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Posted Date: 30 April 2026

doi: 10.20944/preprints202604.1864.v1

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Review

Biomarkers for Sustainable European Aquaculture: Current Applications and Future Directions

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Simple Summary

Aquaculture is an important and growing source of food in Europe, where sustainability and animal welfare are key priorities. Biomarkers, biological indicators of physiological and environmental responses, are increasingly used to monitor fish health, detect disease early, and assess environmental conditions. This review summarizes current applications of biomarkers in European aquaculture and highlights emerging technologies such as omics approaches and biosensors. It also discusses existing challenges and future directions for improving their use in sustainable aquaculture systems.

Abstract

Aquaculture in Europe has experienced significant growth in recent decades, driven by rising demand for sustainable production and strong policy frameworks promoting environmentally responsible aquaculture practices. Biomarkers, defined as measurable biological indicators reflecting physiological, biochemical, or molecular responses to environmental and biological stressors, have greatly expanded their use in aquaculture applications. In this regard, biomarker-based approaches are increasingly applied in multiple areas of aquaculture, including health and disease monitoring, welfare assessment, environmental toxicology, reproductive biology, population management, and the optimization of cryopreservation protocols. This review provides a comprehensive overview of current biomarker applications in European aquaculture, highlighting recent technological advances, methodological challenges, and emerging research directions. By synthesizing current knowledge and identifying future research priorities, this review aims to contribute to the development of biomarker-driven monitoring strategies that enhance the resilience, efficiency, and sustainability of aquaculture in Europe.

Keywords: biomarkers; aquaculture; health monitoring; biosensing; cryopreservation

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1. Introduction

Aquaculture is the fastest growing food production sector globally and increasingly contributes to global food security. Currently, aquaculture supplies nearly half of the aquatic animal products consumed by humans, and its contribution is expected to continue increasing in response to population growth, changing dietary patterns, and pressures on fisheries by capture [1]. Although Asia dominates global aquaculture production, Europe represents a distinctive aquaculture region characterized by advanced technologies, strict regulatory frameworks, and a strong emphasis on environmental sustainability, animal welfare, and food safety [2]. The aquaculture production in Europe was estimated at 2.87–3.0 million tonnes in 2023, which constitutes nearly 2.1–2.2% of global production according to the [3].

Despite its relatively modest share in global production, European aquaculture exhibits a highly structured and technologically advanced production system. The European sector is characterized by stringent regulatory compliance, rigorous traceability requirements, and management systems focused on sustainability [4]. In addition, the spatial distribution of aquaculture production across Europe exhibits significant heterogeneity. Norway dominates European aquaculture production, accounting for nearly 44% of total farmed fish output, largely driven by its highly developed Atlantic salmon industry. In contrast, aquaculture production in many other European countries is more diversified, involving multiple species and a variety of production systems, including both marine and freshwater aquaculture [5–7].

Key farmed species in Europe include rainbow trout (*Oncorhynchus mykiss*), Atlantic salmon (Salmo salar), gilthead seabream (*Sparus aurata*), European seabass (*Dicentrarchus labrax*), common carp (*Cyprinus carpio*), and several mollusc species such as mussels and oysters [8]. These diverse production systems create complex biological and environmental interactions that require reliable monitoring tools to ensure fish health, welfare, and environmental sustainability.

European aquaculture systems are highly heterogeneous, reflecting diverse environmental conditions, species composition, and production practices across regions. For instance, Northern European aquaculture is largely dominated by intensive salmon farming under cold-water conditions, whereas Mediterranean systems focus on species such as seabream and seabass under warmer and more variable environmental conditions. These regional differences influence both the selection and interpretation of biomarkers, emphasizing the need for context-specific approaches tailored to local production systems.

In this context, biomarkers have emerged as valuable tools for monitoring biological processes in aquaculture species. Biomarkers can be broadly defined as measurable biological responses that reflect physiological, biochemical, molecular, or cellular changes occurring within an organism in response to internal or external stimuli. In aquaculture research and management, biomarkers are widely used to detect early signs of disease, evaluate stress and welfare status, determine reproductive performance, and monitor environmental impacts. Depending on their functional role, biomarkers can include physiological, immunological, biochemical, genetic, and omics-based indicators that provide insights into organism health and environmental interactions [9,10]. Their ability to provide early-warning signals before clinical symptoms appear makes them particularly valuable for preventive health management in aquaculture systems.

The importance of biomarker research is further amplified by the policies and regulatories shaping European aquaculture. The European Union has placed aquaculture at the center of several strategic initiatives, including the European Green Deal and the Farm-to-Fork Strategy, which aim to promote sustainable food systems, reduce environmental impacts, and minimize the use of antimicrobials in food production [11,12]. To achieve these objectives, effective monitoring approaches are needed to assess the health of fish, environmental impacts, and ecosystem connectivity. Consequently, biomarkers are increasingly recognized not only as research tools but also as potential components of monitoring frameworks supporting regulatory compliance, biosecurity, and sustainability assessments.

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European research initiatives have played a significant role in advancing biomarker-based approaches in aquaculture. Large collaborative programs such as AQUAEXCEL2020, AQUA-FAANG, the BioAqua COST Action, and MedPlants4Vet have contributed to the development of novel molecular, physiological, and genomic biomarkers applicable to aquaculture species. These initiatives have strengthened interdisciplinary collaboration and promoted the integration of advanced Technologies, including proteomics, transcriptomics, metabolomics, and epigenomics, into aquaculture research.

Despite these significant advances, several challenges continue to limit the widespread application of biomarkers in commercial aquaculture systems. Many biomarkers have been developed and validated primarily under controlled laboratory conditions, with limited testing under real farm environments where animals are exposed to complex and fluctuating environmental conditions [13–15]. Furthermore, issues related to methodological standardization, cost-effectiveness, and accessibility remain important constraints, particularly for small and medium-sized enterprises (SMEs), which constitute a large proportion of European aquaculture producers. In addition, although omics-based technologies have generated promising biomarker candidates, their integration into routine health and welfare monitoring systems is still at an early stage, limiting their practical implementation in commercial aquaculture operations [16–18].

In light of the regulatory complexity, technological capacity, and sustainability ambitions of European aquaculture, a comprehensive synthesis of biomarker applications is required. This review is based on a structured literature survey conducted using major scientific databases, including Web of Science, Scopus, and PubMed. Keywords such as “biomarkers”, “aquaculture”, “fish health”, “stress indicators”, “omics”, and “European aquaculture” were used in various combinations. Priority was given to peer-reviewed articles published between 2010 and 2025, with particular emphasis on recent developments in biomarker applications. Studies were selected based on their relevance to aquaculture systems, biological significance, and methodological robustness. Although this review follows a narrative approach, efforts were made to ensure a comprehensive and balanced representation of the current state of knowledge.

This review aims to provide an overview of biomarkers currently applied in European aquaculture, with particular emphasis on their roles in disease diagnosis, stress and welfare monitoring, environmental assessment, and reproductive biotechnology. Furthermore, this study highlights key methodological challenges, knowledge gaps, and emerging research directions that could facilitate the development of more effective biomarker-based monitoring systems for sustainable aquaculture in Europe.

