

Application of Biotechnology for Food Production and Quality Improvement in the View of Food Security Aspect

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Received April 18, 2025; Revised May 19, 2025; Accepted May 27, 2025

Abstract With the global population rapidly increasing and cultivable land remaining limited, a significant portion of the world's population continues to suffer from undernourishment. Addressing this issue necessitates the exploration and adoption of all available alternatives under current global conditions. In this context, modern biotechnology has emerged as a vital complementary tool to traditional agricultural practices, offering potential solutions to challenges related to food insecurity. Biotechnology involves the use of biological systems, living organisms, or their components to develop or modify products and processes for specific applications. It encompasses a wide range of techniques, from age-old practices, such as brewing wine and fermenting cheese, to advanced methods involving the genetic manipulation of plants, animals, and microorganisms. Agricultural biotechnology can be broadly categorized into two main approaches. The former enhances conventional breeding by utilising genetic information to accelerate and improve selection. The second involves direct genetic modification to create new organisms with desired traits. This latter method has led to the development and commercialisation of Genetically Modified Organisms (GMOs), which often exhibit characteristics not naturally found within a species. Globally, the most widely cultivated GMOs include soybean, maize, and cotton, which are primarily engineered for improved agronomic traits such as pest resistance and herbicide tolerance. These traits are expected to remain central to the future development of GM crops. In addition to crops, transgenic animals, such as fast-growing salmon and genetically modified cattle, with enhanced protein production are in the advanced stages of research, while many other genetically engineered animals for food purposes are still undergoing early research and development. Genetically modified microorganisms are extensively used in the production of enzymes and other processing aids in a broad array of processed foods. Therefore, biotechnology has the potential to optimise food production and distribution systems, aligning them with the nutritional demands of a growing global population. Its strategic application can strengthen food supply chains and ensure stable, affordable, and sustainable access to safe and nutritious food on both regional and global scales. Additionally, integrating biotechnology with nutritional education, especially for vulnerable populations, can contribute to global food security and public health.

Keywords: Biotechnology, Food security, Genetically modified organisms, Public health, Technologies

Cite This Article: Mahendra Pal, Ravindra Zende, Tesfaye Rebuma, Alemayehu Bekele, Aishwarya Nair, and Dhvani Upadhyay, "Application of Biotechnology for Food Production and Quality Improvement in the View of Food Security Aspect." *Biomedicine and Biotechnology*, vol. 10, no. 1 (2025): 1-10. doi: 10.12691/bb-10-1-1.

1. Introduction

The United Nations has reported that over 900 million individuals worldwide suffer from inadequate nutrition. However, this situation is expected to worsen by 2050, when the global population will increase by 50% and the amount of cultivable land will decrease by 50%. These changes will place unprecedented pressure on global agricultural systems. Numerous international bodies

recognize that modern biotechnology holds significant promise for tackling food insecurity, particularly through its application in agriculture and food systems to mitigate key factors driving global hunger. The United Nations projected that the global population would rise by 25%, reaching approximately 7.5 billion by the year 2020. On average, an additional 73 million people are added annually, of which 97% will live in developing countries. It is estimated that around 1.2 billion people globally are living in severely impoverished conditions. Of these, approximately 800 million face food insecurity, and

approximately 160 million preschool-aged children suffer from malnutrition [1].

Biotechnology is broadly defined as the application of techniques that utilise living organisms or substances from those organisms to develop or modify a product, improve plants or animals, or develop microorganisms for specific purposes. One of the most notable outcomes of modern biotechnology is the development of genetically modified organisms (GMOs), which are organisms whose genetic makeup has been altered through genetics. Recombinant DNA technology entails integrating genes of interest from various sources into a single DNA molecule to generate a novel genetic construct [2]. Food security is realized when all individuals, at all times, possess reliable physical and economic access to sufficient, safe, and nutritious food that aligns with their dietary needs and cultural preferences, thereby supporting an active and healthy life. This concept encompasses not only the availability of nutritionally sufficient and safe food, but also the consistent ability to obtain food through socially acceptable means [3]. Several significant trends in both the agricultural production and food processing sectors have led to closer integration of these sectors. Over the past decade, there has been a noticeable shift from a traditional focus on commodities to value-added agricultural products. This shift, driven by increasing competition and market demands, has led to the emergence of the concept known as the "Agri-Food Value Added Chain" a framework emphasising the linkages between production and processing in enhancing the overall value of agricultural goods [4].

