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The Role of Genetically Engineered Animals in Modern Biotechnology

Abstract

This article provides a comprehensive overview of the growing significance of genetically engineered animals in the field of modern biotechnology. Beginning with the historical development and foundational breakthroughs in genetic engineering, the paper traces the evolution of transgenic animal technologies and their expanding applications across multiple sectors. In the field of biomedical research, genetically modified animals serve as critical models for studying complex human diseases such as cancer, neurodegenerative disorders, and metabolic syndromes. In agriculture, transgenic livestock and poultry are utilized to enhance productivity, disease resistance, and nutritional content. Additionally, environmental biotechnology benefits from genetically engineered species designed for pollution detection and bioremediation, while industrial biotechnology employs such animals as bioreactors for the cost-effective production of therapeutic proteins, enzymes, and monoclonal antibodies. The article further explores the ethical concerns surrounding animal welfare, biodiversity, and the long-term ecological impact of releasing genetically modified organisms. It examines the evolving regulatory frameworks that govern the use of transgenic animals in research and industry, highlighting both national policies and international guidelines. Finally, the article discusses current challenges and emerging trends, including advancements in genome editing technologies like CRISPR/Cas9, which promise greater

precision and efficiency in the creation of genetically engineered animals. By analyzing both the benefits and risks, this article aims to provide a balanced perspective on the present and future role of transgenic animals in science and society.

Keywords: *animals, genetically engineered, biotechnology*

Introduction

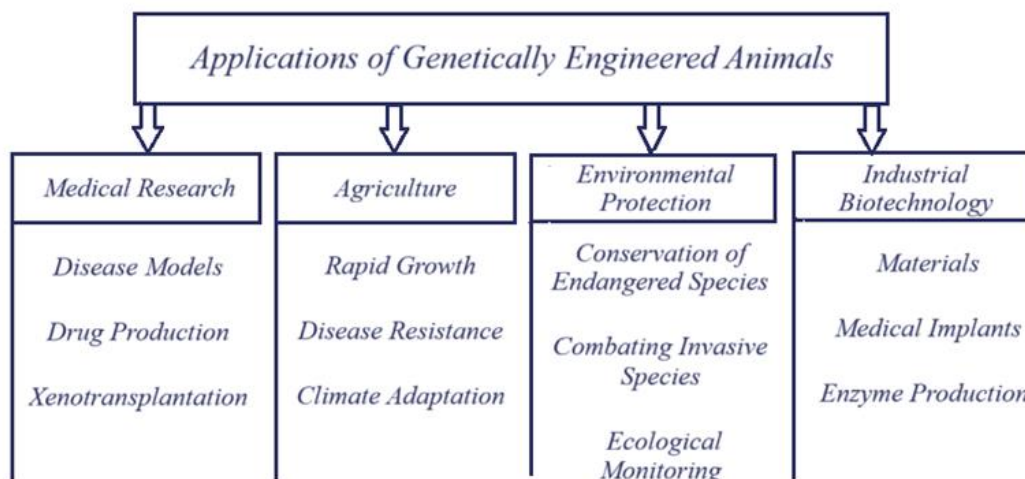
Since the dawn of humanity, food has been a vital resource essential for human survival. Ensuring food security, storing it under optimal conditions, and producing it in sufficient quantities are fundamental to sustaining human life. Nowadays, consumers are increasingly concerned about the quality and safety of food, and sensitivity toward the consumption of healthy and safe food is steadily growing (Sevim, et.al., 2021; Çağlar, Mustafa, 2018).

The food supply chain encompasses the entire journey of food from farm to table, with consumers representing the final point of contact. Food safety plays a crucial role in protecting both the health and the economic interests of consumers and food service professionals worldwide. While regulatory authorities are tasked with overseeing food safety within the food-service industry, maintaining proper food safety practices at home falls under the responsibility of consumers. Therefore, knowledge and application of food safety principles significantly influence the occurrence of foodborne illnesses (Çiğdem, et al., 2021).