2. The Role of Biomarkers in Aquaculture Industry

Biomarkers are measurable indicators of physiological, biochemical, molecular, or behavioural responses that provide early and sensitive insights into how aquatic organisms respond to stressors, pathogens, pollutants, and aquaculture practices [19–22]. These indicators range from classical physiological markers, such as cortisol, glucose, and enzyme activities, to advanced molecular approaches, including transcriptomics, proteomics, metabolomics, and environmental DNA (eDNA) analyses.

Within aquaculture systems, biomarkers play several important roles, including the early detection of pathogens, the evaluation of immune responses to vaccination, the monitoring of physiological stress and animal welfare, and the determination of environmental and toxicological exposure. By revealing early signs of physiological or microbial imbalance, biomarker-based monitoring allows for more timely and proactive management. In practice, such approaches can help prevent disease outbreaks, support improved animal welfare, and reduce risks linked to environmental conditions and production performance [23–25].

Beyond health and welfare monitoring, biomarkers also play a critical role in reproductive biotechnology, which underpins the sustainability and genetic improvement of aquaculture [26,27].

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Reproductive success in farmed fish depends on gamete quality, broodstock condition, and the effectiveness of breeding programs. Biomarkers such as steroid hormone levels, vitellogenin concentrations, gametogenesis-related gene expression, and sperm motility indices are widely used to assess reproductive status, predict spawning success, and optimize artificial propagation techniques [28–30]. These indicators support efficient hatchery management and selective breeding programs to improve productivity and adaptability in aquaculture species.

An important extension of reproductive biomarker research is cryopreservation, which enables the long-term storage of gametes and embryos for genetic resource conservation [31,32]. In this regard, biomarkers are used to evaluate the viability, structural integrity, and functional competence of cryopreserved cells, ensuring that stored genetic material retains its reproductive potential when reintroduced into breeding programs [33].

Another important category of biomarkers in aquaculture is sex determination biomarkers. These markers enable the early and accurate identification of genetic sex long before external sexual characteristics become visible, thereby overcoming key limitations associated with traditional phenotypic sexing methods in juvenile fish [34].

Furthermore, functional biomarkers, including post-translational protein modifications and host-associated microbiome profiles, are increasingly recognized for their ability to capture rapid regulatory processes and complex host–environment interactions that may not be fully reflected by gene or protein abundance alone [35,36]. Their integration provides more comprehensive understanding of physiological plasticity, health resilience, and environmental adaptability in aquaculture species, highlighting their potential to improve monitoring and management strategies. A conceptual overview of biomarker categories and their integration into aquaculture systems is presented in Figure 1.

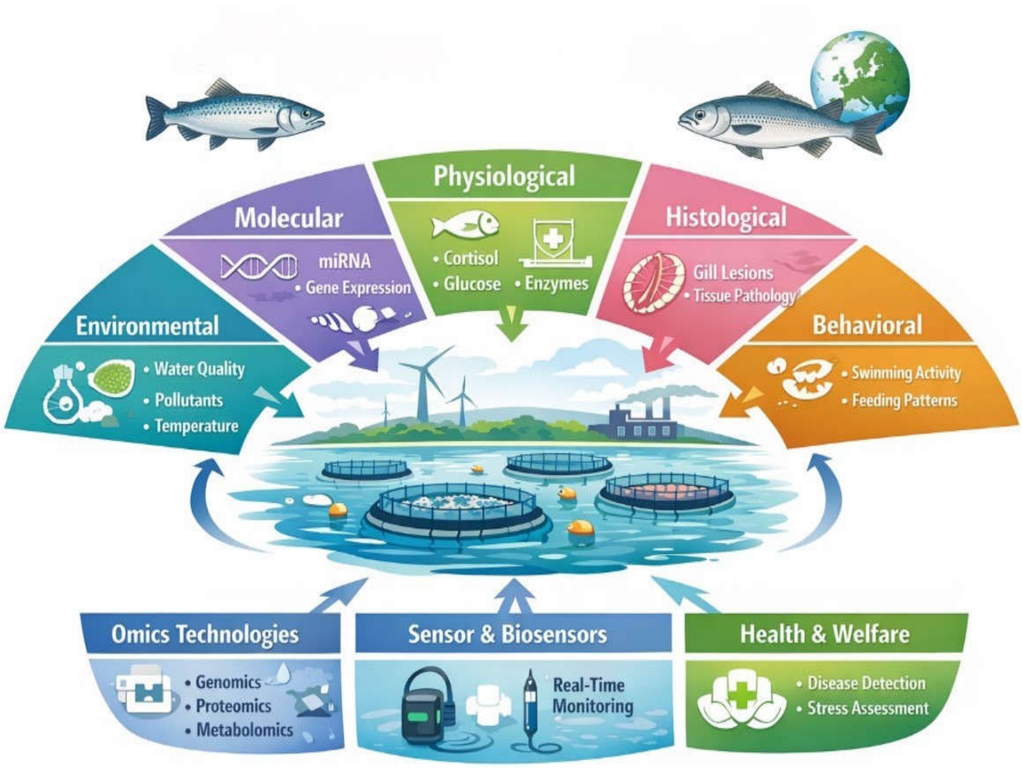

Figure 1. Integrated overview of biomarker categories and applications in European aquaculture.

This figure illustrates the main categories of biomarkers used in aquaculture, including molecular, physiological, histological, environmental, and behavioral indicators, and their

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interactions within aquaculture systems. It also highlights the integration of advanced technologies such as omics approaches, biosensors, and real-time monitoring tools in supporting fish health, welfare, and sustainable production. The diagram emphasizes the multidimensional and interconnected nature of biomarker applications in modern European aquaculture.

3. Classification and Description of Biomarkers Used in Aquaculture

Biomarkers in aquaculture are typically categorized based on their biological level, functional role, and detection method. This categorization highlights both the complexity of biological responses in cultured aquatic species and the advancing sophistication of analytical tools used for their evaluation.

3.1. Classification Based on Biological Level

Table 1 summarizes the classification of biomarkers employed in aquaculture based on their biological levels.

Table 1. Classification of biomarkers in aquaculture based on their biological levels: examples and applications at different biological scales.

Biomarker type	Example	Applicability
Genetic/Molecular	Enzymes, epigenetic, sexing	Early detection of stress or disease; monitoring gene expression responses to pathogens, toxins, or environmental changes; early sex identification
Biochemical	Enzymes, metabolites, hormone levels	Assessment of physiological stress; evaluation of metabolic and immunological responses; detection of toxic effects
Cellular	Cell structures, membranes, phagocytosis activity	Monitoring cellular health and immune function; evaluating cell-level responses to pathogens or pollutants
Physiological	Growth rate, behavior, feed intake	Organism-level responses to nutrition, stress, and environmental changes; detection of subclinical effects
Histological	Confocal microscopy, 3D tissue imaging, automated morphometry	Detection of structural alterations in organs and tissues
Behavioral	Shoaling and spatial distribution, swimming patterns and velocity, feeding latency and appetite	Non-invasive, continuous and real-time measures of fish welfare and environmental suitability

3.1.1. Genetic/Molecular Biomarkers

Molecular biomarkers are among the earliest indicators of stress, disease, and environmental change, as they capture rapid responses occurring at the level of genes and nucleic acids. A common example is the expression of heat-shock proteins, such as HSP70 and HSP90, which are typically upregulated in response to thermal stress or handling and can signal both cellular stress and immune activation. In addition, assays that evaluate DNA integrity, including the comet assay, are frequently used to identify genotoxic damage [37].