The selection and application of biotechnology are often guided by the specific needs and priorities of local communities. Numerous developing nations have identified genetic modification as a potential tool for addressing key priorities in their agricultural development plans. In several African nations, for instance, major priorities include enhancing drought tolerance, improving disease resistance, and increasing crop yields. Staple crops, such as cassava, millet, yams, and sorghum, are particularly suitable candidates for genetic modification to address these challenges. Modifications that seek to prolong the shelf life of foods could help significantly reduce postharvest losses. Another high-priority application in low-till agriculture is the development of herbicide-tolerant crops. This approach can reduce the labour intensity of farming and create opportunities for farm workers, many of whom are women, to participate in alternative income-generating activities [5]. An additional promising application of biotechnology lies in the development of livestock breeds with enhanced tolerance to various tropical diseases.

Modern methods, such as genomics, can be applied in this area without the need for transgenic approaches. Revegetation of degraded and marginal lands also plays a crucial role in agricultural sustainability. Investment in fast-growing plants can facilitate ecological restoration in many denuded regions of the world. This research not only contributes to environmental rehabilitation, but also boosts the availability of fodder, which is essential for livestock production in many developing countries [6]. For instance, the International Livestock Research Institute (ILRI) developed transgenic *Boran cattle* (e.g.,

the cloned calf "Tumaini") by introducing resistance genes from baboons [7]. Currently, the use of transgenic technology is primarily concentrated in a few major crops such as soybeans, corn, cotton, and canola. By the year 2000, genetically modified crops were widely cultivated, with soybeans leading at around 25.8 million hectares, followed by corn at 10.3 million hectares, cotton at 5.3 million hectares, and canola at 2.8 million hectares. The bulk of crops exhibit traits such as herbicide tolerance and disease resistance. These trends show that the early diffusion of transgenic crops has been largely confined to temperate zones and has been limited to a few major commercial crops. Thus, genetic modifications have been employed to bring about gradual improvements in existing crop traits. These modest yet targeted modifications help explain why transgenic crop adoption remains regionally concentrated in areas with comparable ecological environments [8].

The promise of transgenic applications has not yet been realized for two reasons. First, unlike the Green Revolution, which was largely driven by public-sector initiatives aimed at supporting low-income populations, modern biotechnology has predominantly evolved within the private sector. Private enterprises often lack motivation to invest in crop development targeted at the needs of resource-poor farmers. Second, agricultural research in the public sector has been declining, and therefore little investment has gone into developing crops for low-income families. A shift in the current scenario requires reorienting the research agendas of private firms, which hinges on suitable incentives and a marked enhancement in public funding for agricultural research [9]. Projections indicate that by 2030, the global population will reach approximately 8.1 billion, growing by more than 75 million individuals annually, with the majority of this growth concentrated in developing nations—regions already facing substantial socio-economic and environmental pressures. Assuming per capita consumption remains unchanged, cereal production must increase from around 1.92 billion tons in 1990 to approximately 2.88 billion tons by 2030 to meet global demand [10,11]. Although the proportion of undernourished people in developing countries is expected to decrease, the overall state of the global food system is expected to remain inadequate. Meeting future food demands requires overcoming the dual challenge of increasing output while contending with less farmland, fewer nonrenewable inputs, limited water, and declining agricultural labour [12].

Therefore, the objectives of this paper are to review

- ✓ Application of biotechnology for food production and quality improvement
- ✓ Role of biotechnology in food security