Genetic engineering is a collection of biotechnological methods used to modify or manipulate the genetic material of organisms. In recent decades, especially with the development of widely used genome editing technologies such as CRISPR-Cas9, genetically engineered animals have become an integral part of modern biotechnology (Doudna, Charpentier, 2014). These animals are used to model diseases, test drugs, increase food production, and even protect the environment.

The history of genetic engineering began in the 1970s with the discovery of recombinant DNA technology. The first transgenic mouse was created in 1974, but the first patented transgenic animal - the "oncomouse" - was only created by Harvard University in 1988 (Sherkow, Greely, 2015). This significant scientific achievement laid the foundation for the large-scale development of genetically modified animals in subsequent decades.

Among modern genome editing technologies, Zinc Finger Nucleases (ZFNs), TALENs, and especially CRISPR-Cas9 systems hold significant importance. The CRISPR-Cas9 system has revolutionized genome editing. This system consists of guide RNA that recognizes the target DNA sequence and the Cas9 enzyme that cuts DNA. The simplicity, efficiency, and affordability of the technology make it suitable for widespread application (Doudna, Charpentier, 2014). In recent years, improved versions of CRISPR technology, such as Base Editing and Prime Editing, have been developed to create more precise mutations.



Scheme1: Applications of Genetically Engineered Animals (Li, et al., 2019)

2. Materials and Methods

2.1. Genetically Engineered Animals in Medical Research

In the field of medical research, genetically engineered animals, especially mice, have become indispensable tools for studying many human diseases (Whitelaw, et al., 2016). Transgenic mice are widely used in oncology research to study the growth and metastasis of cancer cells. Such models allow for better understanding of cancer cell behavior and response to treatment methods (Whitelaw, et al., 2016; Brian, et al., 2018).

Genetically modified animals also play an important role in studying neurodegenerative diseases, including Alzheimer's, Parkinson's, and Huntington's diseases (Whitelaw, et al., 2016; Michael, et al., 2024). For example, transgenic mice modeling Alzheimer's disease demonstrate the formation of beta-amyloid plaques in brain tissue and the development of neurological symptoms. These models create valuable opportunities for developing and testing potential treatments.

Genetically engineered animals are also widely used in the research of metabolic diseases, including diabetes, obesity, and metabolic syndrome (Wang, et al., 2014). For instance, genetically modified mice that overexpress or deactivate insulin receptors have been created for diabetes research. These models are used to study the basic mechanisms of diabetes and test new treatment methods.

In the field of drug production, genetically engineered animals are used as "bioreactors." They can produce important proteins that are produced in the human body (e.g., insulin, coagulation factors) in their milk or blood (Ran Zhang, et al., 2018). This method allows for cheaper and more effective production of natural human proteins. At the same time, transgenic animals are also used for the production of monoclonal antibodies. These antibodies are used to treat various diseases, including cancer, arthritis, and multiple other diseases (Ran Zhang, et al., 2018; Chojnacka-Puchta, Sawicka, 2020).

In the field of xenotransplantation, genetically engineered animals, especially pigs, are considered as a potential solution to the problem of human organ shortage (Cooper, et al., 2016). Special genetic modifications are made for the human immune system to accept pig organs. For example, pig antigens recognized by the human immune system are deleted, and genes that regulate the defense mechanisms of the human immune system are added (Cooper, et al., 2016). Additionally, it is possible to reduce the risk of infection by deleting endogenous retroviruses from the pig genome. Research in this area is approaching a solution to the problem of organ shortage for transplantation.