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Genetic biomarkers, which form a subset of molecular indicators, focus specifically on variation at the DNA level. These include microsatellites, gene mutations, and single nucleotide polymorphisms (SNPs), and are widely applied in studies of population structure, genetic diversity, and selective breeding efficiency [38]. In the context of European aquaculture, such markers are particularly useful for identifying genotypes with improved tolerance to stress or resistance to disease, thereby supporting more sustainable breeding programs [27].

Recent advances have broadened the scope of molecular biomarkers to include epigenetic regulation, such as histone modifications, and DNA methylation, as well as non-coding RNAs like microRNAs (miRNAs). These mechanisms can reflect longer-term adaptive responses and in some cases, transgenerational effects linked to environmental or nutritional pressures [18]. In parallel, post-translational modifications, including acetylation, phosphorylation, methylation, and ubiquitination, are gaining attention as sensitive indicators of cellular signalling pathways, offering insights into stress responses and reproductive processes [36].

In fish, sex determination is highly variable and often depends on genetic or genomic differences between males and females [39,40]. As a result, most biomarkers used for sex identification are genetic in nature, although some rely on differences in gene expression and can therefore be considered within the broader category of molecular biomarkers.

3.1.2. Biochemical Biomarkers

Biochemical biomarkers link molecular-level changes with whole-organism physiology and are widely applied to evaluate stress responses, metabolic regulation, immune status, and toxicological effects in fish. Frequently used indicators include plasma cortisol, glucose, lactate, lysozyme activity, and extracellular vesicles, all of which can reflect both short-term and prolonged stress, as well as shifts in metabolism and immune function [41–43].

In addition, mucosal and mucin-related biomarkers, such as mucins, goblet cells, and rodlet cells, offer valuable non-invasive options for assessing immune defence and stress responses in barrier tissues like the skin, gills, and intestine [44,45]. These markers are particularly useful for monitoring fish health without the need for invasive sampling.

Metabolomics-based approaches further expand biochemical assessment by profiling amino acids, lipids, and energy-related metabolites. This type of analysis enables the early identification of nutritional imbalances, stress conditions, or disease development and is gaining increasing attention in aquaculture research [46].

Hormonal profiling also plays an important role, with panels including estradiol, testosterone, cortisol, melatonin, and thyroid hormones providing integrated information on stress, reproductive function, and circadian rhythms in cultured fish [47].

3.1.3. Cellular Biomarkers

Oxidative stress biomarkers are widely used to assess how fish respond at the cellular level to environmental and husbandry-related stress in aquaculture systems. Measures associated with energy metabolism, such as lactate dehydrogenase (LDH) activity and the electron transport system (ETS), can provide insight into shifts in metabolic processes and aerobic capacity under stress conditions [48].

Markers linked to liver function and overall toxicity, particularly aspartate aminotransferase (AST), alanine aminotransferase (ALT), and alkaline phosphatase (ALP), are often used to detect tissue damage, as their levels tend to increase when hepatocellular integrity is compromised. At the same time, antioxidant enzymes such as catalase (CAT), superoxide dismutase (SOD), and glutathione peroxidase (GPx) play a central role in controlling reactive oxygen species (ROS) and maintaining cellular redox balance [48].

If these protective mechanisms are insufficient, elevated ROS levels can lead to oxidative damage, particularly through lipid peroxidation. In this context, compounds like thiobarbituric acid-

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reactive substances (TBARS), and malondialdehyde (MDA) are commonly measured as indicators of oxidative damage, especially under conditions of poor water quality or pollutant exposure [49].

3.1.4. Physiological Biomarkers

Physiological biomarkers reflect the overall condition of an organism by linking biochemical and cellular processes. Among these, hematological parameters, such as red and white blood cell counts, haematocrit, and haemoglobin levels, are commonly used to evaluate stress and disease status in fish [50]. Other indices, including the condition factor (K), hepatosomatic index (HSI), and gonadosomatic index (GSI), provide broader insights into growth, nutritional condition, and reproductive status [18,51].

Respiratory biomarkers, such as oxygen consumption, cardiac function, and blood oxygen-binding capacity, are useful for assessing tolerance to hypoxia and temperature-related stress. These indicators are particularly relevant for aquaculture management under changing climate conditions [52]. Similarly, osmoregulatory markers, including plasma ion levels and gill Na^+/K^+-ATPase activity, are widely applied to evaluate the ability of fish to cope with variations in salinity and temperature [18,53]. Taken together, these physiological measures are essential for understanding how fish perform under fluctuating aquaculture conditions.

Recent technological developments have also made it possible to monitor physiological parameters in real time. While glucose has traditionally been measured through blood sampling, new wireless and implantable biosensors now allow continuous tracking of glucose as a stress-related indicator [54,55]. These systems typically combine a biosensor with a potentiostat and data transmission components, and in some cases include optical or color-based interfaces for immediate visualization. Sensors can be placed in interstitial fluids, where glucose concentrations closely mirror those in the blood, while external components handle data collection and transmission. In addition, heart rate loggers, often positioned near the pericardial region, enable continuous monitoring of cardiovascular responses to stress [56].

Overall, these emerging technologies offer powerful opportunities for continuous physiological monitoring, providing valuable information to support fish welfare assessment and more responsive aquaculture management practices.

3.1.5. Histological Biomarkers

Histological biomarkers indicate structural changes in organs and tissues caused by nutritional imbalances, exposure to pollutants, or disease. Under chronic stress or contaminant exposure, common observations include deformation of gill lamellae, vacuolization of hepatocytes, and histopathological changes in gonads. In reproductive biotechnology, analyzing the histology of gonadal maturation stages offers valuable insights into spawning readiness and reproductive success [57].

Advances in imaging techniques, including confocal microscopy, 3D tissue imaging, and automated morphometry, enable precise analysis of structural changes in organs and tissues. Furthermore, histological assessments can be integrated with molecular biomarkers, such as organ-specific post-translational modifications (PTMs), to provide a multi-level understanding of organismal health and reproductive performance [36].

3.1.6. Behavioral Biomarkers

Behavioral biomarkers provide non-invasive and real-time insights into fish welfare and environmental suitability, often responding earlier than biochemical indicators. Common behavioral endpoints include changes in shoaling behavior and spatial distribution, as well as alterations in swimming activity, feeding response, and appetite. Other traits such as risk-taking, boldness, and aggression are also used to assess stress under conditions like handling, high stocking density, hypoxia, temperature fluctuations, poor water quality, and contaminant exposure. In addition,

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respiration rate, measured as opercular beat frequency, is widely used as a simple and non-invasive indicator of respiratory and metabolic stress in farmed fish [58–60].

