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Evaluating CRISPR applications in marine animal biotechnology for improved food industry sustainability

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Abstract

Objective

Aquaculture is the world's fastest-growing food-producing industry, its offer's solutions to food insecurity driven by climate change, population growth, and limited resources. However, this sector faces many challenges, including outbreaks of disease, poor growth rates, reproductive issues, and environmental risks caused by fish escaped from the farm. This study aims to solve the above problem by using CRISPR-Cas9 gene editing technology as a solution in marine animal biotechnology. The main goal of this study is to find how the CRISPR technology works to improve the genetic traits of farmed fish. It looks at how this technology can help fish like Atlantic salmon, tilapia, and catfish grow faster, resist diseases, handle stress better and control reproduction. The study also explores the ethical concerns, environmental effects, and trade issues related to using gene editing in fish farming.

Materials and methods

This study is based on a detailed review of earlier scientific research, mainly looking at gene-editing experiments, changes in fish traits, rules and regulations, and how CRISPR is used in fish farming. It focuses on the successful use of CRISPR-Cas9 to make sterile fish (to stop them from passing genes into the wild), lower the risk of viral infections, help fish use feed more efficiently, and improve their nutritional value.

Results

The results show that CRISPR-Cas9 can greatly boost fish farming by creating fish that grow faster, have better muscle quality, and are more resistant to diseases. It also helps reduce the use of chemicals and antibiotics. However, there are still some concerns, such as the risk of unwanted genetic changes, the chance of edited genes spreading to wild fish, the possible loss of biodiversity, and the fact that small farmers may not have easy access to this technology.

Conclusions
The CRISPR-Cas9 has strong capability to improve eco-friendly in the aquaculture industry. It provides innovative tools to defend the key challenges and can help meet the growing global demand for safe and nutritious seafood. However, to use the CRISPR technology in a safe way, we need stricter rules, better awareness, equal access and long-term tracking of environmental impacts.

Keywords: aquaculture, CRISPR- Cas9, food security, gene-editing, marine biotechnology

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Introduction

Aquaculture is the world's fastest-growing way of producing food. It plays an important role in solving food shortages acused by population growth, climate change, and limited natural resources (Verdegem et al., 2023). The anticipated worldwide population of 9.8 billion by 2050 would require a 30% to 72% increase in agricultural output, depending on factors such as dietary trends, food waste levels, and climate change impacts on yield. From 2000 to 2025, the global use of fish and other aquatic foods is expected to more than double from 82.4 million to 175.2 million metric tons each year. In 2024, aquaculture provides 55% of marine animal-based food; the remaining 45% comes from capture fisheries, also known as wild-caught fisheries. In 2012, experts predicted that aquaculture could supply 84-92% of the seafood for home use, helping feed both the general population and those who are undernourished (Thi & Dang, 2010). The aquaculture sector can help address issues regarding the growing demand for aquatic products due to population growth. *Researchers have worked hard to improve genetic engineering, particularly using CRISPR-Cas technologies, to prevent disease and regulate growth in aquaculture species* (Kazemipour et al., 2025). *Separately, efforts are also being made to reduce environmental and handling stress in farmed fish, which can significantly affect their health and productivity* (Valladares & Planas, 2021). CRISPR-Cas9 is the major genetic engineering tool that can able to precisely alter fish DNA to enhance color, growth, muscle strength, and disease resistance (Jeong et al., 2023; Hemasa et al., 2017). This technology presents a simple, accurate, and reasonably priced to improve genes much better that conventional breeding techniques. By edit of the genes it can helps to improve important traits such as muscle quality, disease resistance, gender selection, and growth rate. By this technology we can also alter the visible improvements like heavier body weight, thicker limbs, and increased fiber development (Myoa et al., 2023). Fish will not need as many medications and chemical treatments if CRISPR-Cas9 technology helps make them more resistant to disease or harmful pathways (Kaur & Chandra, 2024). This approach has revolutionized modern farming by significantly improving many kinds of fish. Researchers have effectively eliminated germ cells in Atlantic salmon to control reproduction, enhanced the ability of yellow catfish to convert feed into energy for faster growth, improve the efficiency of gene editing in tilapia to work better, and reduced the non-intended side effects by the CRISPR technology to support the food industries (Palash & Dhurvey, 2024; Assegid & Ketema, 2023). CRISPR-Cas9 innovation has attracted attention in aquaculture in the past few years. There is an absence of a thorough analysis addressing its many uses and the obstacles associated with altering essential desired features in fish. Prior research has focused on elucidating the technology's rules, benefits, and use in improving financial characteristics (Zhu et al., 2024; Khan & Taha, 2023). Recent studies have evaluated the effectiveness of CRISPR-Cas9 in improving key traits in farmed fish, including growth rate, muscle development, disease resistance, and stress tolerance. In addition to technical outcomes, other research has explored the ethical considerations and sustainability challenges associated with gene editing in aquaculture (Shi et al., 2024).