2.2. GMO Animals in Agriculture

The main purpose of genetically engineered animals in agriculture is to increase food production, enhance disease resistance, and provide adaptability to climate change (Van Eenennaam, 2017). Creating animals with rapid growth characteristics is one of the main directions in this field. For example, AquAdvantage salmon - a transgenic fish that produces growth hormone excessively and grows twice as fast as ordinary salmon (Van Eenennaam AL.,2017, Ledford H.,2015). Such animals allow for the production of more food with the same resources. Feed conversion efficiency is also an important factor in agriculture. Genetically modified animals can produce more meat, milk, or eggs with less feed (Cooper, et al., 2016). This is both economically efficient and reduces environmental impact. Additionally, genetic engineering is also used to change the composition of food products. For example, transgenic animals are created that produce healthier fatty acids or additional nutrients (Van Eenennaam, 2017; Alexandr, et al., 2024).

Disease resistance is also an important issue in agriculture. Genetic engineering allows for the creation of animals resistant to specific pathogens (Van Eenennaam, 2017, Lillico, et al., 2016). For example, work is being done on creating pigs resistant to the African Swine Fever virus. Such modifications both improve animal welfare and help farmers minimize disease-related losses. At the same time, it is also possible to reduce the spread of zoonotic diseases, i.e., diseases that can be transmitted from animals to humans.

In the context of climate change, the adaptability of animals to changing conditions is becoming increasingly important. Genetic engineering allows for the creation of animals that are resistant to

heat stress and require less water and food (Kiplangat, 2023). Such animals can help form sustainable agricultural systems in the context of global warming.

2.3. The Role of Transgenic Animals in Environmental Protection

In the field of environmental protection, genetic engineering is used to save endangered species, combat invasive species, and monitor environmental pollution (Robert Costanza & Shuang Liu, 2014, Frankham, 2015). For saving endangered species, genetic engineering is used to increase genetic diversity and enhance the sustainability of populations. For example, the problem of low genetic diversity in small and isolated populations can be solved by adding genetic material from other populations of the same species (Frankham, 2015). A more radical approach is de-extinction attempts - i.e., creating genetic similars of extinct species (Shapiro, 2017). This approach is implemented by modifying the genome of the extinct species' closest relative. For example, work is being done on "resurrecting" mammoths by adding specific genetic characteristics of mammoths to modern elephants. Gene drive systems can play a significant role in combating invasive species (Esvelt, et al., 2014). This technology, using the CRISPR-Cas9 system, reduces the reproductive ability of invasive species or allows for the rapid spread of certain genetic characteristics throughout the population (Doudna, Charpentier, 2014; Esvelt, et al., 2014). For example, experiments are being conducted on gene drive systems to reduce populations of malaria-carrying mosquitoes. For monitoring environmental pollution, transgenic animals that respond to pollutants in natural conditions are created (Garcia-Reyero, 2015). Such "biosensor animals," for example, zebrafish that change color when certain toxic substances are present in water or soil, can be significant tools for ecological monitoring.

3. Results

3.1. Applications in Industrial Biotechnology

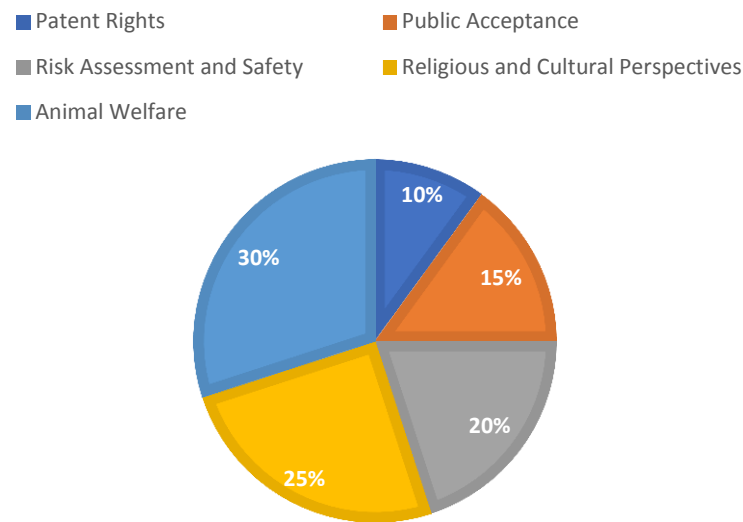
In industrial biotechnology, transgenic animals are used for the production of new materials and chemicals. In the field of fiber and material production, transgenic silkworms that produce higher quality silk are created (Xiangping Dai, 2024). Natural silk is a very valuable material, but its production is complex and expensive. Genetic engineering allows for increasing the quality of silk and production efficiency. Additionally, transgenic animals are also used in the production of new biomaterials for medical implants and tissue engineering (Ran Zhang, et al., 2018, Saif AL-Hafedh, et al., 2024). For example, transgenic goats carrying the human collagen gene can secrete human collagen with milk for medical applications. Such approaches allow for more efficient production of new biomaterials and biologically active substances. The production of enzymes and industrial chemicals is also one of the industrial applications of transgenic animals (Ran Zhang, et al., 2018). Transgenic animals that produce enzymes used in various industrial processes allow for cheaper and more environmentally friendly production of these substances.