Behavioral monitoring systems are increasingly applied in precision aquaculture to quantify these responses [18]. Social hierarchy plays an important role in fish welfare; for example, in gilthead sea bream (*Sparus aurata*), dominant–subordinate interactions are linked to higher stress levels and reduced immune performance in subordinate individuals. Such findings can support practical decisions on stocking density and tank design to improve overall welfare [54,55].

3.2. Classification Based on Functional Role

Table 2 presents classification of biomarkers used in aquaculture based on their functional roles.

Table 2. Classification of biomarkers in aquaculture based on their functional roles: examples and applications.

Biomarker Function	Example	Applicability
Health and Disease	Lysozyme activity, complement system function, cytokine expression	Early detection of infection, vaccination efficiency, antimicrobial resistance tracking
Stress and Welfare	Cortisol, glucose, lactate, and behavioral responses	Physiological response to stress
Environmental	Metallothioneins, acetylcholinesterase inhibition, DNA damage assays	Indicate heavy metal accumulation; neurotoxic pesticide exposure; integrative measures of cumulative exposure to contaminant mixtures
Reproductive and Cryobiology	Sex steroid hormones, gametogenesis-related gene expression, sperm motility and morphology, egg fertilization rate, mitochondrial activity, ROS accumulation, DNA fragmentation	Broodstock management, gamete quality assessment, and selective breeding
Food Safety and Quality	MDA, peroxide value, histamine content	Product freshness, residue monitoring, and consumer protection
Sexing	Sex-specific genetic markers	Early sex identification and breading efficiency

3.2.1. Health and Disease Biomarkers

Health and disease biomarkers are widely used to assess fish health in aquaculture, as they reflect how organisms respond to environmental, nutritional, and pathogenic challenges. A range of immune-related parameters, such as lysozyme activity, complement system function, cytokine expression, and antibody production, can be particularly informative. These indicators are commonly applied for early detection of infection, evaluation of vaccine responses, and monitoring of antimicrobial resistance. For instance, increased lysozyme or peroxidase activity is often associated with enhanced non-specific immune defense [18]. In recent years, shifts in gut and gill microbiome

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composition have also been recognized as useful indicators of disease susceptibility and dysbiosis, as they reflect both host condition and environmental influences [35].

Metabolic biomarkers, including enzyme activities and hormones such as IGF-1 and catecholamines, provide insight into digestion, stress physiology, and nutrient utilization [61–65]. Similarly, oxidative stress biomarkers, such as antioxidant enzymes (SOD, CAT, GPx), glutathione levels, and lipid or protein oxidation products like MDA and TBARS, are widely used to evaluate cellular damage caused by reactive oxygen species [45,66,67].

Additional immunological indicators, including lysozymes, proteases, complement proteins, acute-phase proteins (e.g., CRP), and leukocyte respiratory burst activity, offer more detailed information on the status of both innate and adaptive immune responses [68,69]. Taken together, these biomarkers provide a comprehensive picture of fish health, helping to assess disease risk and evaluate the effectiveness of management strategies in aquaculture systems.

3.2.2. Stress and Welfare Biomarkers

In intensive aquaculture conditions, fish frequently face various stressors, such as high stocking densities, handling, fluctuations in water quality, and transport. When these stressors persist or occur repeatedly, they can negatively affect immune function, growth, and reproduction. For this reason, stress- and welfare-related biomarkers are commonly used to assess the physiological condition of cultured species [18].

Quantitative indicators such as glucose, lactate, and cortisol are frequently measured alongside behavioral observations to evaluate both short-term and prolonged welfare challenges, including handling, transport, and crowding. In addition, non-invasive approaches, such as sampling mucus or waterborne metabolites, are increasingly being used. These methods, together with sensor-based monitoring systems, make it possible to assess fish welfare in near real time. Such tools are valuable for routine monitoring, improving husbandry practices, and supporting welfare certification within EU regulatory frameworks [18].

3.2.3. Environmental Biomarkers

Environmental biomarkers are widely used to evaluate interactions between aquaculture activities and surrounding aquatic ecosystems, making them an important component of sustainable production. They are commonly applied to assess the exposure of cultured species to pollutants, toxic compounds, and environmental stressors such as temperature fluctuations, hypoxia, and harmful algal blooms [70–72].

Biochemical indicators, including metallothioneins, acetylcholinesterase (AChE) activity, and detoxification enzymes, are frequently used to detect exposure to heavy metals, pesticides, and organic contaminants. In addition, oxidative stress markers and heat shock proteins provide insight into how organisms respond at the cellular level to environmental stress [71,73,74].

Well-established biomarkers, such as cytochrome P4501A activity measured via ethoxyresorufin-O-deethylase (EROD), metallothionein induction, and AChE inhibition, are routinely used to evaluate exposure to hydrocarbons, heavy metals, and neurotoxic compounds, respectively [75]. These approaches have been validated in European sentinel species, including Mytilus galloprovincialis, as well as in wild fish populations from coastal areas influenced by aquaculture [76].

More recently, attention has shifted toward emerging biomarkers, such as changes in gut and gill microbiome composition and metabolomic profiles, which can reflect water quality, pollutant-induced dysbiosis, and metabolic disruption in cultured fish [77]. DNA damage assays and other genetic biomarkers are also used to assess long-term genotoxic effects in aquaculture environments [78]. By combining multiple endpoints, multi-biomarker indices allow both spatial and temporal evaluation of ecosystem health and support environmental risk assessment under European policy

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frameworks, including the Water Framework Directive [79]. These tools also help distinguish aquaculture-related impacts from broader sources of anthropogenic contamination.

3.2.4. Reproductive and Cryobiology Biomarkers

Reproductive and cryobiology biomarkers are central to improving the productivity and sustainability of aquaculture, particularly in areas such as selective breeding, hatchery management, and genetic resource conservation. Biomarkers linked to reproductive physiology provide valuable information on broodstock condition, gamete quality, and reproductive readiness. In females, indicators such as steroid hormones and vitellogenin levels are commonly used to assess reproductive status. In males, parameters including sperm motility, mitochondrial activity, and the expression of genes related to spermatogenesis are widely applied to evaluate reproductive performance [26–30]. These measurements are routinely used to support decisions on spawning induction, artificial fertilization, and broodstock management.

Additional reproductive biomarkers include sex steroid hormones (e.g., estradiol, testosterone, and 11-ketotestosterone), gonadotropins, and genes involved in gametogenesis. Functional indicators such as sperm motility and morphology, fertilization success, and embryo survival provide direct and practical measures of reproductive performance [80,81].

Cryobiology represents an important extension of this field. Cryopreservation allows for the long-term storage of gametes and embryos, supporting both breeding programs and the conservation of genetic resources. In this context, biomarkers are used to evaluate cell integrity, viability, and functionality after storage, helping ensure that preserved material remains suitable for future use [31–33]. Commonly assessed indicators include membrane integrity, mitochondrial activity, reactive oxygen species (ROS) levels, DNA fragmentation, and post-thaw motility. Together, molecular and biochemical markers provide insight into the mechanisms of cryodamage and support the refinement of cryopreservation protocols, including the selection of appropriate cryoprotectants [82,83].

