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PROOF
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A Comprehensive Review of Aquaponics Systems Supported by Biotechnology to Increase Productivity

Abdulkadir Bayır[1,*], Esraa Sayed Al Soughaier[2], Mehtap Bayır[3], Harun Arslan[1]

[1]Department of Aquaculture, Fisheries Faculty, Atatürk University, Erzurum.
[2]Western Caspian University, Baku, Azerbaijan.
[3]Department of Agricultural Biotechnology, Faculty of Agriculture, Atatürk University, Erzurum, Türkiye.
[4]Department of Basic Sciences, Fisheries Faculty, Atatürk University, Erzurum, Türkiye.

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Corresponding Author
E-mail: abayir@atauni.edu.tr

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Abstract

Aquaponics systems combine aquaculture and hydroponics, providing a sustainable food production method by recycling water and nutrients between fish and plants. Advanced biotechnological tools have improved these systems, especially in fish breeding, environmental management, and plant growth. Environmental management and bioremediation optimize water quality and nutrient cycling. Bioinformatics supports informed breeding decisions, while epigenetics reveals genetic-environment interactions affecting fish growth. Omics technologies (genomics, transcriptomics, proteomics, and metabolomics) deepen the understanding of biological processes, and CRISPR/Cas9 gene-editing allows precise genetic modifications. Together, these technologies are advancing aquaponics, boosting sustainability, resource conservation, and biodiversity, and enhancing overall productivity.

Introduction

Aquaponics combines the techniques of aquaculture and hydroponics, creating a balanced system where plants and aquatic species coexist, offering a sustainable approach to food production. The system operates on the principle that fish provide essential nutrients for plant growth, while the plants act as natural purifiers, filtering and cleaning the water that sustains the fish. This cyclical relationship significantly reduces water consumption and eliminates the need for artificial fertilizers. Additionally, aquaponics addresses critical environmental challenges such as soil erosion, chemical pollution, and excessive water use by replicating natural ecosystems. As a forward-thinking solution, it presents a viable alternative to the challenges posed by conventional farming (Rizal et al., 2018).

Aquaponics offers numerous environmental and economic benefits that contribute to sustainable food production. It enables increased fish farming without overexploiting wild fish populations, helping to preserve natural ecosystems. Additionally, this method supports the production of high-quality, locally sourced food, making it especially valuable in regions facing water shortages. Furthermore, aquaponics facilitates efficient food production in urban environments, reducing transportation costs and enhancing local food security (Somerville et al., 2014).

Recognized as a knowledge-intensive field, aquaponics requires expertise across multiple disciplines to ensure efficient operation. The complexity increases even further in large-scale, multi-loop aquaponics systems, which demand intricate management and seamless integration of various components (Greenfeld et al., 2020). For instance, surplus nutrients from aquaculture can be efficiently utilized by hydroponic systems, while energy generated from waste can power essential operations. By adopting this model, aquaponics can enhance sustainability and scalability, particularly in resource-limited urban settings. Furthermore, integrating advanced technologies—such as sensors and analytical data tools—can streamline operations and improve overall system performance (Greenfeld et al., 2020). Thus, this study aims to explore the role of biotechnology in enhancing the productivity of aquaponics systems.

Methodology

A comprehensive literature review was conducted to identify relevant studies on the biotechnological applications in researching aquaponics systems' productivity. This review was conducted across the following electronic databases: PubMed, Scopus, Web of Science, ResearchGate, and Google Scholar, covering 2004 to 2024. Various combinations of the following keywords were used in the review: Aquaponics, Biotechnology, Biotechnological tools, and Sustainable food production. An initial review of titles and abstracts was conducted to identify potentially relevant articles. The following criteria were used for selecting articles for full-text review: Environmental Management and Bioremediation, Bioinformatics, Epigenetics, Omics Applications (Metagenomics, Metatranscriptomics, Proteomics, Metabolites, and Nutrigenomics), CRISPR/Cas9 applications, and gene editing for precision breeding in aquaponics systems, focusing on peer-reviewed studies published in English. Review articles, meta-analyses, and book chapters were also incorporated into the study to provide a comprehensive overview and uncover key research trends.

