. (2020). Enhanced antibacterial performance of gelatin/chitosan film containing capsaicin loaded MOFs for food packaging. Appl. Surf. Sci., 510: 145418.

Zhao Z., Wang H., Zhang D., Guan Y., Siddiqui S.A., Feng-Shan X., Cong B. (2022). Oral vaccination with recombinant *Lactobacillus casei* expressing *Aeromonas hydrophila* Aha1 against *A. hydrophila* infections in common carps. Virulence, 13: 794–807.

Zhen N., Wang X., Li X., Xue J., Zhao Y., Wu M., Zhou D., Liu J., Guo J., Zhang H. (2022). Protein-based natural antibacterial materials and their applications in food preservation. Microb. Biotechnol., 15: 1324–1338.

Zhu W., Luan H., Bu Y., Li J., Li X., Zhang Y. (2021). Changes in taste substances during fermentation of fish sauce and the correlation with protease activity. Food Res. Int., 144: 110349.

Zhu Z., He L., Chen S. (1985). Novel gene transfer into the fertilized eggs of gold fish (*Carassius auratus* L. 1758). J. Appl. Ichthyol., 1: 31–34.

Zilda D.Z. (2014). Microbial transglutaminase: source, production and its role to improve surimi properties. Squalen Bull. Mar. Fish. Postharvest Biotechnol., 9: 35–44.

Received: 23 XI 2022
Accepted: 12 IV 2023