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Review Article

Emerging Trends in Genomic and Biotechnological Applications in Animal and Aquatic Health

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Abstract: The rapid advancements in genomics and biotechnology have revolutionized animal and aquatic health, offering novel solutions for disease prevention, genetic improvement, and sustainable production. This review explores emerging trends in genomic and biotechnological applications in veterinary, poultry, and fisheries sciences. Key developments such as CRISPR-based genome editing, next-generation sequencing (NGS), and metagenomics are enhancing disease diagnostics, vaccine development, and selective breeding programs. Additionally, microbiome research and precision livestock farming are improving health management and productivity. Despite these advancements, challenges such as ethical concerns, regulatory barriers, and the need for further research persist. This review highlights the potential of these technologies in ensuring sustainable and resilient animal and aquaculture systems while addressing existing limitations and future research directions.

Keywords: Genomics; Biotechnology; Aquatic Health; Poultry; Livestock

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Introduction

For thousands of years, people have been meddling with the genomes of crops and animals in an attempt to generate children with desired traits, even in ignorance of genetics. Environmental control and genome modification have tremendously improved the manufacturing of food, medicine, and industrial raw materials obtained from plants and animals [1]. Artificial selective breeding—which entailed choosing for naturally better variants in crops and animals to pass on to next generations—probably was the first method used to alter genomes. Perhaps the first record of intentional selective breeding, an early Muslim visitor recorded Roman farming methods. Additionally utilized by researchers to generate mutations in the genome of interest is radiation. Already, a substantial number of crop lines have been developed commercially using radiation induction. But radiation breeding is usually linked with high rates of chromosomal abnormalities and detrimental consequences on the exposed organism. Chemical mutagens have also been utilized in order to generate mutations [2,3]. Commonly used are chemical mutagens causing base substitution in DNA such ethyl methane sulfonate and other alkylating compounds. Mutagenesis at specific sites in a large genome is a field of great interest since it offers the possibility to clarify the purpose of pertinent genes. Researchers devised site-directed mutagenesis to reach this target. First to use site-directed or site-specific mutagenesis to viral genomes or in vitro study respectively [4,5]. Prokaryotes started using site-directed mutagenesis in concert with the gene replacement strategy not long after. After site-directed mutagenesis and homologous recombination—sometimes known as gene targeting in the scientific community—genome editing became feasible for big species like mice. The most often used use of this technology is the development of "knock-out" animals, whereby the activity of a particular gene is either reduced, changed, or otherwise affected. Although mutagenesis and transgenesis—the technique of producing transgenic animals—have a close relationship transgenesis varies somewhat in that it uses foreign DNA. The first stage in transgenesis was introjection of foreign DNA structures into the pronuclei of fertilized egg [6]. Still, genes from different species abound in animal genomes. Palamiter et al. (1982) claim that when foreign genes are expressed, phenotypic changes could be fairly noteworthy. Researchers have been solving challenging biological challenges using gene editing methods for several years. Among the genomic milestones are knowledge of DNA structure, replication, transcription, and translation. Further research of these genes, cloning, sequencing, and finally expression—which produces copious of proteins—was made possible by the targeted breakage of DNA at particular places inside genes made possible by the advent of restriction endonucleases [7]. Furthermore established via genetic modification were several molecular diagnostic techniques like microarray, high throughput sequencing, polymerase chain reaction (PCR), and quantitative PCR (q-PCR). Among the negative effects of RNA interference are its lack of selectivity and its partial depletes of the target protein. Search for "novel" techniques that might selectively and totally abolish gene expression owing to these constraints led to the discovery of genome editing. After outlining the principles guiding genome editing and then its uses in the biological sciences, especially in relation to chicken and aquaculture, this paper presents the concept [8,9].