Aquaponics and Aquaculture Systems

In traditional aquaculture, water is often lost through waste discharge. However, in aquaponics, water is recirculated, improving water efficiency and promoting sustainability. Additionally, aquaponics can be implemented in metropolitan areas, reducing reliance on long-distance food transportation and enabling local food production. This, in turn, helps lower the ecological impact associated with food supply systems, making aquaponics particularly attractive as a solution to the growing challenges of global warming and food security (Vermeulen and Kamstra, 2013). The integration of fish farming and soilless agriculture allows farmers to produce high-quality food in limited spaces, making it particularly beneficial in urban environments where land is scarce. Selek et al. (2017) and Bartelme et al. (2018) highlight the significance of aquaponics in efficiently producing nutrient-rich food while reducing environmental impact (Figure 1). Additionally, ongoing research continues to improve the technology and techniques, making aquaponics more adaptable to various climates and environments (Roy et al., 2021).

Aquaponics Systems Types

Aquaponics systems are categorized into two types based on their structural principles: coupled and decoupled. In a coupled aquaponics system, the hydroponic and aquaculture components are integrated into a single interconnected closed-loop arrangement. In this system, water is continuously cycled from the fish tank to the hydroponic system, where plants are grown before returning to the fish tank. The system relies on a reciprocal interaction between the two components, with fish excrement providing essential nutrients for

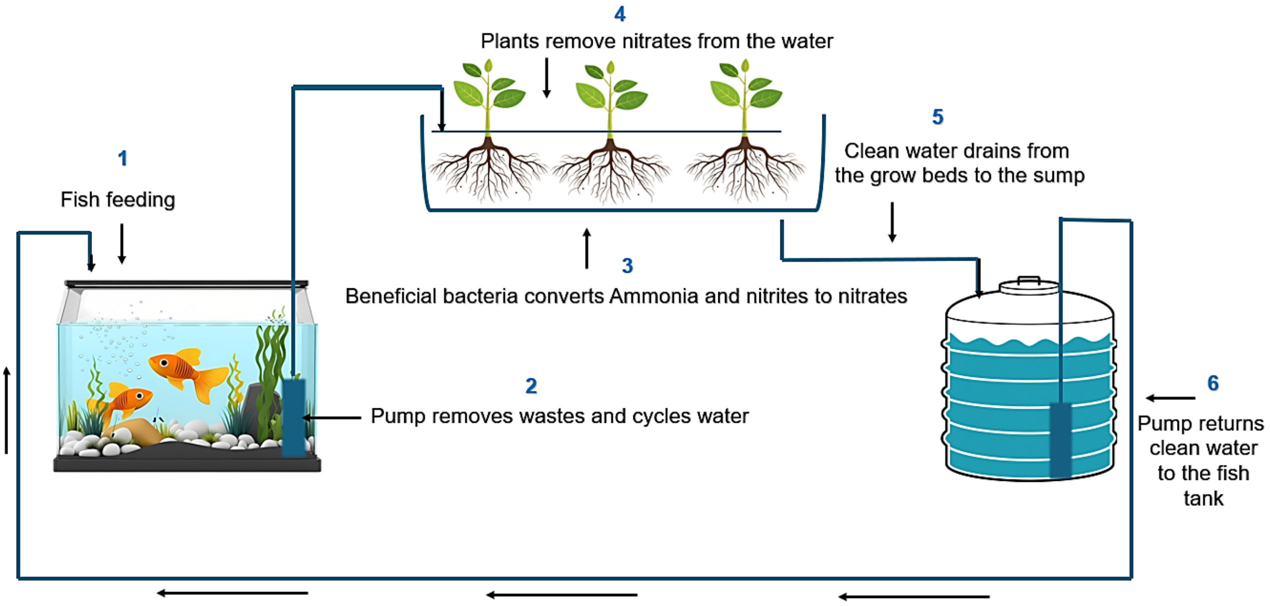

Figure 1. The key components of an aquaponic system, where fish waste provides essential nutrients for plants, and the plants, in turn, filter and purify the water, creating a sustainable, closed-loop ecosystem.

plant growth, while the plants purify and filter the water for the fish. This closed-loop integration promotes efficient nutrient cycling and water conservation, making it a preferred technique in aquaponics agriculture.