Impact of CRISPR-Cas9 gene editing on various fish species

The CRISPR-Cas9 gene editing technique has shown considerable promise for enhancing many characteristics in fish and aquaculture animals. Scientists have used this potent approach to acquire significant insights into the genetic control of essential physiologic and production-related traits. Although gene drives—developed using CRISPR-Cas9, are powerful tools for altering genetic inheritance, their application in aquaculture or marine plant biotechnology remains limited and ethically debated. Therefore, their relevance to current food production systems is still emerging (Ferdous et al., 2022). This helps some traits to be distributed faster across the population than in line with traditional inheritance systems. Genetic drives ensure that the altered gene is passed at relatively high frequencies, addressing 100%, instead of the conventional 50% inheritance ratio (Barredo-Damas et al., 2010; Jung et al., 2019). One notable use is creating sterile, all-male Nile tilapia colonies using CRISPR-Cas9. Their studies found that these genetically altered tilapias showed significantly faster development rates than standard mixed-sex groups (Wang et al., 2017). Producing the sterile tilapia helps reduce environmental risks if these fish escape from farms. Because of they can't breed, they are less likely to hybridize or compete wild fish. This helps protect native species and keeps the natural ecosystem more stable (Kaul &

Prasad, 2024). This study has extensively demonstrated how well the CRISPR-Cas9 approach could increase aquaculture results while lowering environmental impact (Thi & Dang, 2010). Using CRISPR-Cas9 modification of genes in Atlantic salmon, the study yielded resistance to critical viral illnesses such as salmon alphavirus and Infectious Pancreatic Necrosis Virus (IPNV) (Qin et al., 2022). By changing or disrupting the host genes that infections depend on for invasion and development, the researchers effectively created salmon lines showing improved illness resistance. This is especially important since viral infections cause significant losses in Atlantic salmon agriculture (Verkuijl et al., 2025).

CRISPR-Enhanced Aquaculture's Impact on Aquatic Product Commerce and Food Security

Using the CRISPR technology to produce disease-resistant fish can greatly increase the supply and efficiency of aquaculture in countries that use this technology. Those countries can get a big advantage from other countries that use the traditional fish farming methods, which may be slower and more vulnerable to disease (Kazemipour et al., 2025). Which nations with the CRISPR technology can produce and export more fish, with lower costs, remaining countries making it hard for other countries to compete. This shift in power leads to uneven competition in the global fish market. To respond, some countries without CRISPR may introduce trade barriers, like tariffs or bans, to protect their local fish farmers from being pushed out by high-tech competitors (Al-Khasawneh et al., 2024; Singhal et al., 2024). The commercialization and patenting of CRISPR-based technologies in aquaculture have led to increased market control by a few multinational companies and major research institutions. This concentration of ownership creates a form of monopoly over the production and distribution of genetically modified aquatic species. As a result, global fish trade dynamics are affected—impacting pricing, supply chains, and reducing the bargaining power of small-scale fishers, particularly in developing countries (Allioui & Mourdi, 2023).