3.2. Ethical Issues and Public Acceptance

The use of genetically engineered animals raises a number of ethical issues (Ishii, Araki, 2016; Thompson, 2018). Animal welfare problems are one of the main concerns in this area. Can genetic modifications negatively affect animal welfare? How should the ethical status of genetically engineered animals be determined? These questions are actively discussed both in the scientific community and in public debates (Thompson, 2018). Various religious and cultural perspectives also shape attitudes toward genetically engineered animals (Mohd Izhar, et al., 2018). Islam, Christianity, Judaism, and other religions have different attitudes toward GMO animals. According to some religious views, genetic modifications are seen as "playing with nature" or "interfering with the divine order." Other religious perspectives evaluate these technologies as the use of knowledge and skills given by God to humans to improve human welfare.

Cultural acceptance and rejection also differ in different societies (Ishii T. and Araki M., 2016). Some countries have strong public resistance to GMO products, while in others these technologies are more accepted. These differences depend on both historical and cultural context, as well as the level of information and education (Ishii, Araki, 2016, Kübra Sinem, et al., 2023). Risk assessment and safety are also important issues. The potential impacts of releasing genetically modified animals into the natural ecosystem should be seriously investigated (Kübra Sinem, et al., 2023). There is a

risk of transgenic genes transferring to wild populations and causing unexpected ecological consequences. At the same time, the potential effects of consuming GMO animal products on human health should also be carefully studied (Michael, et al., 2024, National Academies Press (US), 2016).



Scheme 2: Ethical Issues (Ormandy, et al., 2011).

3.3. Regulatory Frameworks

Various international, regional, and national frameworks exist to regulate the use of genetically engineered animals (Yunus, Yilmaz, 2019). At the international level, the Cartagena Protocol is one of the main agreements on biosafety. This protocol regulates the international movement of "living modified organisms" and establishes rules to ensure their safe use.

CODEX Alimentarius provides international standards for food safety. These standards establish guidelines for assessing the safety and labeling of GMO food products (Codex Alimentarius Commission, 2003). These international standards play an important role in the international trade of genetically engineered food products.

Various regulatory mechanisms also exist at regional and national levels. In the USA, the FDA (Food and Drug Administration), USDA (United States Department of Agriculture), and EPA (Environmental Protection Agency) play a role in regulating genetically engineered organisms (Carter, et al., 2014). In the USA, the evaluation of GMO products is carried out on the basis of the principle of "substantial equivalence" - i.e., the GMO product is compared with its traditional analog. Regulation of GMOs in the European Union is stricter (Norio, 2016). Here, the "precautionary principle" is applied, and comprehensive safety assessment is required before permitting the use of GMO products. At the same time, labeling of GMO products is mandatory in the European Union, which allows consumers to make informed choices (Norio, 2016).

Regulatory approaches in Asian countries differ (Robert Costanza & Shuang Liu, 2014). For example, China actively conducts research in the field of genetic engineering and supports GMO products at the level of official policy. Japan applies strict rules for the evaluation and labeling of GMOs. The differences in these approaches stem from both scientific and political and public factors (Robert Costanza & Shuang Liu, 2014; Zhang, Guo, & Zhu, 2016).