On the other hand, decoupled aquaponics systems are designed with separate loops for the aquaculture and hydroponic components. Water is cycled independently back to each unit, with distinct systems controlling the flow for aquatic enclosures and the hydroponic modules. In this setup, the water from the fish tanks can be treated separately before being supplied to the plants, offering greater flexibility and control over water quality in both systems. The decoupled approach can also reduce the potential for cross-contamination between the fish and plant components, enabling better management of water parameters and nutrient levels (Kloas et al., 2016).

Benefits and Limitations of Aquaponics Systems

Aquaponics is particularly well-suited for urban environments, offering a space- and resource-efficient solution for food production. It reduces environmental impact while providing a sustainable means of growing food for expanding populations. Producing both fish and vegetables within a closed-loop system is an effective way to address food security, especially in densely populated regions (Banerjee et al., 2023).

Traditional aquaculture practices, including water pollution, habitat destruction, and resource depletion, pose significant environmental challenges, raising concerns about the sector’s long-term sustainability. To address these issues, it is essential to integrate aquaculture into the broader water-food-energy system, aligning agricultural practices with sustainable water and energy management. By adopting technologies that reduce water consumption, minimize energy use, and lessen environmental impacts, the sector can contribute to global food security goals without compromising ecological health (FAO, 2014).

According to Goddek et al. (2019), The system relies on the metabolic activities of microbial communities, which play a crucial role in improving water quality. These communities also supply plants with the essential macro- and micronutrients necessary for healthy growth. The initial stage involves breaking down unused food, fish waste, and nitrogen-containing compounds—both organic and inorganic. This breakdown promotes the growth of microorganisms, whose activity transforms these compounds into nutrients that plants can absorb, creating a sustainable nutrient cycle (Somerville et al., 2014).

However, this also means that various microorganisms are present, some of which can act as pathogens, potentially affecting plants, fish, and, especially, humans. As a result, food safety is one of the most critical considerations in these systems. In agricultural practices, food safety has become an essential aspect of harvesting and management operations to ensure that the food produced is safe for consumption. To achieve this, certain microorganisms have been used as safety indicators for the products and the water quality within the system. Microorganisms such as *Escherichia coli* and *Salmonella spp.* are commonly used as safety indicators for assessing the quality of products and water in aquaponics systems. These bacteria are typically found in the intestines of warm-blooded animals and are well-established indicators of fecal contamination and water quality concerning microbial safety. Furthermore, these zoonotic enteric bacteria can temporarily appear in the gut microflora of fish, particularly in open systems (Fox et al., 2012).The microbial profile of lettuce grown in soil-free aquaponics systems has been compared to that of lettuce grown in traditional soil-based systems to assess the microbial safety levels in both production methods (Fox et al., 2012; Sirsat et al., 2014). The comparative analysis revealed notable differences between aquaponic and conventional lettuce concerning aerobic plate counts (APC), coliform levels, E. coli presence, and yeast counts. Aquaponic lettuce exhibited significantly lower concentrations of coliform bacteria (with no detectable E. coli), spoilage microorganisms, and fecal contaminants. In contrast, market lettuce contained 2-3.5 log CFU of E. coli per gram. Additionally, yeast counts were lower in aquaponic lettuce, ranging from 2-3 log CFU per gram, compared to conventional and organic lettuce, which had yeast counts of 5-5.5 log CFU per gram. Subsequent studies indicate that conventional and organic lettuce faced postharvest contamination due to packaging and transportation processes. In contrast, aquaponic lettuce experienced minimal postharvest contamination, as its postharvest procedures were kept to a minimum (Sirsat et al., 2014).