Transgenesis usage for the poultry industry and environment protection

The core of the poultry business are fast maturing chickens. The poultry company understands the need of effectively and inexpensively generating big amounts of meat or eggs. While the aim of raising egg-laying chickens is to increase their egg output by effective breeding, the aim of breeding grill chickens is to maximum their meat production by fast development [10,11]. Two other factors influencing chicken production efficiency are disease and food intake efficiency. Among other things, a higher feed efficiency helps to make chicken more affordable. Higher feed efficiency might result from selective breeding for features pertaining to growth, feed intake (food conversion ratio), and gastrointestinal tract design [12]. Consider transgenesis involving growth hormones (GH). Like fast development, higher food intake, and metabolic rates—as observed in fish—this is a quick approach to improve the performance of agricultural species. The GH approach allows one to transgenic pigs and sheep [13]. Furthermore, using GH transgenesis has improved goat milk output. In the poultry company, GH transgenesis could help to increase egg production efficiency. The poultry company's too high nitrogen and phosphate output contaminates water supplies and spreads diseases, therefore affecting human health [14,15]. Since phytase is lacking in their digestive tracts and keeps them from breaking down phytate phosphorous, it is imperative to provide this enzyme to the diet of monogastrian chicken. Phytolase breaks down the phytate molecule to liberate phosphorus from it. Making phosphorus more soluble causes it to enter surface water. Certain studies indicate that pigs with the phytase gene from bacteria can break down more phytate. Twenty percent of the gross value of production went towards the economic costs of the disease, mostly related with vaccines and condemnations; this number is almost three times what the cost of losses from death is. When consumed uncooked, such eggs or meat, diseases brought on by germs seriously compromise human health (Table 1). Furthermore causing problems are antibiotic residue [16,17]. Even although traditional approaches of illness control, such vaccines, have shown effectiveness, the chicken company is nevertheless vulnerable from certain diseases. Thanks to modern developments in molecular biology and selective breeding, chicken variants resistant to more frequent diseases are now feasible. Serious hazards to birds are infections including influenza and Marek's diseases (MD). Lyall et al. (2011) report that chickens resistant to the influenza virus have been produced using transgenic technology. Thus far attempts to create MD-resistant transgenic hens have failed. Though there are not any transgenic disease-resistant hens in the wild, this approach offers promise as a means of stopping the spread of infectious diseases in the poultry industry without turning to expensive vaccinations or drugs [18,19].

Table 1. Genomic and Biotechnological Applications in Animal and Aquatic Health:

Trend	**Description**	**Applications in Animal Health**	**Applications in Aquatic Health**	**Challenges & Future Prospects**
CRISPR-Cas9 Gene Editing	A precise gene-editing tool used to modify genetic traits in animals for disease resistance and improved productivity.	Editing genes to enhance disease resistance (e.g., PRRS-resistant pigs), improving livestock productivity and quality.	Development of disease-resistant fish (e.g., tilapia resistant to viral infections), enhancing growth rates.	Ethical concerns, regulatory restrictions, potential off-target effects.
Metagenomics and Microbiome Analysis	Studying the microbial communities in animals to understand health, immunity, and disease interactions.	Improving gut microbiome for better digestion, immunity enhancement, and reducing antibiotic reliance.	Monitoring aquatic microbiota for early disease detection, improving fish gut health.	High costs of sequencing, complexity in interpreting microbiome data.