3.2.5. Food Safety and Quality Biomarkers

Food safety and quality biomarkers are widely used to provide the safety, freshness, and marketability of aquaculture products. These indicators support the monitoring of chemical residues, spoilage processes, and nutritional quality, helping to protect consumers and maintain traceability along the production chain. Markers of oxidative stability, such as malondialdehyde (MDA) and peroxide value, are commonly used to assess lipid oxidation and estimate product shelf life. Histamine levels are also routinely measured in fish species susceptible to scombroid poisoning, ensuring compliance with food safety regulations.

In addition, metabolomic approaches offer a more detailed understanding of the biochemical changes that take place during storage, handling, and processing. This allows for improved quality control and supports regulatory requirements. Taken together, these biomarkers form a practical toolkit for aligning aquaculture products with European Union food safety legislation and international standards [18].

3.2.6. Sexing Biomarkers

Sexing biomarkers are genetic and molecular tools used to distinguish between males and females, supporting more efficient breeding, early sex identification, and the development of monosex cultures or conservation strategies. For instance, male-specific markers identified through 2b-RAD sequencing and whole-genome analysis have revealed an XX/XY sex-determination system in mud carp (*Cirrhinus molitorella*), enabling accurate early genotyping for breeding applications [84]. In mulloway (Argyrosomus japonicus), a PCR-based marker targeting a deletion in the dmrt1 gene allows reliable sex differentiation across life stages, improving broodstock management and supporting conservation efforts for this species [85].

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Whole-genome resequencing studies in blunt snout bream (Megalobrama amblycephala) have led to the identification of male-specific markers that can be used for sex-controlled breeding and may also be applicable to closely related species [86]. In paiche (*Arapaima gigas*), non-invasive genotyping using duplex qPCR and male-specific genomic regions enables sex identification from gill mucus samples, offering a practical alternative to more invasive methods [87]. Similar genome-based approaches have been applied in Spinibarbus hollandi, where an XY system has been confirmed and candidate sex-determining genes identified. Comparable strategies have also been developed in other aquaculture species, such as small abalone (*Haliotis diversicolor*) and ayu (*Plecoglossus altivelis*), where sex-linked markers support reliable molecular assays [88]. Together, these advances improve the accuracy of early sex identification while also contributing to a better understanding of sex-determination mechanisms in fish.

From a practical standpoint, these markers are valuable tools for selective breeding and broodstock management. By enabling the establishment of optimal sex ratios, they can enhance growth performance, stock uniformity, and overall production value. This is particularly relevant for species where monosex populations are preferred, such as all-male tilapia or all-female turbot and sturgeon, and where reducing reliance on hormonal treatments is desirable. In addition, sexing biomarkers support marker-assisted selection by allowing genetic sex to be identified even in sex-reversed individuals, thereby improving the efficiency of breeding programs [34]. Beyond their applied value, these tools also contribute to research on sex determination and sexual dimorphism, providing insights that are important for long-term sustainability in aquaculture.

Recent work has extended the application of sexing biomarkers to sturgeon (*Acipenseridae*), a group of high economic value for caviar production but difficult to sex at early stages due to the absence of clear external differences. A major advance has been the identification of female-specific genomic regions, particularly the AllWSex2 locus, which appears to be conserved across several sturgeon species. This marker shows strong agreement with phenotypic sex and enables early, non-invasive identification using standard tissue samples [89].

Building on this, quantitative PCR (qPCR) assays targeting AllWSex2, combined with melt curve analysis, have been developed for lake sturgeon (Acipenser fulvescens), providing a rapid and practical tool for both conservation and aquaculture management [90]. Studies in Russian sturgeon (Acipenser gueldenstaedtii) have further confirmed the conservation of this region and identified additional sex-associated loci, improving understanding of the genetic basis of sex determination and supporting the development of reliable commercial assays [91,92]. These approaches are increasingly being applied in sturgeon aquaculture, where early sex identification can substantially minimize the time and costs typically associated with traditional methods.

3.3. Classification Based on Detection Approach

Table 3 presents classification of biomarkers used in aquaculture based on their detection methods.

Table 3. Classification of biomarkers in aquaculture based on their functional roles: examples and applications.

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Biomarker Detection	Example	Applicability
Classical	Histology, biochemical and physiological assays	Stress and health assessments
Omics-Based	Genomics, proteomics, transcriptomics	Whole organism response to stressors - disease, environmental changes, stress
Non-Invasive	Mucus, blood and faeces analyses, water metabolites	Stress and immune monitoring without culling animals

3.3.1. Classical Biomarkers

Classical biomarkers include well-established biochemical and physiological assays, histological analyses, and hormone measurements. These approaches are generally cost-effective, standardized, and widely used to assess stress, health status, and overall physiological condition in aquaculture systems. Their reliability and ease of application make them particularly useful for routine monitoring and day-to-day management. In practice, they provide essential baseline information that can complement more advanced molecular, genetic, or omics-based techniques [93].

3.3.2. Omics-Based Biomarkers

Omics-based biomarkers rely on high-throughput techniques, such as transcriptomics, genomics, metabolomics, and proteomics, to capture broad patterns of how organisms respond to stress, disease, and environmental change. These approaches are especially useful for identifying new indicators linked to resilience, disease resistance, growth, and reproductive performance [18].

In practice, genomics- and transcriptomics-based methods often use qPCR or RT-qPCR, which can be adapted to work with complex samples such as tissue homogenates rather than fully purified nucleic acids. This reduces processing time and simplifies workflows, making large-scale screening more feasible in aquaculture settings.

Overall, omics approaches complement classical and functional biomarkers by providing a broader, multi-level view of fish health, physiology, and interactions with the environment.

3.3.3. Non-Invasive Biomarkers

Non-invasive biomarkers rely on non-lethal sampling methods, such as the analysis of mucus, faeces, or waterborne metabolites, to monitor stress, immune responses, and overall physiological condition without harming the animals. These approaches are increasingly used in welfare assessment, as well as in monitoring gamete quality and managing broodstock, particularly in high-value species [18].

Taken together, the wide range of biomarkers used in aquaculture, from genetic and molecular indicators to behavioural, reproductive, and cryobiology-related markers, provides a comprehensive framework for assessing animal health, environmental conditions, and breeding performance. The integration of omics-based and non-invasive approaches further improves the precision of these assessments, while also supporting more sustainable practices, higher welfare standards, and long-term conservation of genetic resources [18,82,83].

4. Applications of Biomarkers in European Aquaculture

Biomarkers are increasingly used in European aquaculture as practical tools to support more sustainable, welfare-focused, and resilient production systems. Their applications cover a broad range of areas, including health monitoring, disease prevention, environmental assessment, and reproductive management. By detecting early signs of physiological stress, immune responses, and

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metabolic imbalance, biomarkers make it possible to take action before visible disease symptoms appear [27]. They are also commonly used to evaluate vaccine performance, nutritional status, and the effects of emerging stressors such as temperature changes and declining water quality linked to climate variability [94].

Environmental and toxicological biomarkers are particularly important for assessing exposure to pollutants and for supporting compliance with European regulations aimed at protecting aquatic ecosystems [95]. In addition to routine monitoring, biomarkers are now being incorporated into selective breeding programs and cryopreservation strategies, contributing to genetic improvement and the long-term conservation of broodstock. Recent developments in metabolomic and lipidomic approaches have further expanded their use, improving product traceability, physiological assessment, and quality control along the production chain [96].