Role of Biotechnology in Enhancing Productivity of Aquaponics Systems

Recent advancements in biotechnology have led to a significant shift in conventional aquaponics practices, steering the industry toward more sustainable and efficient methods. As global demand for aquaponics products continues to rise, the sector needs to adopt high-tech, eco-friendly, and science-based strategies to stay competitive and sustainable (Figure 2) (Bello and Elezuo, 2024). In the following pages, we will explore several biotechnological methods and examine their contributions to enhancing the sustainability of aquaponics systems.

Environmental Management and Bioremediation Strategies in Aquaponics Systems

Aquaponics systems, like other intensive farming methods, can produce nutrient-rich effluents that may lead to environmental pollution. To address these concerns, biotechnological solutions such as bioremediation, probiotics, and vaccination offer promising options. Bioremediation uses microorganisms or organisms like bivalves to break down pollutants, improving water quality. Probiotics enhance gut health in farmed organisms, boosting digestion and immunity while reducing reliance on antibiotics. These approaches support sustainable breeding practices, promote healthier organisms, and minimize environmental impact (Biswas and Maurye, 2017).

Bioinformatics in Aquaponics

Bioinformatics is essential in fish breeding, enabling researchers to analyze genetic data to identify traits and optimize breeding strategies. It improves productivity, sustainability, and profitability while supporting data-driven decisions that enhance fish quality and resilience, fostering ongoing innovation in the industry (Rather et al., 2023). Bioinformatics and genomics provide insights into the structures and functions of genes to improve breeding strategies. By analyzing genomic data, breeders can enhance traits such as growth rate and disease resistance, leading to more efficient and sustainable breeding programs (Tan et al., 2022).

By combining traditional breeding methods with modern genomic advancements, fish farmers can significantly enhance genetic traits in various species. This approach is effective for large-scale breeding of popular fish such as salmon, as well as for breeding niche or rare species in smaller programs (Rathe et al., 2023).

Using advanced biological data ("omics data") in breeding programs has shown great potential for enhancing selective breeding. This approach helps identify optimal traits more accurately, making the breeding process more efficient and effective (Dwivedi et al., 2020).

By integrating multiomics data, panomics, and systems biology, scientists can gain a deeper understanding of crop traits and predict complex characteristics. This approach enhances trait prediction and enables more precise, efficient crop breeding (Rather et al., 2023).

Omics databases are essential for enhancing plant traits and food production. By analyzing and integrating biological data, researchers can improve breeding efficiency, resulting in stronger crops and improved global food security (Xu et al., 2015).

Epigenetics in Aquaponics

Epigenetics studies changes in gene function that do not alter DNA, driven by factors such as diet and water quality. These modifications, including DNA methylation and histone changes, can be inherited, impacting fish growth, health, and adaptability in aquaculture systems (Roy et al., 2022).

Epigenetics helps fish adapt to changing environments by passing down desirable traits, such as growth and health, influenced by factors like water quality, temperature, and diet, without altering DNA. This process improves fish quality and resilience in breeding programs (Granada et al., 2018). Environmental factors, such as temperature and water quality, influence fish sex, with epigenetics playing a key role in this process. Preserving fish reproductive cells (germplasm) is crucial for developing new breeds with improved disease resistance, growth, and adaptability (Moghadam et al., 2015).

Recent studies suggest that epigenetic mechanisms play a crucial role in determining and differentiating the sex of fish and other vertebrates. These mechanisms can influence the determination of sex and the developmental process of the fish (Piferrer, 2013). In many fish species, differences between the sexes cannot be fully explained by genes alone, especially when sex ratios shift due to temperature or in species that can change sex throughout their lives (Navarro-Martín et al., 2011). Epigenetic changes may be a key mechanism that allows environmental factors to influence the processes of sex determination and differentiation in fish (Piferrer, 2013; Shao et al., 2014).