Mitigation approaches for the sustainable implementation of CRISPR-Cas9 in fish farming

One wonders about the likely environmental and biological consequences. The transfer of genes from genetically modified fish to wild fish can cause serious problem, such as harming natural ecosystem, reducing the variety of genes in wild population, and creating imbalance in the environment. Unexpected ecological consequences and disturbance of aquatic systems are produced by gene flow. Unintentional off-target effects of CRISPR-Cas9 generate genomic changes outside of the intended modifications, possibly leading to unexpected outcomes. Preventing unexpected environmental consequences depend on evaluating off-target impact and knowledge of broader ecological interactions. Unintentional genetic changes brought about by off-target events disturb gene activation and influence cell behavior. In ecological environments, these interactions affect the degree of competition among several fish species and the distribution of changed features. Off-target effects generate safety concerns in pharmacological applications. Good containment strategies will help to reduce the risk of transgenic fish escaping and enable gene flow to wild populations. Studies reveal that rigorous physical confinement rules, including several barriers, decreased the likelihood of transgenic fish escape. Strict biosafety regulations and a complete legal framework are necessary to lower the hazards related to CRISPR-Cas9 in aquaculture. These issues disturb the ecological equilibrium and start chain reactions across the food chain since they cover the possibility of escapes and interbreeding with wild populations, the spread of modified traits, and the change of the fitness and behavior of wild fish. Unexpected ecological consequences of non-target species could lead to a loss of biodiversity. First, fish with limited reproductive potential or infertile nature should be produced using specific confinement techniques, including biotechnological approaches like triplet induction. It guarantees physical containment using secure cages. It is crucial to establish long-term tracking structures to examine shifts in population structure, biodiversity, and ecological services and their effects on our environment. Considering fresh studies and information, create management plans that react quickly to unanticipated environmental impacts. Many people, including legislators, business leaders, professionals, and residents, will participate in the decision-making. Good marketing plans will help people to see the advantages and drawbacks of CRISPR-Cas9 developments. This will increase confidence and enable individuals to make wiser decisions.

The moral dilemmas raised by using CRISPR in fishing and how this compromises food security

The CRISPR-Cas9 technology has revolutionized many industries, including fish farming, by allowing exact DNA modifications in aquatic species. Before CRISPR-Cas9 can be applied in farming to maximize its benefits and minimize as many issues as possible, many moral and pragmatic questions must be answered. The explosion of CRISPR-modified species generates environmental problems. The ecosystem is threatened, and uncertain long-term ecological consequences follow from the potential of unexpected escape and distribution of genetically engineered organisms. Reducing these possible ecological effects depends on careful risk analysis and strict regulation. Another important factor is public opposition to the consumption of fish produced by CRISPR. Openness, clear labelling, and addressing customer worries on food security and ethics must be prioritized in areas where genetically engineered animals encounter mistrust to win the public's support. Fostering the acceptance of CRISPR-modified products from fish farming will depend primarily on efficient involvement and moral conflict resolution.

Enhanced traits of principal fish species via genome engineering in aquaculture

Aquaculture is essential for ensuring that food is safe worldwide and for getting energy from algae. China is very good at improving genes, and they use the CRISPR-Cas9 method to strengthen carp strains. This method has changed things that are wanted in fish farming, especially in countries that aren't very well developed. CRISPR-Cas9 is used to accurately target and change specific fish genes, making them better in different ways. This method has been used to change the paths of coloring, which has led to better color differences in ornamental fish, like zebrafish and common carp. CRISPR-Cas9 is also used to speed up the growth of species that are important for business, like tilapia and common carp, which makes output more efficient. Focusing on making fish more resistant to diseases is important because genetic changes have strengthened fish like Atlantic salmon and rainbow brook trout, reducing the number of fish that die from common farming infections. In medicine, CRISPR-Cas9 has improved the efficiency of feed processing, which has cut down on costs and had a positive impact on the environment. In Atlantic salmon, CRISPR-Cas9 has been applied to modify genes involved in lipid metabolism such as *elovl2* and *fads2* to enhance the biosynthesis and assimilation of omega-3 fatty acids, thereby improving their nutritional profile. Additionally, CRISPR has been used to induce sterility in farmed fish species like Atlantic salmon and Nile tilapia by targeting genes essential for reproductive development, such as *dnd* (dead end) or *gnrh* (gonadotropin-releasing hormone). These interventions help prevent uncontrolled breeding, reduce the risk of genetic pollution in wild populations, and support more sustainable aquaculture practices. Changing genomes to control sex has made it possible to change markers that determine sex in fish like Nile tilapia and rainbow trout. This has increased output by controlling the ratios of males to females. The method has made Atlantic salmon more resistant to abiotic problems like low oxygen levels and higher salt levels, which increases their chances of living in harsh environments. Many researchers have used CRISPR-Cas9 to change genes linked to the immune system in different fish types, making them healthier and less likely to get sick. Gene editing has come a long way, removing many unwanted traits and increasing the number of useful ones. This has made fish farming more efficient and better for the environment. CRISPR-Cas9 technologies help fish farming move forward and meet the growing demand for an adequate protein diet that is sourced in a responsible way around the world.