2. Literature Review

2.1. The Role of Biotechnology and Issue of Food Security

According to the 1992 Convention on Biological Diversity, the scope of biotechnology spans from traditional practices, such as fermenting wine and cheese,

to advanced modern techniques involving the genetic modification of living organisms, including plants, animals, and fish. Two principal categories of biotechnological processes are commonly recognized: one involves the use of genetic information to enhance and accelerate conventional breeding in plants and animals, whereas the other employs more advanced methods to directly alter the genetic structure of an organism to produce entirely new traits [13]. Improved cold tolerance lentils in the Syrian Arab Republic are an example of conventional breeding outcomes. A clear example of advanced biotechnology is the creation of insect-resistant crops such as genetically modified (GM) cotton and maize by incorporating genes from specific bacteria [14]. Current biotechnology can increase crop yields and reduce production costs, even for small-scale farmers in developing countries at small scale, who make up a large part of the global poor and hungry population. However, the majority of biotechnological research and development is driven by private commercial interests. To ensure the technology benefits all, particularly marginalized communities, the public sector must play an active role in guiding research efforts and ensuring equitable access for those most in need [15]. Figure 1 gives an overview of biotechnology-based applications in food security, encompassing genetic engineering in crops (e.g., pest/drought resistance, micronutrient fortification), transgenic animals (e.g., fast-growing fish, disease-resistant livestock), and microbial biotechnology (e.g., enzyme production, probiotics).

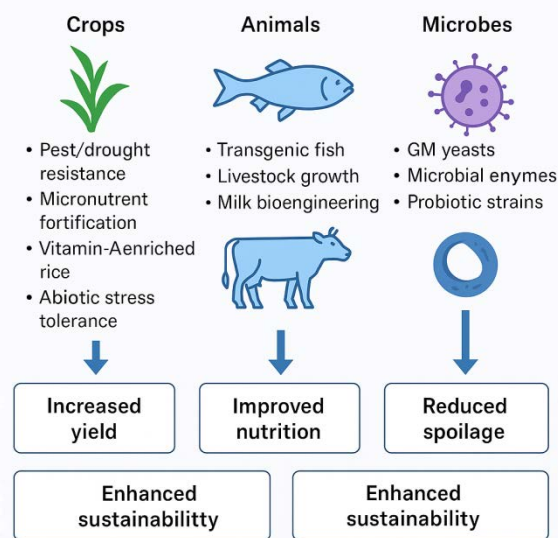


Figure 1. Schematic Representation of Biotechnological Interventions in Food Production and Security

The cultivation of crops, rearing of livestock, aquaculture and utilization of microorganisms in food production systems present a wide array of potential advantages, including increased productivity and yield, through the GMO technique. The technology can be utilized in both developing and developed countries to enhance food availability, particularly for populations facing hunger. It can also reduce the need for agricultural inputs, such as chemical sprays and pesticides, thereby lowering production costs and potentially stabilizing or reducing food prices for consumers. Moreover, GMOs

may contribute to the conservation of natural resources and habitats of indigenous animals. However, questions remain about the long-term sustainability of intensive planting practices, particularly whether soil ecosystems can withstand such pressure without degradation. The use of agrochemicals has raised serious health concerns, including miscarriages, stunted growth in children, respiratory illnesses in adults, and increased cancer rates. There are also risks associated with the transfer of allergenic genes/or antibiotic resistance and other unknown effects, such as access to unauthorized GMO products in the food chain (for example GMO intended for animal could be used accidentally in products for human consumption) [16].

2.2. The Challenge with World Population Growth and Food Supply

Biotechnology holds significant promise for addressing the agricultural challenges faced by poor farmers and developing nations. According to UN officials, this should be viewed as a complementary approach to traditional farming methods. By increasing per-hectare productivity and reducing input costs, such as by decreasing ploughing and pesticide use, biotechnology can contribute to global food security and strengthen the economic stability of rural communities. With 70% of the world's poorest population depending directly on agriculture—comprising smallholder farmers and landless labourers—enhancing their incomes plays a vital role in poverty reduction. Significantly, biotechnological crops such as cotton in India, China, and South Africa, as well as maize in the Philippines and South Africa, have positively impacted the livelihoods of more than 12 million smallholder farmers [17].

A large number of people also suffer from micronutrient deficiencies such as iron, zinc, and vitamin A which continue to pose serious public health concerns, exacerbated by food insecurity and undernutrition. The land area suitable for crop cultivation is steadily shrinking as a result of urban expansion and land degradation, with this trend anticipated to be significantly more pronounced in developing nations than in developed ones. Nations such as Egypt, Kenya, and China had already fallen below the threshold of 0.25 hectares of cropland per capita by 1990, and many others, including Pakistan and Indonesia, are projected to follow suit by 2025. This shrinking land base for crop production and increase in human population will have major implications for food security over the next 2-3 decades. Although a significant rise in grain production was observed between 1950 and 1980, the growth rate has slowed considerably since, highlighting the need for sustainable innovations such as biotechnology to secure future food supplies [18].