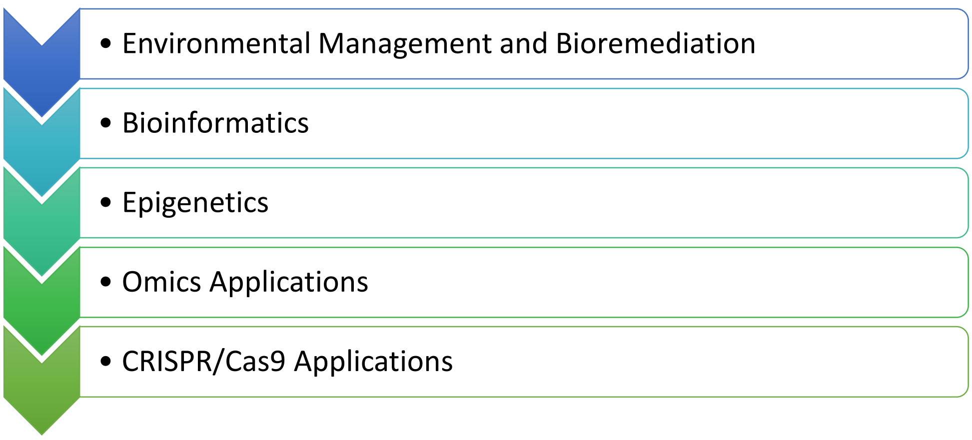

Figure 2. Biotechnological applications in aquaponics systems.

Omics Applications in Aquaponic Systems

Omics technologies refer to scientific methods used to study the molecular biology of living organisms. These include genomics, which focuses on studying an organism's complete DNA; transcriptomics, which analyzes all the RNA produced in cells; and proteomics, which examines the proteins within organisms (Figure 3). Each of these fields helps us understand how organisms' function at the molecular level (Bhatnagar et al., 2008).

Metagenomics for Microbial Diversity Description

Microbial studies focus on understanding the positive and negative effects of microbes on cultured animals such as fish, crustaceans, and mollusks. Metagenomics, which analyzes the genetic material from organisms or ecosystems, can provide valuable insights into how microbes interact with these animals under different conditions, including whether they are healthy, diseased, or growing slowly or rapidly. This section highlights the applications of metagenomics in aquaculture (Kumar et al., 2019).

PCR amplification has advanced the study of microbial diversity, but much remains unknown due to the inability to culture many prokaryotes in laboratories. Techniques such as 16S rRNA sequencing, hybridization, and DGGE/TGGE provide valuable insights, though they have limitations and offer only partial views of microbial communities (Handelsman et al., 2004). The 16S rRNA gene amplification targets hypervariable regions (V1 to V9), which vary in length and are crucial for identifying different microbes. Primers designed for these regions help detect a wide range of bacterial species (Nikolaki and Tsiamis, 2013).

To obtain a clear and accurate representation of complex microbial communities, primers targeting the V1–V3 and V7–V9 regions are recommended. These regions provide a comprehensive overview of the microbes (Martínez-Porchas et al., 2017). This technique provides insights into the types of microorganisms present in an environmental sample, revealing their taxonomic composition (Kemp and Aller, 2004).

Quantitative analysis of microbial communities is a crucial aspect of studying microbial ecology. When combined with 16S rRNA techniques, significant progress has been made, particularly in simple ecosystems like endosymbionts or extreme environments. These methods have enhanced our understanding of ecosystem function, including the role of microbial communities in ocean environments (Gilbert and Dupont et al., 2011).

Alternatively, Next-Generation Sequencing (NGS) technologies offer significantly higher capacity, being 100 times more efficient at sequencing than the traditional Sanger method. NGS works by sequencing DNA molecules in large quantities simultaneously within a flow cell. Sequencing can occur in two ways: either continuously in real-time or in a step-by-step process. In both methods, each DNA molecule or clonal template is sequenced and counted among all the sequences generated (Nikolaki and Tsiamis, 2013).