Overall, biomarker-based approaches are helping to support more data-driven decision-making in precision aquaculture. They contribute to better fish welfare, improved resistance to disease, and stronger sustainability outcomes, while also enhancing the competitiveness of European aquaculture in the face of changing environmental conditions, regulatory requirements, and market demands. The application of biomarkers in aquaculture follows a multi-step process from sampling to decision-making, as illustrated in Figure 2.

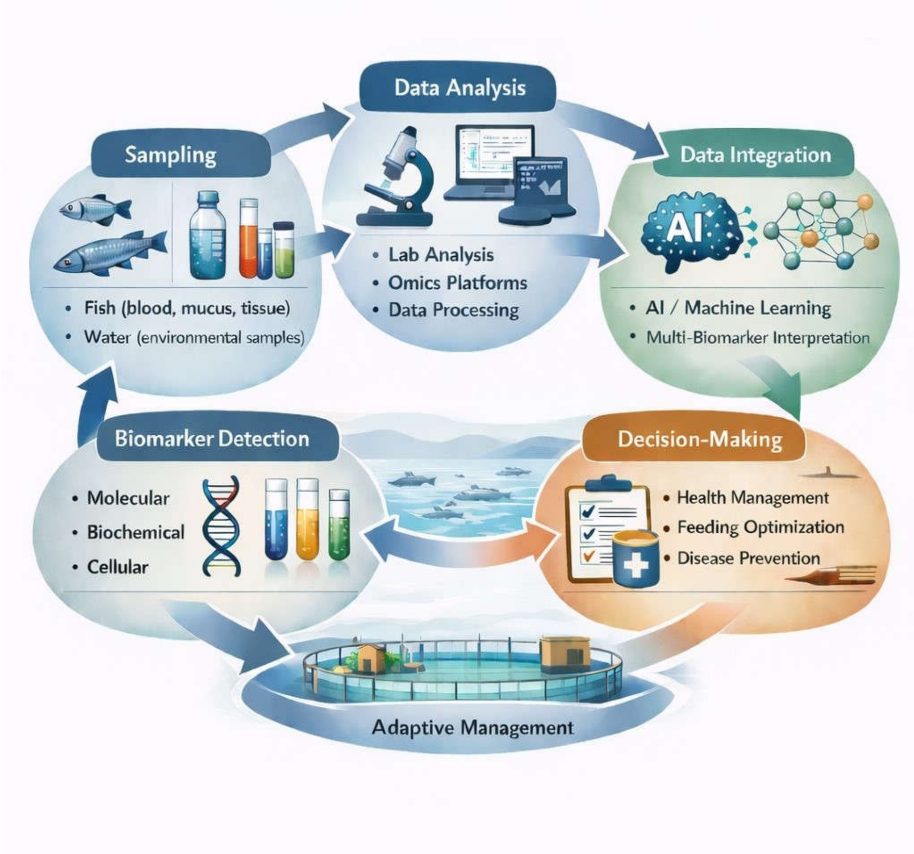

Figure 2. Workflow of biomarker-based monitoring in aquaculture systems.

This figure illustrates the workflow of biomarker-based monitoring in aquaculture, from sample collection to decision-making. Biological samples obtained from fish and the surrounding environment are analyzed using molecular, biochemical, and cellular approaches. The resulting data are processed and integrated, increasingly with the support of artificial intelligence tools, to inform management decisions such as health monitoring, feeding strategies, and disease prevention. The feedback loop highlights the dynamic and adaptive nature of modern aquaculture systems.

4.1. Applications in Health and Disease Monitoring

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Health-related biomarkers are widely used in aquaculture to support early disease detection, assess immune status, and guide preventive health management. Indicators such as lysozyme activity, components of the complement system, cytokine expression, and antibody levels are commonly measured to evaluate how fish respond to bacterial, viral, and parasitic infections [97,98]. These markers can reveal subclinical infections, allowing producers to respond before disease outbreaks lead to major economic losses.

Molecular biomarkers have further strengthened diagnostic capabilities in aquaculture. Changes in the expression of genes that are involved in immune regulation, stress response, and inflammation can signal early stages of pathogen exposure, often before visible symptoms develop [99,100]. When used alongside molecular tools such as PCR-based pathogen detection and serological assays, these biomarkers form a robust framework for disease surveillance and risk assessment.

More recently, attention has turned to microbiome-based biomarkers. Shifts in microbial community structure and metabolite production can indicate dysbiosis linked to disease susceptibility, nutritional imbalances, or environmental stress [35,77]. Combining microbiome data with traditional immune indicators provides a more complete picture of host health and disease dynamics in aquaculture systems.

In addition to diagnosis, biomarkers are increasingly applied to evaluate vaccine performance, the effectiveness of antimicrobial treatments, and the impact of functional feeds containing immunostimulants or probiotics [23,101]. Overall, biomarker-based approaches support more targeted health management, helping to reduce reliance on antibiotics, improve disease control, and enhance the sustainability of aquaculture production.

While molecular and immunological biomarkers provide highly sensitive tools for early disease detection, their routine application in commercial aquaculture remains limited by cost, technical complexity, and the need for specialized laboratory infrastructure. In contrast, classical biomarkers such as enzyme activity and hematological parameters are more readily applicable but may lack sensitivity and specificity. This trade-off highlights the importance of balancing accuracy with feasibility when selecting biomarkers for routine monitoring.

4.2. Applications in Welfare Assessment

The assessment of animal welfare has become an important aspect of responsible aquaculture, and biomarkers provide objective tools for evaluating stress and physiological disturbance in cultured species. In fish and other aquatic organisms, stress responses are often described using endocrine and metabolic indicators, with cortisol being the most widely used marker of both chronic and acute stress [25,47,102]. Increases in cortisol are typically accompanied by metabolic changes, including elevated plasma glucose and lactate levels, which reflect the mobilization of energy reserves needed to cope with environmental challenges [102,103].

At the cellular level, heat shock proteins (HSP70 and HSP90) are commonly used as indicators of physiological stress. Their expression is triggered by a range of stressors, such as hypoxia, temperature fluctuations, handling, and high stocking densities. As a result, they provide useful insight into cellular stress responses and the capacity of organisms to adapt to changing conditions [74,104].

Behavioral indicators have also proven to be sensitive measures of welfare status. Changes in swimming activity, feeding behavior, ventilation rate, and social interactions can signal underlying stress before biochemical responses are fully evident [59,60]. With recent advances in automated video systems and artificial intelligence, it is now possible to monitor these behaviors continuously in aquaculture settings, allowing early detection of abnormal patterns without disturbing the animals [105].

Bringing together endocrine, physiological, and behavioral indicators within a multi-parameter framework offers a more complete approach to welfare assessment. However, several European studies highlight the need for standardized sampling methods and clearly defined thresholds to

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ensure that biomarker-based indicators can be reliably applied in practice and aligned with EU animal welfare regulations and certification schemes [106,107].