Prospective Outlook and Concluding Observations

With CRISPR-Cas9, ecological biotechnology has bright prospects, providing creative answers to problems including resource management, environmental pollution, and climate change. Important future uses of ecological biotechnology employing CRISPR-Cas9 comprise:

By modifying the cattle’s gut microbes with the CRISPR-Cas9 technology, there is a possibility for reducing methane emission. Because methane is a major greenhouse gas, this method can significantly help to control climate change. Combining the fourth-generation biofuels with carbon capture and utilization (CCU) technologies gives a promising solution for developing a renewable energy solution. Carbon monoxide (CO), a waste gas, was used as a nutrient substrate in the microbial process by the CCU. This supports circular economy goals by reducing our reliance on finite natural resources. With the help of CRISPR-Cas9, microbial metabolic pathways can potentially be optimized to improve carbon conversion efficiency. These innovations collectively support the advancement of next-generation biorefineries that use both anaerobic and aerobic microbes to capture and utilize CO_2 more effectively. It refers to the cattle's gut microbes. It was used to produce the methane gas from the cattle's dung.

Environmental concepts, artificial intelligence, BIM, and Deep Learning can be combined with CRISPR-Cas9 technology in future, these approaches present great possibilities for developing, researching, and enhancing long-lasting genetic treatments. These fields are constantly exploring and generating fresh ideas.

From a simple analytical tool to a vital component of agricultural and ecological advancement, CRISPR-Cas9's revolutionary potential calls for constant research, communication, and responsible use to completely maximize its benefits for a sustainable future.

Conclusion: The CRISPR-Cas technology is the predominant method among contemporary genetic engineering techniques; hence, most anticipated genetically engineered fish items for commercial use will be derived from CRISPR-Cas. The approach can provide extensive answers to the many difficulties afflicting the fish farming business. The ongoing national and international discourse is on regulating goods derived from genetic engineering methods, particularly CRISPR-Cas. Considering the significant relevance of the issue, choices regarding the regulation of genetically modified seafood products, and more critically, the manner of such regulation, should be grounded on insights obtained from a comprehensive scientific study. The existing regulatory assessment frameworks do not include CRISPR-Cas genetically engineered fish. This will test the structures of undesired and pleiotropic impacts and the detection, identification, tracking, and monitoring of genetically engineered fish in the event of unintentional or purposeful environmental release. Critical information necessary for significant choices and practical decisions is lacking. Studies using modern and cost-effective biological tools, such as transcriptomics, proteomics, and metabolomics, will address these understanding requirements. Including the welfare of animals and ethical, sociological, and environmental factors in the policy decision-making process would enhance risk evaluation and guarantee that cultural and social goals are acknowledged.

Author contributions

Both authors were contributed equally.

Data availability statement

No new data were generated or analyzed during this study. All information presented is derived from previously published sources, which are appropriately cited.

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Ethical considerations

This study is based solely on a review of existing literature and does not involve any experiments on humans, animals, or genetically modified organisms conducted by the authors. As such, ethical approval and informed consent were not required. All references, data, and studies have been properly cited by academic and publishing ethics.

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Conflict of interest

The authors declare no conflict of interest.