These advanced technologies focus on sequencing large DNA fragments, such as entire genomes or plasmids, rather than individual genes or operons. To achieve this, the total DNA is fragmented into smaller pieces, typically up to 700 base pairs (bp). In shotgun sequencing, the fragments can range from 3 kb to 8 kb, or even up to 40 kb (Nikolaki and Tsiamis, 2013).

After the DNA fragments are sequenced, further bioinformatics analysis is required to assemble them

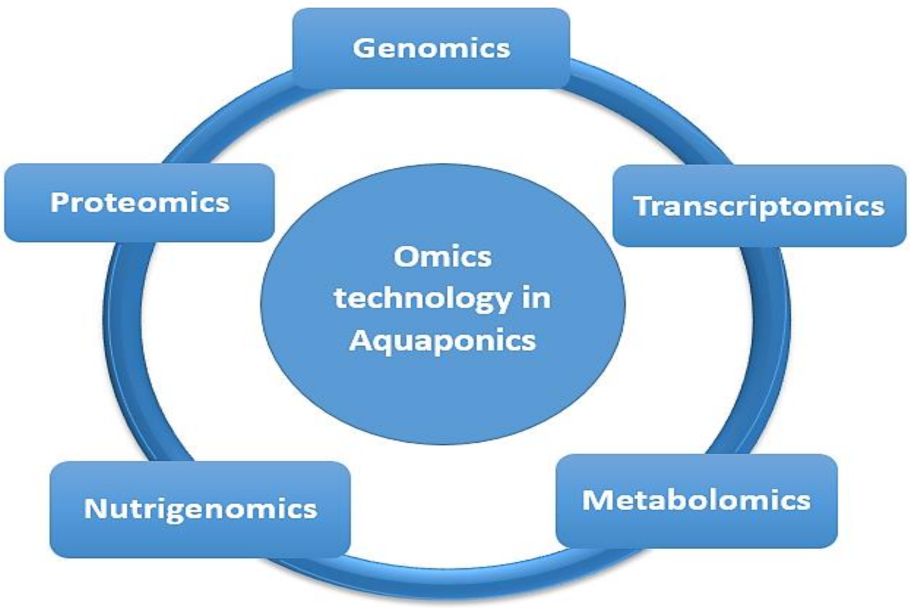

Figure 3. Omics technology in aquaponics.

into complete linear sequences that make up the genome. This process involves overlapping the fragments to form continuous sequences, known as contigs. While assembling the entire genome can be challenging, it is feasible if the fragments cover the entire genome. The main difficulty with this approach lies in the substantial computational work required, demanding significant analysis and computing power (Venter et al., 2004).

Metagenomics involves two main approaches: single-gene surveys, where specific genes are amplified and sequenced, and random shotgun sequencing, where all DNA from an environmental sample is sequenced. Unlike genomics, which focuses on the genome of a single organism, metagenomics examines the genomic DNA of an entire community (Kennedy et al., 2010). Metagenomic studies, combined with next-generation sequencing (NGS), are advancing microbial ecology. While these approaches show promise for studying simpler ecosystems, challenges persist in highly complex environments due to the difficulty in assembling data caused by high genetic diversity (Nikolaki and Tsiamis, 2013).

Metatranscriptomics in Aquaponics Systems

Metatranscriptomic data consists of cDNA derived from the RNA of a community of microorganisms. This data provides insights into what microorganisms are doing at a specific moment, how they are reacting to their environment, and how they communicate with other cells and the broader community (Blakeley-Ruiz, et al., 2022).

In transcriptomic methods, genes must be isolated at specific times during their expression, as the transcriptome (the set of active genes) can vary over time. The primary goals of functional "omics" studies are: first, to understand the functionality and metabolism of each community member and how they impact the system, and second, to identify variations in the functional structure across different communities (Blakeley-Ruiz M. et al., 2022).