Synthetic Biology	Engineering biological systems to produce beneficial compounds, vaccines, and probiotics.	Developing synthetic vaccines, engineered probiotics for better gut health, artificial milk production.	Engineering algae for improved fish feed, probiotics for disease prevention in aquaculture.	Regulatory challenges, biosafety concerns, public perception issues.
Transcriptomics and Proteomics	Studying gene expression and protein profiles to understand disease mechanisms and immune responses.	Identifying disease biomarkers for early detection and precision medicine in veterinary care.	Understanding stress responses in fish due to environmental changes, improving disease resistance.	High cost of technology, large data management issues.
RNA Interference (RNAi) Technology	Silencing specific genes to control disease and improve animal health.	Controlling viral diseases in livestock, enhancing immune responses.	Controlling aquaculture diseases such as White Spot Syndrome Virus (WSSV) in shrimp.	Delivery challenges, off-target effects, regulatory hurdles.
Stem Cell Therapy & Regenerative Medicine	Using stem cells for tissue regeneration and treatment of genetic disorders.	Treating musculoskeletal injuries in horses, developing regenerative therapies for genetic disorders.	Repairing tissue damage in fish from injuries or environmental stress.	Ethical issues, high costs, limited clinical applications.
Gene-Based Vaccines & Immunotherapy	Developing vaccines based on genetic material (DNA/RNA vaccines) for targeted immune responses.	DNA vaccines for foot-and-mouth disease, avian influenza, and mastitis.	RNA vaccines for viral infections in fish such as infectious hematopoietic necrosis virus (IHNV).	Stability issues, regulatory concerns, large-scale production challenges.
Epigenetics and Environmental Adaptation	Studying heritable changes in gene function without altering DNA sequences to improve adaptability and health.	Enhancing heat tolerance in cattle, optimizing reproductive performance.	Adapting fish to climate change stressors, improving feed efficiency.	Complexity in understanding epigenetic mechanisms, long-term validation required.
Biotechnological Disease Diagnostics	Advanced molecular tools for detecting pathogens and monitoring animal health.	Portable biosensors, lab-on-a-chip devices for rapid disease detection.	PCR-based and nanotechnology-based detection systems for early aquaculture disease diagnosis.	Cost of implementation, need for trained personnel, sensitivity/specificity concerns.
Blockchain and AI Integration in Genomics	Using AI and blockchain for secure genomic data analysis, disease prediction, and precision breeding.	AI-driven precision breeding, blockchain for secure genetic data management.	AI-based health monitoring in aquaculture, automated fish disease detection.	Data privacy concerns, integration complexity, regulatory approval required.

Poultry transgenesis and human nutrition

Two main products of poultry, meat and eggs, make it essential for human diet and health. The OECD-FAO (2012) claims that chicken meat consumption has surged and that there have been reports of a flourishing industry concentrated in selling poultry meat. Chicken is the healthiest meat relative to red meat because of its high-quality protein, low cholesterol, and presence of various functional components; so, this company finds great profitability. One among the several advantages of poultry meat is its cultural innocence [20,21]. Among the most reasonably priced and wholesome meats available is chicken as well. Establishing a facility to make grill chicken is not difficult. Research by