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ارزیابی کاربردهای CRISPR در زیست‌فناوری جانوران دریایی برای بهبود پایداری صنعت غذا

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چکیده

هدف: آبزی‌پروری سریع‌ترین صنعت تولید غذا در جهان به شمار می‌رود و راهکارهایی برای مقابله با ناامنی غذایی ناشی از تغییرات اقلیمی، رشد جمعیت و محدودیت منابع ارائه می‌دهد. با این حال، این بخش با چالش‌های متعددی از جمله شیوع بیماری‌ها، نرخ رشد پایین، مشکلات تولیدمثلی و خطرات زیست‌محیطی ناشی از فرار ماهیان پرورشی به طبیعت مواجه است. این مطالعه با هدف بررسی استفاده از فناوری ویرایش ژن CRISPR-Cas9 به‌عنوان راهکاری نوین در زیست‌فناوری جانوران دریایی برای رفع این مشکلات انجام شد. هدف اصلی پژوهش، بررسی نقش فناوری CRISPR در بهبود صفات ژنتیکی ماهیان پرورشی است. در این راستا، تأثیر این فناوری بر افزایش سرعت رشد، مقاومت به بیماری‌ها، تحمل تنش و کنترل تولیدمثل در گونه‌هایی مانند سالمون آتلانتیک، تیلاپیا و گربه‌ماهی بررسی شده است. همچنین، نگرانی‌های اخلاقی، پیامدهای زیست‌محیطی و مسائل تجاری مرتبط با استفاده از ویرایش ژن در آبزی‌پروری مورد بحث قرار گرفته‌اند.

مواد و روش‌ها: این پژوهش مبتنی بر یک مرور جامع از مطالعات علمی پیشین است که عمدتاً بر آزمایش‌های ویرایش ژن، تغییرات صفات فنوتیپی ماهیان، قوانین و مقررات مرتبط و کاربردهای CRISPR در صنعت آبزی‌پروری تمرکز دارد. در این بررسی، استفاده موفق از CRISPR-Cas9 برای تولید ماهیان نابارور (به‌منظور جلوگیری از انتقال ژن به جمعیت‌های وحشی)، کاهش خطر عفونت‌های ویروسی، افزایش کارایی مصرف خوراک و بهبود ارزش تغذیه‌ای ماهیان مورد توجه قرار گرفته است.

نتایج: نتایج نشان داد که فناوری CRISPR-Cas9 می‌تواند به‌طور قابل توجهی بهره‌وری آبزی‌پروری را افزایش دهد؛ به‌طوری‌که ماهیانی با رشد سریع‌تر، کیفیت عضلانی بهتر و مقاومت بالاتر به بیماری‌ها تولید می‌شوند. همچنین، این فناوری می‌تواند مصرف مواد شیمیایی و آنتی‌بیوتیک‌ها را کاهش دهد. با این حال، نگرانی‌هایی همچون خطر بروز تغییرات ژنتیکی ناخواسته، احتمال انتقال ژن‌های ویرایش‌شده به جمعیت‌های وحشی، کاهش تنوع زیستی و دسترسی محدود کشاورزان کوچک به این فناوری همچنان مطرح است.

نتیجه‌گیری: فناوری CRISPR-Cas9 ظرفیت بالایی برای ارتقای پایداری زیست‌محیطی صنعت آبزی‌پروری دارد و ابزارهای نوآورانه‌ای برای مقابله با چالش‌های اساسی این بخش فراهم می‌کند. این فناوری می‌تواند در تأمین تقاضای رو به رشد جهانی برای غذاهای دریایی سالم و مغذی نقش مهمی ایفا کند. با این حال، استفاده ایمن و مسئولانه از CRISPR مستلزم تدوین قوانین سخت‌گیرانه‌تر، افزایش آگاهی عمومی، دسترسی عادلانه به فناوری و پایش بلندمدت اثرات زیست‌محیطی آن است.

کلمات کلیدی: آبزی‌پروری، امنیت غذایی، زیست‌فناوری دریایی، ویرایش ژن، CRISPR-Cas9

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