Combining metagenomic and metatranscriptomic data has uncovered many unexplored transcripts, highlighting that much remains to be understood about gene and protein functions in ecosystems. Although mRNA levels are often used to estimate protein activity, new technologies suggest that transcript levels only partially predict protein abundance, indicating that other regulatory mechanisms are involved (Vogel and Marcotte, 2012).

Proteomics Applications in Aquaponics Systems

Proteomics research focuses on studying proteins and their interactions. It aims to identify and catalog all the proteins in a sample, understand their functions, and explore how they interact with each other and other substances (Dai and Shen, 2022). Proteomics is a valuable tool for studying the proteins produced by an organism. It has been used to explore various aspects, such as welfare, safety, nutrition, and diseases, all of which directly impact the quality of the final product (Rodrigues et al., 2018).

This approach in fish breeding helps identify proteins in a sample, understand their structure and function, and examine how they interact with other proteins and molecules. It enhances breeding programs by providing valuable insights into fish health, growth, and other important traits (Rodrigues et al., 2018; Causey et al., 2019).

Proteomics can help compare the protein profiles of different fish breeds and identify proteins linked to traits such as faster growth, better disease resistance, and higher meat quality. This enables researchers to pinpoint which proteins are responsible for these valuable characteristics (Causey et al., 2019). For example, a study focused on the protein profiles of two fish breeds: one with a fast growth rate and the other with a slow growth rate. The study identified several proteins expressed differently between the two breeds, such as those related to energy use, muscle growth, and stress response. These findings could help breeders identify the genes associated with these proteins and develop new breeding methods to enhance growth rates in fish (Rodrigues et al., 2016).

Metabolites Role in Aquaponics Systems

Metabolites are the end products of cellular chemical reactions and reflect the cell's biochemistry. Their levels provide insights into how cells respond to genetic or environmental changes, making them valuable for understanding traits. Similar to the "transcriptome" and "proteome," the complete set of metabolites is known as the "metabolome," which can be studied at various levels. In biological experiments, controlling environmental conditions is crucial for obtaining accurate results (Patti et al., 2012).

Nutrigenomics and Aquaponics Systems

Feed is a major cost in fish farming, and the rising price of feed is outpacing the growth of aquaculture and aquaponics. This is largely due to the decreasing availability of fish for fish meal production. To address this issue, alternatives such as plant protein and poultry feather meal have been suggested as replacements for fish meal. However, it is crucial to carefully study how these changes impact the fish's metabolism (Kumar et al., 2019).

Nutrigenomics is an excellent approach for studying how different feeds affect fish. It helps us understand the biochemical and metabolic processes involved in how fish utilize the nutrients and energy from their food. This knowledge is crucial for understanding how fish respond to various nutrients, improving their food utilization, and developing better diets. Since enzymes play a key role in nutrient processing, a molecular approach is essential for studying nutrition (Kumar et al., 2019).

Impact of Omics Technologies on Aquaponics Systems

Omics technologies are widely used in the fisheries and aquaponics fields to improve breeding strategies for economically important species. These technologies enable the identification of genes and traits that can enhance fish growth, disease resistance, and overall performance in aquaponics systems. By pinpointing beneficial traits at a molecular level, breeders can improve characteristics such as disease resistance, growth rates, and adaptability to environmental changes. Ultimately, this can lead to more sustainable and productive aquaponics systems (Nguyen et al., 2022). These methods are used to understand how fish grow, respond to diseases, and cope with stress.

Additionally, these methods contribute to the development of more resilient fish capable of withstanding diseases, diagnosing ailments, producing vaccines, analyzing fish populations, verifying fish species in food products, and improving the quality of fish post-harvest (Mohanty et al., 2019). Omics technologies have played a significant role in enhancing fish breeding in aquaponics systems. These advancements have led to stronger, healthier farmed fish with improved growth rates and increased disease resistance, resulting in greater production efficiency. However, the implementation of genetic enhancement programs in aquaculture still faces several challenges (Lokman and Symonds, 2014).