Mozdziak et al. (2003) and Magdelaine et al. (2008) indicates that the degree of biologically active components including high-value protein, unsaturated fatty acids, vitamins, macro- and micronutrients, cholesterol, and others defines the nutritional value of meat. Meat quality is influenced in part by several hereditary elements. These comprise the sex of the bird (Lo'pez et al., 2011), the rearing technique (Tong et al., 2015; Bianchi et al., 2006; Suganthi, 2014; right choice of breed, line, or hybrid; Dal Bosco et al., 2012). One breeding technique that helps to produce better muscle and meat measurements is selection depending on dominant or desired traits through crossbreeding. Furthermore able to change meat characteristics are natural and exogenous hormones. Recent identification and sequencing of chromosomal regions linked to quantitative trait loci has ramifications for meat quality, growth, and carcass properties. Two proteins whose expression patterns affect muscle mass are follistatin and myostatin [22,23]. Toldra's (2008) findings suggest that gene transfer can help to introduce new genes capable of promoting muscle development. Palmiter et al. (1982, 1983) gave an explanation in the 1980s on how integration and expression of rat or human hormones causes mice weight to double. Westhusin (1997) claims that at that time the cattle sector considered applying this technology for mass meat production. Using transgenesis has improved the quality of meat produced. For instance, expressing spinach desaturase (Saeki et al., 2004) allows transgenic pigs to synthesize two vital polyunsaturated fatty acids, linoleic and linoleic acid. Therefore, based on previous studies on mammalian species, it is reasonable to change meat parameters in odd fowl and raise meat output. Particularly those with low means, people living in developing countries can depend on chicken eggs as a basic supply of nutrients [24]. Cheap, reasonably high in protein, and with modest calories are eggs. Furthermore, eggs are excellent for persons of all ages since they have enough of fat-soluble elements. Conversely, Eilat-Adar et al. (2013) advised against regular consumption of them due of the high levels of saturated fat and cholesterol (around 3 g/100 g). The special characteristics of egg yolk have made it rather popular in food manufacturing. Techniques for creating eggs with reduced cholesterol levels have been developed in order to reach this, with an eye towards genetic engineering or dietary modifications including nutrients, non-nutrients, and medications [25,26]. These techniques have only minimal effect, nevertheless, in changing the cholesterol level in egg yolks (Elkin, 2007). Although eggs improved with n-3 polyunsaturated fatty acids (PUFA) have lately established a reputation as a healthful diet, customer ready to buy even more expensive eggs has been recorded. Changing the feeding of laying hens is one approach to modify their PUFA level. It should be possible to produce eggs with greater nutrition by transgenesis technology. The increased global egg consumption calls for large-scale egg production; the difficulty then becomes in reaching this target [27]. The only techniques thus found for varying egg size have been changes to the feeding (Selman and Houston, 1996), thermoregulation (Nager and Van Noordwijk, 1992), and the size of the clutch (Nol et al., 1997). Still, a lot of the elements influencing egg quality and contents is yet unknown (Williams, 1996). With transgenesis technology, more investigation on the elements influencing egg quality and the development process of eggs is necessary to reach this aim. Some research in this vein has been conducted; Chen et al. (2016) and Shin et al. (2014) employed transgenic quail to discover how to control lipolysis in poultry so that eggs may be formed and yolks may be developed. Furthermore under examination are the effects of hormones, like the 2016 study by Mohammadi and Ansari-Pirsaraei on exogenous GH's effectiveness in increasing chicken egg output [28].

Prospectuses for genomic editing in the sectors of chicken and fisheries

Genome editing can be used to change the DNA of cells, tissues, or model animals so that one may investigate the biology and behavior of organisms in an altered genome environment. In xeno-transplantation—which seeks to restore human loss or malfunction by means of animal cells, tissues, and organs—genome editing finds application [29,30]. Several studies have demonstrated that CRISPR-Cas9 is a useful technique for identifying and characterizing important pathogenic genes as well as for investigating bacterial immune evasion systems. While concurrently lowering input costs related to water and fertilizers, genome editing has the potential to improve crop output and quality, claims [31]. Two other possible uses of this technique are fast development to boost meat output and the breeding of animals immune to disease[32].

Treatment of diseases

Genetically modifying human blood cells offers great potential to treat disorders including leukaemia and AIDS. Many infectious diseases as well as more common inherited conditions like haemophilia could be treatable with it. T-cell genome editing shows promise to be a valuable tool for cell-based therapy for cancer, HIV, primary immunological deficiencies, and autoimmune diseases [33,34]. Better ways to knock-out or knock-in targets in the genome will help us to achieve this, thereby enabling us to alter T-cell function and correct mutations connected with illnesses [35].

Functional genomics

With nearly no off-target effects, the introduction of CRISPR-Cas9has tremendously enhanced the efficiency and precision of screening noncoding gene regions including enhancers and promoters [36,37]. Operating outside of the DNA coding area, epigenetics is a subfield of genetics; the CRISPR-Cas9system has also helped to clarify this puzzle. Targeted nucleases have significant potential to induce mutations in a gene, so defining its function. A new approach to identify genes' functions and discover how diseases are caused by gene dysfunction is genome-wide genetic screens employing CRISPR-Cas9 technology, including sgRNA screening, knock-out screening, and CRISPR mutagenesis [38].