2.3. Ethical Implications of Biotechnology

Transgenic animal research is regulated by existing regulations governing the ethical use of animals in scientific studies. Compliance with the Animal Welfare Act enacted in 1966 is a prerequisite for institutions applying for or receiving federal funding, requiring the establishment of an Institutional Animal Care and Use Committee (IACUC) to ensure ethical oversight of animal

research activities. The committee holds the responsibility of assessing research protocols that involve a diverse array of animal species, including pets, rodents, primates, farm animals utilized in non-agricultural scientific and educational activities [19]. The Animal Welfare Act further stipulates that scientific organizations must establish a veterinary care program, ensure that individuals responsible for the use and care of live animals are properly qualified, and implement a system for reporting concerns related to animal care and use within the institution. The Animal Welfare Act was implemented by the United States Department of Agriculture (USDA) and imposed via random inspections conducted without prior notice conducted by USDA Veterinary Medical Officers. Internationally, the Association for Assessment and Accreditation of Laboratory Animal Care (AAALAC) manages the voluntary accreditation and evaluation of research institutions dedicated to ethical and responsible animal care and use [14].

2.3.1. Genetic Engineering of Animals

Several techniques have been used to produce transgenic livestock, each with varying efficiency. Over the last twenty years, the process of injecting exogenous DNA into freshly fertilized embryos has remained the predominant method employed. However, this method remains relatively inefficient, with only 3–5% of the resulting animals successfully incorporating the transgene. Moreover, this method causes the integration of foreign DNA at random locations, leading to inconsistent expression levels of the introduced gene in the transgenic offspring. Unregulated expression of this gene results in adverse effects on animal welfare. For instance, the appearance of developmental defects in animals engineered to express growth hormone genes, where variable gene expression has led to unintended physiological effects (NRC, 2002). Methods such as intracytoplasmic sperm injection (ICSI) have been explored to improve DNA delivery, although success rates remain modest [20].

2.3.2. Moral Dimensions of Animal Genetic Engineering

Surveys of public opinion have shown that people experience ethical discomfort with the idea of genetically modified animals. Genetic modification of animals commonly gives rise to two primary ethical concerns. The first is related to breaching species barriers or playing God, thus reducing life to a manipulable commodity for monetary profit. Subsequently, the disruption of an animal's integrity or *telos*, defined as the genetically and environmentally shaped set of needs and behaviors that constitute its natural way of life. It has been argued that such concerns are not unique to genetic engineering and that traditional breeding and selection practices can change animals in similar ways [21]. In USA, there is no clear framework to address the ethical issues associated with genetically modified species. Survey conducted in 2005 revealed that 63% of Americans support the inclusion of ethical considerations in governmental decisions about cloning or genetically modifying animals, the FDA maintains a risk-based approach that prioritizes scientific evaluation over moral or philosophical concerns [22].

2.4. Biotechnology in Plant Production

2.4.1. Potential of Biotechnology in Crop Improvement

Crop yield growth is notably slower in many developing regions, with Africa experiencing some of the lowest gains. It is estimated that cereal yields in Africa have increased by nearly half of those in Latin America since 1970. Traditional breeding techniques for crops, livestock, and fish primarily aim to boost productivity, improve tolerance to pathogens and pests, and enhance quality in terms of nutrition and food processing. Significant progress in cellular genetics and biology during 1960 played a key role in the Green Revolution, which introduced high-yielding and disease-resistant varieties of staple food crops. This transformation has significantly impacted food production in both developed and developing nations [23].

Genomics revolution

Whole genome sequencing projects are underway for several critical plant species, including *Zea mays*, *Sorghum bicolor*, *Medicago sativa* and *Musa* spp. Systematic whole-genome sequencing will offer essential insights into gene and genome organization and function, potentially transforming our understanding of crop production and enabling the manipulation of traits that enhance crop productivity [23,24]. Likewise, advancements in microarray technology will enable the simultaneous expression and analysis of numerous genes, shedding light on gene functions and intricate interactions between genes that lead to diverse phenotypes across different environmental conditions. These studies will be augmented by more specific investigations based on gene suppression, co-suppression, or anti-sensing of a defined sequence, alongside DNA marker-assisted selection. Furthermore, recombinant DNA technology not only helps determine gene sequences and functions but also enables the identification of specific chromosomal regions associated with economically valuable traits [24].