CRISPR/Cas9 Applications in Aquaponics Systems

CRISPR/Cas9 is a groundbreaking gene-editing tool that enables scientists to make precise alterations to the DNA of living organisms. It has revolutionized medicine, aiding in the treatment of genetic diseases and advancing research (Singh et al., 2018). The CRISPR/Cas9 system is a revolutionary gene-editing tool composed of two key components: the Cas9 enzyme and the guide RNA. The Cas9 enzyme functions as molecular scissors, enabling precise cuts at specific locations on the DNA. The guide RNA directs the Cas9 enzyme to the exact site where the DNA should be cut. This powerful combination allows for accurate and targeted genetic modifications, making CRISPR/Cas9 a groundbreaking advancement in genetic research, medicine, and biotechnology (Wong et al., 2015).

The CRISPR-Cas9 system is derived from an antiviral defense mechanism found in bacteria. It enables gene editing within living organisms by inserting synthetic guide RNA (gRNA) and the Cas9 enzyme into a cell, which then cuts the DNA at a precise location (Singh et al., 2018). This method is significant because it is easy to use, affordable, and precise, making it a valuable tool in biotechnology and medicine. It holds great potential for treating genetic disorders and diseases, such as cancer, which are caused by DNA mutations (Lal et al., 2024).

The CRISPR-Cas9 system is a powerful tool that uses RNA to guide precise changes in DNA at specific locations. By making targeted alterations in the genome, scientists can influence various traits or phenotypes, such as eye color or susceptibility to certain diseases. These genetic modifications enable researchers to study the effects of specific genes and explore potential treatments for genetic conditions (Javaid et al., 2022). The CRISPR-Cas9 system utilizes RNA molecules to match specific DNA sequences. These RNA molecules direct the Cas9 enzyme to the exact location in the DNA where it can make a precise cut, enabling targeted genetic modifications. This approach allows for precise changes in the genome, making it an invaluable tool for research and medicine (Jiang et al., 2020).

CRISPR/Cas9 offers significant potential, but it also comes with limitations. These include concerns about the accuracy of genome editing and ethical questions surrounding the modification of human germline genes. While the technology could revolutionize biotechnology and medicine, its use requires careful ethical considerations and cautious application to avoid unintended consequences (Singh et al., 2018; Lal et al., 2024).

Gene Editing for Precision Breeding in Aquaponics Systems

CRISPR/Cas9 technology holds great promise for the aquaculture industry by enabling precise genetic modifications to improve important traits like growth rates, disease resistance, and adaptability to changing environmental conditions. Through targeted genome editing, CRISPR/Cas9 can help create fish that are more resilient, faster-growing, and better suited for farming, which could lead to higher production efficiency and sustainability in aquaculture. However, careful regulation and ethical considerations are needed to ensure the responsible use of this powerful technology in food production (Gratacap et al., 2019). CRISPR/Cas9 indeed offers several advantages in aquaculture, such as reduced off-target effects, easier cell delivery, and lower costs compared to previous genetic modification methods. By improving fish traits like growth, color, and disease resistance, CRISPR/Cas9 has the potential to revolutionize the industry.

Additionally, it could enhance disease diagnostics, helping to detect and manage diseases more efficiently in fish populations. However, ethical concerns, such as the potential impact on biodiversity, ecological balance, and unintended consequences of gene editing, need to be carefully considered and regulated before widespread application in aquaculture. Balancing innovation with responsible practices will be crucial (Okoli et al., 2022).

Ethical Statement

No ethical statement was reported.

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Author Contribution

All the authors write the article together.

Conflict of Interest

The authors declare that they have no known competing financial or non-financial, professional, or personal conflicts that could have appeared to influence the work reported in this paper.

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The names, degrees, and affiliations who have contributed substantially to a study but do not fulfill the criteria for authorship can be listed in the Acknowledgments section.

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