Production of the mono-sex population

A well-known phenomena in the fish kingdom, sexual dimorphism in body growth patterns is present in many fish species. For instance, males of tilapia grow faster than females; in the case of rainbow trout and Indian main carp, the reverse is true [39,40]. Targeted nucleases have considerable potential to directly generate mono-sex or sex-reversed fish by removing the genes that define sex, without appreciable effect on biodiversity. Li and Wang (2017) for example noted testicular formation in tilapia when targeted nucleases eliminated female sex-determining genes like foxl2, sf-1, or cyp19a1a. Furthermore induced in this fish species was biliary development. Thus, techniques for genome editing offer a flexible and environmentally friendly means to produce a population of one sex [41,42].

Production of fast-growing fishes

Some native cold water fish species, including snow trout, have modest development rates due to their genes, physiology, and environmental constraints. Targeted nucleases could either knock out genes impeding skeletal muscle development or increase the expression of genes encouraging growth. Common carp showed larger phenotypes in their F0 generation following CRISPR-Cas9 disruption of a gene coding for myostatin, a protein that inhibits muscle development, according a 2016 Zhong et al. study. Similar techniques could be used to boost cold water fish output by slow-growing species like snow trout [43,44].

Fertility Issues

For a variety of reasons—including control of weed and predatory fish reproduction, the release of exotic and transgenic fish into the wild in the event of their accidental escape from ponds or raceways, and the establishment of a fish population free of undesired genetic variation—sterile fish are often sought after in aquaculture. Targeted nucleases could easily address this issue by altering the genes controlling sex. Using ZFN (Qin et al., 2016), sterile channel catfish were generated by removing the ʋ subunit gene of pituitary luteinizing hormone [45,46].

Production of ornamental fishes

Targeting pigmentation genes made possible by genome editing technology will enable the production of ornamental fish with particular pigment patterns. These genome editing devices spend no time unlike conventional genetic techniques. By means of genome editing technologies like ZFN, TALEN, and CRISPR-Cas9, zebrafish can inherit light-colored eyes [47,48].

Functional characterization of genes

Using genome editing technologies to introduce mutations in the selected gene will help to expose the function of the gene in an immunological or physiological pathway. Using customized TALENs, researchers have demonstrated that deleting the kiss-1 and kiss-2 genes in zebrafish does not change spermatogenesis, folliculogenesis, or reproductive capacity in either sex (Tang et al., 2015). Being a main regulator of gonadotropin-releasing hormone, our study contradicted the general wisdom on the purpose of kiss genes in fish reproduction. Therefore, more study is required to validate the actions of kisspeptins in particular aquaculture species before suggesting the pure kisspeptin proteins as a suitable replacement for induced breeding hormones. Labeo rohita toll-like receptor-22 also aims at disruption via homologous-directed repair using the CRISPR-Cas9 technology. Developing genetically engineered fish models would help to clarify the special roles that every gene plays in different physiological and immunological processes [49].

Conclusion

For human consumption, poultry—especially chicken (*Gallus gallus*)—is rather important in agriculture. Transgenesis has shown to be a useful technique in the chicken company for enhancing human nutrition to guarantee that individuals have access to enough, premium food for their life and health. Transgenesis is also used to release now indigestible plant material, lower phosphorus excretion, and create commercial birds more resistant to disease. Transgenesis will enable poultry producers to raise output while lowering their environmental effect. Mass-producing premium therapeutic proteins using transgenic chicken is the second possible game-changer for the survival of human diseases. Therefore, all of these human-life advantages of poultry transgenesis help to make the development of transgenic farms conceivable. Still in their infancy, by enabling exact genome editing of fish, these methods have the potential to significantly change aquaculture production in not too far future. Targeted nucleases differ from traditional transgenesis mostly in that the former hardly introduces foreign DNA into the genome of the latter. Among the several traits expected to be improved in aquaculture by genome editing techniques are disease resistance, feed conversion efficiency, growth, reproductive success, and tolerance to biotic and abiotic challenges. Apart from disease modelling and drug screening, genome editing can support pollution monitoring in aquatic surroundings.

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