4.3. Applications in Monitoring of Environment

Environmental biomarkers are widely used to evaluate the effects of aquaculture activities and surrounding stressors on aquatic organisms and ecosystems. They can provide early warning signs of sublethal exposure to pollutants and help identify ecological risks linked to chemical contamination, eutrophication, and habitat degradation [70,72]. In Europe, biomarker-based monitoring is increasingly combined with conventional chemical analyses required under frameworks such as the Water Framework Directive, strengthening environmental risk assessment around aquaculture sites [79].

Unlike chemical measurements alone, biomarker approaches offer insight into the biological effects of contaminants rather than just their presence. In aquaculture systems, this makes it possible to detect early physiological disturbances in cultured or sentinel species, supporting ecosystem-based management and more informed environmental impact assessments [70].

A range of biochemical and molecular indicators has proven useful in ecotoxicological monitoring. Metallothioneins are commonly applied to detect exposure to heavy metals, while reduced acetylcholinesterase activity is associated with contamination by organophosphate and carbamate pesticides [73,108]. In addition, oxidative stress biomarkers, such as antioxidant enzymes including catalase (CAT), superoxide dismutase (SOD) and glutathione peroxidase (GPx), are widely used to assess cellular damage caused by environmental pollutants and other stressors [71].

More recently, emerging tools such as environmental DNA (eDNA) analysis and metabolomic profiling have expanded the scope of environmental biomonitoring. These methods enable sensitive detection of pathogens, invasive species, and shifts in biodiversity, contributing to a more comprehensive understanding of ecosystem health in aquaculture areas [109,110].

4.4. Applications in Reproductive Biology and Cryobiology

Biomarkers are increasingly used in aquaculture to assess reproductive status, gamete quality, and overall reproductive performance. Hormonal indicators such as estradiol, testosterone, 11-ketotestosterone, and vitellogenin are commonly measured to track gonadal development, maturation, and endocrine regulation in fish [81,111,112]. These markers provide useful information for broodstock management, helping producers better understand reproductive timing, fecundity, and gamete quality in commercial systems.

In recent years, biomarker-based approaches have also become increasingly important in cryobiology and aquatic germplasm conservation. Cryopreservation is widely used for the long-term storage of sperm, oocytes, and embryos, supporting both selective breeding and the preservation of genetic resources [113,114]. To evaluate the success of these processes, researchers commonly monitor indicators such as mitochondrial function, membrane integrity, oxidative stress, and DNA damage, which reflect post-thaw cell viability and functionality [112,113].

Using these biomarkers, it is possible to refine cryoprotectant formulations, as well as freezing and thawing protocols, ultimately improving reproductive outcomes. European cryobanking initiatives have shown that biomarker-guided optimization can enhance post-thaw gamete performance across a range of species of both commercial and conservation interest [114]. As a result, biomarkers play an important role in maintaining high-quality aquatic biobanks and supporting selective breeding, stock enhancement programs, and the long-term preservation of genetic diversity in aquaculture [112,115].

4.5. Applications in Food Quality and Safety

Biomarkers are increasingly used to assess the quality, safety, and traceability of aquaculture products. Indicators such as oxidative stability parameters, histamine levels, metabolomic profiles,

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and DNA-based species identification markers are commonly applied to evaluate freshness, detect chemical residues, and confirm species authenticity across seafood supply chains [116]. These tools also support compliance with European food safety and traceability policies, including the Farm to Fork Strategy and related regulatory frameworks designed to enhance transparency and sustainability in the EU food system [4].

A range of biochemical indicators is routinely used to monitor freshness, oxidative stability, and microbial spoilage in fish and seafood. Lipid oxidation markers such as malondialdehyde (MDA), peroxide value, and thiobarbituric acid reactive substances (TBARS) are widely applied to assess oxidative deterioration during storage and processing [117]. These compounds provide practical and reliable measures of lipid peroxidation and are commonly incorporated into quality control protocols.

Histamine concentration is another important biomarker in seafood safety, particularly for species prone to histamine accumulation under improper storage conditions. Elevated histamine levels are typically associated with microbial spoilage and can cause scombroid poisoning in consumers [118]. As a result, histamine monitoring remains a key component of food safety assessment in both national and international regulatory systems.

Alongside biochemical indicators, molecular biomarkers are increasingly used to verify species identity and ensure traceability in seafood markets. DNA-based methods, including species-specific and DNA barcoding markers, enable accurate identification of fish species and help prevent mislabeling and seafood fraud [119,120].

More advanced analytical techniques, such as metabolomics and lipidomics, are further expanding the scope of biomarker applications. These approaches generate detailed biochemical fingerprints of aquatic products, enabling the identification of species-specific metabolic signatures and quality-related indicators. In doing so, they enhance traceability, support fraud detection, and improve quality control across global seafood supply chains [96,121].

4.6. Biomarkers in Precision Aquaculture

The use of biomarkers within precision aquaculture is becoming an increasingly important direction for modern aquaculture management. Precision aquaculture itself depends on automated monitoring systems, sensor networks, and data-driven tools to improve production efficiency, support environmental sustainability, and maintain animal welfare [105]. These systems enable the continuous collection of biological and environmental data, allowing managers to respond more quickly and make more informed decisions in aquaculture operations.

Biomarkers add an additional layer of insight by reflecting the biological state of the cultured organisms. For example, biosensors that can detect physiological indicators such as stress-related hormones, metabolic byproducts, or immune responses make it possible to monitor fish health in near real time [122,123]. When this type of data is combined with artificial intelligence and machine learning approaches, it becomes possible to integrate biological signals with environmental and behavioral information to anticipate disease risks, refine feeding practices, and better manage water quality [105].

In addition, advances in multi-omics approaches, such as genomics, proteomics, transcriptomics, and metabolomics, are expanding the range of detectable biomarkers and supporting more comprehensive health monitoring strategies in aquaculture species [100,124]. These high-throughput methods provide deeper insight into how organisms respond to stress, disease, and nutritional changes. As these technologies continue to develop, biomarker-driven precision aquaculture is expected to contribute significantly to greater sustainability, resilience, and productivity across aquaculture systems worldwide.

5. Challenges and Limitations

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Although biomarker research in aquaculture has expanded considerably in recent years, its practical application in commercial settings still faces several persistent challenges. These limitations are not linked to a single factor but rather emerge from the interaction of biological variability, environmental complexity, and technical constraints [25,102,103]. As a result, translating promising laboratory findings into reliable field applications remains difficult.

One of the most frequently encountered issues is the discrepancy between laboratory results and farm conditions. Under controlled experimental settings, many biomarkers exhibit clear and consistent responses. However, aquaculture environments are inherently variable, with multiple stressors, such as temperature changes, handling procedures, stocking density, and fluctuations in water quality, acting simultaneously [103,106]. In such contexts, biomarker signals are often less distinct, making interpretation more uncertain and, in some cases, less reliable for decision-making [58,106].

A related concern is the limited specificity of widely used biomarkers. Parameters such as cortisol, glucose, or oxidative stress enzymes are popular because they are relatively easy to measure and respond rapidly to stress. At the same time, these indicators are influenced by a wide range of factors and do not point to a single underlying cause [102,125]. This can complicate interpretation, particularly when biomarkers are used on their own. For this reason, there is growing recognition that combining multiple biomarkers, rather than relying on a single parameter, provides a more robust and biologically meaningful assessment [100,126].