Resistance to insects, diseases, and herbicides

Most insect-resistant transgenic plants have been developed using *Bacillus thuringiensis* (Bt) δ -endotoxin genes; however, ongoing research is exploring the use of non-Bt genes that disrupt insect nutrition. These include genes encoding protease inhibitors, chitinases, secondary plant metabolites, and lectins. Insect resistance genes have been incorporated into a variety of crop plants, such as maize, cotton, potato, tobacco, rice, broccoli, lettuce, walnuts, apples, alfalfa, and soybean. Bt Cry toxins have shown effectiveness against major pests, such as cotton bollworm, corn earworm, European corn borer, and rice stem borers. Successful expression of Bt genes has also been achieved in other crops, such as tomato, brinjal, groundnut, chickpea, and potato, particularly for managing lepidopteran pests [25]. The introduction of insect-resistant crops led to a reduction of 1 million kilogram in pesticide use for pest control in the United States in 1999 compared to 1998. Transgenic papaya resistant to the ringspot virus has been successfully cultivated in Hawaii since 1996. Rice Yellow Mottle Virus (RYMV), a challenging pathogen to manage using traditional methods, can now be effectively controlled through transgenic rice. This strategy greatly minimizes

the likelihood of total crop failure. Globally, herbicide-resistant soybean, insect-resistant maize, and genetically improved cotton account for 85% of the total area of transgenic crops [26].

Tolerance to abiotic stresses

Development of crops with inherent resistance to abiotic stresses would help stabilize crop production and significantly contribute to food security in developing countries. In transgenic plants, the expression of the bacterial enzymes trehalose phosphate synthase and trehalose phosphate phosphatase, which are responsible for trehalose production, has led to increased leaf size, modified stem growth, and improved stress tolerance. Similarly, the overexpression of glutamate dehydrogenases (GDH), especially the α - and β -subunits from *Chlorella sorokiniana*, has been shown to boost plant growth under stress conditions [27]. Rice plants engineered with the barley late embryogenesis abundant (LEA) gene also displayed enhanced resilience, further highlighting the potential of genetic interventions. Other promising strategies include engineering plants to increase citric acid production in the roots, thereby providing tolerance to aluminium toxicity in acidic soils. The incorporation of a gene encoding plant farnesyltransferase boosts salinity tolerance by activating functional calcineurin activity. When expressed in plants, inhibitors of this enzyme improve drought resistance, delay senescence, and alter plant growth patterns. A salt tolerance gene isolated from the mangrove species *Avicennia marina* has been successfully cloned and shows promise for application to crop plants. Additionally, the gutD gene from *Escherichia coli* has been utilized to further enhance salt tolerance in plants [26].

2.4.2. GM Crops Currently in Commercial Production

Between 1996 and 2004, herbicide tolerance emerged as the most commonly introduced trait in commercial genetically modified (GM) crops, followed by insect resistance. In 2004, herbicide-tolerant genetically modified soybean, and cotton accounted for 72%, or 58.5 million hectares, of the total global acreage of such crops. Insect-resistant bt crops accounted for 15.7 million hectares (20%), and stacked' genes (GM cotton or Maize crops with both herbicide tolerance and insect resistance) accounted for 8% or 6.8 million Hectares of the global transgenic area. Foods produced through modern biotechnology can be categorised as follows: foods consisting of or containing living/viable organisms (for example, Maize), ingredients derived from GM crops (for example, Flour, food protein products, or oil from gm soybeans); single ingredients or additives produced by GM microorganisms (gmms), (for example Colours, vitamins and essential amino acids); ingredients processed by enzymes produced through gmms, (e.g. High-fructose Corn syrup produced from starch), using the enzyme glucose isomerase (product of a gmm) [28].