4. Discussion

4.1. Future Perspectives and Trends

A number of new technologies and approaches are being developed in the field of genetic engineering. Single-cell Genomics, i.e., genetic analysis and modification technologies at the single-cell level, enable more precise and effective genetic changes (Wang, Navin, 2015). This technology creates new opportunities for studying and modifying the genetic profiles of individual cell types in complex organisms. The creation of artificial chromosomes is also one of the

promising directions for the future (Boeke, et al., 2016). Fully artificial chromosomes could allow for the addition of new genetic functions not present in natural organisms. This approach opens new possibilities for creating and studying complex biological systems. Epigenetic modifications are used to regulate gene activity without changing the DNA sequence (Stricker, et al., 2017). This approach allows for changing the expression of genetic material without touching the material itself. Epigenetic modifications offer less invasive and more precise genetic regulation possibilities.

New application areas are also rapidly developing. In the field of neurobiology, transgenic animals are used to study brain functions and the mechanisms of neurological diseases (Wang, et al., 2014; Kim, et al., 2015). For example, transgenic animals expressing fluorescent proteins to visualize brain activity help to better understand brain functions. Genetic engineering also plays an important role in aging research (Tian-Yi Zhu, et al., 2025). Work is being done on genetic modifications to slow down aging processes and increase longevity. For example, activation of the telomerase gene in mice can reduce signs of aging. Genetic engineering also has potential applications in space biology (Arora, & Mishra, 2016). Organisms modified for long-term space missions can be adapted to the specific conditions of the space environment (e.g., radiation, weightlessness). Such organisms can be used both for food and oxygen production on space stations, and for interplanetary missions and terraforming of exoplanets.

Social and economic impacts are also among the factors that will determine the future of the field of genetic engineering (Van Eenennaam, 2017; Herrero, et al., 2017). GMO animals can have a significant impact on global food security. More efficient and sustainable food production can help solve the food supply problem for the growing population. At the same time, economic issues related to GMO technologies, such as patent issues, market sharing, and the situation of small farmers, should also be considered (Herrero, et al., 2017).

Food safety remains a major concern for consumers and continues to be a central focus for food producers and regulatory authorities overseeing food safety (Tosun, Demirbaş, 2021; Aydan, 2013). In addition to the practical benefits that biotechnological applications and, specifically, genetically modified organisms (GMOs) can offer, protecting human and environmental health as well as socio-economic systems from the potential risks of these applications and products forms the foundation of related policies. At this point, alongside technical and legal measures, establishing a mechanism for "public oversight" plays a critical role (Oğuz, Meltem, 2010).

Conclusion

Genetically engineered animals have become an integral part of modern biotechnology. They play an important role in various fields from medical research to agriculture and environmental protection. In the medical field, genetically engineered animals are used for creating disease models, drug production, and xenotransplantation. In agriculture, they are used to increase food production, enhance disease resistance, and adapt to climate change. In the field of environmental protection, genetic engineering offers new opportunities for saving endangered species and combating invasive species.

However, the development of this technology requires constant consideration of ethical, safety, and regulatory aspects. Animal welfare problems, religious and cultural perspectives, as well as risk assessment and safety issues should be seriously investigated. Existing international, regional, and national frameworks for regulating the use of genetically engineered animals should be continuously improved.

In the future, further improvement of genetic engineering technologies, more precise genome modifications, and the emergence of new application areas are expected. New technologies such as Single-cell Genomics, artificial chromosomes, and epigenetic modifications will enable more precise and effective genetic changes. Genetic engineering will find wide application opportunities in new fields such as neurobiology, aging research, and space biology. These developments can potentially lead to significant advances in human health, food security, and environmental protection. However, along with these, society must use these technologies responsibly and in

accordance with ethical principles. Genetic engineering offers great opportunities and potential benefits, but to properly use these opportunities, a balance must be found between science, politics, ethics, and public opinion.

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