Another important limitation concerns the lack of standardization across studies. Sampling procedures, analytical techniques, and data processing methods can vary considerably, making it difficult to compare results or establish consistent reference values [25]. In addition, differences between species, life stages, and production systems further complicate the definition of universal thresholds. Without commonly accepted protocols and validated benchmarks, the routine use of biomarkers in aquaculture management remains somewhat constrained [27].

Technical and economic factors also play a significant role. Advanced approaches, particularly those based on omics technologies, offer detailed insights into biological processes but often require specialized equipment, trained personnel, and substantial financial resources [127,128]. This limits their use outside well-equipped research settings. On the other hand, simpler and more accessible biomarkers are already used in practice, yet they may not provide the level of sensitivity needed for early detection or fine-scale monitoring. In this sense, there is an ongoing balance between feasibility and analytical depth [25].

Biological and temporal variability add another layer of complexity. Biomarker responses can be influenced by factors such as age, sex, reproductive status, and even daily rhythms [102,103]. These sources of variation are not always easy to control under farm conditions and can affect the consistency of measurements. Moreover, long-term datasets are still relatively scarce, which makes it challenging to develop predictive models or establish reliable monitoring frameworks over time.

Finally, even when high-quality biomarker data are available, their integration into routine management decisions is not always straightforward. While data generation has advanced rapidly, tools that translate this information into clear, actionable guidance for farmers are still developing. Limited availability of real-time monitoring systems and user-friendly decision-support platforms further reduces the immediate practical impact of biomarker-based approaches [105].

Taken together, these challenges highlight the need for a more integrated and application-oriented perspective. Future progress will likely depend on improved standardization, validation under real farming conditions, and the development of cost-effective and accessible technologies. In addition, closer integration with digital tools, such as biosensors and data-driven systems, may help bridge the gap between research outputs and aquaculture practice [1,105].

6. Future Perspectives

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The future development of biomarker applications in aquaculture will likely be shaped by rapid advances in molecular tools, digital monitoring systems, and integrated data analysis. As aquaculture continues to grow and faces increasing pressures related to environmental change and fish health, there is a rising need for reliable biomarkers that can support predictive, efficient, and sustainable management strategies [18,100].

In particular, the development of integrated biomarker panels combining molecular, physiological, and behavioral indicators is expected to enhance predictive capacity and reduce uncertainty in health assessments. Advances in biosensor technology are also paving the way for real-time, in situ monitoring systems capable of continuously tracking key physiological parameters without the need for invasive sampling. These innovations are likely to play a central role in the transition toward fully automated and data-driven aquaculture systems.

One important area of progress is the use of high-throughput multi-omics technologies, such as transcriptomics, genomics, proteomics, and metabolomics. These approaches make it possible to identify complex biomarker profiles linked to stress responses, disease resistance, and environmental adaptation [124]. Moving beyond single biomarkers toward integrated multi-omics frameworks is expected to enhance both the sensitivity and predictive capacity of monitoring systems.

Another promising direction is the development of non-invasive sampling techniques. Methods based on fish mucus, fecal samples, or waterborne metabolites allow for continuous monitoring of health while reducing the need for handling and minimizing stress on the organisms [122]. At the same time, improvements in biosensor technology, microfluidics, and nanotechnology are supporting the creation of compact, real-time diagnostic tools capable of detecting physiological changes directly in aquaculture environments [123].

The combination of biomarker data with artificial intelligence and precision aquaculture systems is also expected to play a major role in future developments. Machine learning models can integrate biological, environmental, and behavioral data to improve predictions of disease outbreaks, optimize feeding regimes, and support more efficient farm management decisions [105].

In addition, research is increasingly focusing on microbiome-related biomarkers and environmental DNA (eDNA) as complementary tools for assessing host health, pathogen presence, and ecosystem conditions in aquaculture systems [35,110]. Alongside these advances, the development of standardized sampling procedures and validated biomarker panels will be essential to ensure consistency and comparability across studies, species, and production settings [18].

Overall, the integration of multi-omics technologies, non-invasive monitoring methods, biosensing platforms, and artificial intelligence is expected to shift biomarkers from primarily research-focused tools into practical components of decision-support systems. This transition has the potential to significantly enhance sustainability, resilience, and productivity in aquaculture worldwide.

Looking ahead, one of the key priorities will be the standardization and validation of biomarker protocols across species and production systems. Establishing internationally accepted guidelines and threshold values will be essential to facilitate the broader adoption of biomarker-based monitoring tools. In addition, improving cost-effectiveness and accessibility, particularly for small and medium-sized enterprises, will be critical for ensuring that these technologies can be widely implemented in practice.

7. Conclusion

Biomarkers have emerged as important tools for advancing more sustainable and science-based aquaculture management. Within European aquaculture systems, biomarker-based approaches are increasingly used to support health monitoring, welfare assessment, environmental observation, as well as applications in reproduction and cryobiology. By combining molecular, biochemical, physiological, and behavioural indicators, biomarkers offer a comprehensive means of identifying early signs of stress, disease, or environmental change in cultured aquatic organisms. This integrated

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perspective enhances the ability of aquaculture systems to respond proactively to emerging health and environmental issues.

However, several challenges still limit the widespread adoption of biomarker-based monitoring in commercial practice. The lack of standardized protocols, the need for greater cost-effectiveness, and limited validation under real farming conditions remain key constraints. In addition, differences among species, environmental settings, and analytical methods can make it difficult to compare and interpret biomarker data consistently. At the same time, ongoing advances in high-throughput omics technologies, biosensor development, and digital monitoring systems are helping to overcome many of these barriers and are expanding the practical use of biomarker tools.

Europe represents a particularly supportive context for the development of biomarker-driven aquaculture. Strong regulatory frameworks focused on environmental protection, animal welfare, and food safety, combined with major funding initiatives such as Horizon 2020 and Horizon Europe, have created favourable conditions for translating research into practical applications.

Looking ahead, the integration of biomarker monitoring with precision aquaculture Technologies, including automated sensing systems, environmental monitoring networks, and data-driven decision-support tools, holds great potential to enhance the efficiency and resilience of aquaculture production. By linking physiological responses with environmental and management data, biomarker-based approaches can support earlier detection of health issues, reduce disease risks, and promote more sustainable farming practices.

From a practical perspective, the successful implementation of biomarker-based monitoring systems will depend on their integration into routine aquaculture practices. Future efforts should therefore focus not only on the discovery of new biomarkers but also on the development of user-friendly, cost-effective, and standardized tools that can be readily applied in commercial settings. By bridging the gap between research and industry, biomarker-driven approaches have the potential to become key components of next-generation aquaculture systems.

Author Contributions: Y.B., conceptualization, original draft preparation, writing, review, editing; M.C., R.B., V.R., C.O.S., P.A., S.S., D.B.D., A.M., I.G.Z., draft preparation. All authors have read and agreed to the published version of the manuscript.

Funding: This publication is based upon work from COST Action CA22160 "Enhancing knowledge of BIOmolecular solutions for the well-being of European AQUAculture sector – BIOAQUA," supported by COST (European Cooperation in Science and Technology).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest Statement: The authors declare no conflicts of interest.

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