2.4.3. Future Trends in GM Crops

Quality traits:

Quality *traits* refer to the output characteristics of crop products, such as their appearance and chemical composition. It also encompasses the enhancement of macro- and micronutrient concentrations, which are

essential for healthy human diets. Incorporating such traits into staple food crops can be particularly beneficial for low-income populations, who often lack the financial means to access more nutritious, higher-value foods. For instance, researchers have been able to develop transgenic rice varieties with significantly enhanced vitamin A content, which are now being integrated into rice breeding programs. Promising advances in biotechnological research to improve micronutrient density in plants have also been reported for a number of other important vitamins and minerals [29].

Agronomic trait

The initial commercialization of transgenic crops with agricultural attributes is typically known as first-generation transgenic plants. Research and innovation in this area continue, with efforts focused not only on improving agronomic characteristics but also on producing GM crops with enhanced nutritional quality [29]. Agronomic traits, often described as *input traits*, include genetic modifications that help stabilise or boost crop yields under field conditions. Prominent input traits include mechanisms of pest and disease resistance, which are often encoded by a single gene (monogenic traits) [30]. Various transgenic crops that are resistant to pests and diseases have been commercialised. This is particularly significant considering that biotic stress factors, such as pests, pathogens, and viruses, are responsible for global crop losses estimated at 25–30%. The enhancement of virus resistance may play a crucial role in boosting farm productivity. Biotechnological interventions offer the ability to substantially mitigate such losses, often reducing the need for chemical pesticides [28]. Other valuable agronomic crop traits include enhanced genetic yield potentials and tolerance mechanisms to abiotic stresses, such as drought, coldness, and nutrient deficiencies in soils. These traits are typically governed by multiple genes, making them polygenic in nature. Recent advances in molecular mapping and functional genomics have demonstrated that the development of such traits is becoming increasingly feasible in the near-to medium-term future [13].

2.4.4. Altered Nutrition and Composition

A variety of quality traits can be targeted to enhance the nutritional value of crop produce, including carbohydrates, proteins, oils, vitamins, iron, and amino acids. The selection of specific traits is typically influenced by the needs of end users, agricultural producers, and agro-based industries. Current research in this domain represents a shift in focus from simple agronomic traits, such as herbicide and insect resistance, to more complex traits that offer direct nutritional benefits to consumers, such as improved seed composition. For example, transgenic rice capable of producing beta-carotene can be used to overcome vitamin A deficiency [30].

Transgenic rice

Rice, a major staple food, is generally low in essential vitamins and minerals such as iron. Through genetic modification, rice varieties with elevated levels of vitamin A (in the form of beta-carotene), iron [31], and improved protein content have been developed. Similar nutritional enhancements have also been applied to other staple crops, such as cassava, plantain, and potato. Enhanced rice is a

genetically modified crop with improved dietary benefits, particularly due to its high beta-carotene content, a precursor to vitamin A, commonly referred to as Golden Rice. Vitamin A plays a critical role in enhancing immune function, preventing visual impairment and blindness, and supporting healthy growth and development. By addressing vitamin A deficiency, such bio-fortified crops could significantly reduce childhood mortality rates and ease the burden on healthcare systems in low-income countries [32]. Several strategies to combat deficiency of vitamin A, including dietary strategies such as food fortification, and supplementation using capsules. In this context, the development and deployment of vitamin A-enriched rice have been widely discussed, including during expert consultations and forums organised by institutions such as the Food and Agriculture Organization (FAO) of the United Nations [32,33].

Reducing allergens and antinutritional components

Cassava roots are rich in cyanogenic compounds that release cyanide. Because cassava is a staple food in many parts of tropical Africa, its regular consumption has led to elevated blood cyanide levels in the affected populations, posing serious health risks. Using advanced biotechnology to lower the levels of this toxin in cassava would minimise preparation time. The introduction of a yeast-derived *invertase* gene in potatoes has been shown to lower the levels of naturally occurring glycoalkaloid toxins, thereby improving food safety. The allergen causing protein content in rice can be minimised by altering its metabolism. However, the impact of these lower levels on human allergenicity has not yet been established. Research has also been carried out to decrease the allergenic potential of wheat [34].

Sugar and starch metabolism

Sucrose phosphate synthase (SPS) plays a key role in regulating sucrose metabolism in plants. Transgenic plants expressing maize SPS under the control of a promoter from the small subunit of tobacco Rubisco demonstrated higher sucrose-to-starch ratios in their leaves, along with reduced levels of foliar carbohydrates when grown under CO₂ enrichment conditions. Additionally, altering the activity of metabolites within the tricarboxylic acid (TCA) cycle, such as by reducing the levels of NAD-malic enzyme, has been shown to enhance starch accumulation. Other metabolic engineering strategies include the introduction of *Escherichia coli* inorganic pyrophosphatase to influence sugar levels and modification of hexokinases, which play a role in sugar sensing. Changes in sucrose-binding proteins and a class of "cupin" proteins, which are involved in sugar unloading during seed development in legumes, have also been investigated. This has opened up exciting possibilities for changing the chemical composition of food grains to meet specific requirements [35].

Altering composition of fatty acids

Advances in genetic engineering have made it possible to modify the fatty acid composition of crops to improve their nutritional and processing quality. For instance, polyunsaturated fatty acids, such as linoleic acid, can be reduced by increasing the content of monounsaturated fatty acids, such as oleic acid. This adjustment enables oil processing without the need for hydrogenation, thereby eliminating the formation of harmful trans-fatty acids. Genetic modifications have also been applied to

manipulate the starch composition of crops, particularly by altering the amylose-to-amylopectin ratio. Reducing certain oligosaccharides, such as raffinose and stachyose, enhances digestibility and minimizes gastrointestinal discomfort, including flatulence. Efforts to modify the starch and lipid profiles are crucial for the development of healthier foods. For example, increasing the starch content of potatoes reduces oil absorption during frying, resulting in lower-fat products. Soybean and canola fatty acid profiles have been engineered to produce oils with reduced saturated fat levels. Current research and development are focused on genetically modified (GM) soybeans, rapeseed oil plant and palm. A pair of genetically modified crops with altered lipid profiles have been approved in the United States for cultivation and use in food and feed: high-oleic acid soybean and high-lauric acid oilseed rape [36].

Increased antioxidant content

Transgenic technology can also be employed to reduce or eliminate antinutritional factors in food crops. It has been used to enhance the levels of beneficial phytonutrients, for example, increasing the lycopene and lutein content in tomatoes and boosting isoflavone concentrations in soybeans [1].

2.5. Animal Biotechnologies and Agricultural Sustainability

2.5.1. Genetically Engineered or "Transgenic" Animal

A genetically engineered, or "transgenic", animal contains a specific recombinant DNA sequence in the cell and passes on that DNA to its progeny. Recombinant DNA comprises of DNA segments that have been artificially combined in laboratory settings. These constructs are typically designed to express specific proteins encoded by inserted genes once integrated into the animal genome. Because all living organisms share the same four nucleotide bases in their genetic code, genes synthesize the corresponding protein regardless of whether it is expressed in zoological, botanical or microorganism. This universal nature of the genetic code allows for the functional expression of foreign genes across species. Some examples of proteins that have been expressed in transgenic animals include therapeutic proteins for the treatment of human diseases, proteins that enable animals to better resist disease, and proteins that result in the production of healthier animal products (milk, eggs, or meat) for consumers [37,47].

Genetic engineering is a powerful tool that enables animals to produce novel and valuable proteins, thereby expanding possibilities beyond the limitations of conventional breeding. Traditional animal breeding relies on naturally occurring genetic variations within a species, which restrict the potential for significant genetic improvement. Genetically engineered animals are being developed for two primary purposes: human medicine and agriculture. Most commercial transgenic animal research focuses on human medicine. Many therapeutic proteins used to treat human diseases require specific modifications that are typically found in animal cells. Currently, these proteins are predominantly synthesized in bioreactors using mammalian cells. The production

capacity for bio-therapeutic proteins struggles to be at par with the progress in drug development, thus increasing manufacturing costs. Transgenic animals offer a cost-effective alternative for producing therapeutic proteins, particularly through the expression of recombinant proteins in mammalian fluids, plasma or eggs. This approach allows for high-yield, biologically active protein production using animal systems. One prominent example of this technology is ATryn® (Antithrombin III), the first human therapeutic protein sourced from bioengineered goats. As per the approval of the European Commission in 2006, ATryn® is used to treat individuals with hereditary antithrombin deficiency [38].

While transgenic livestock have been developed for agricultural purposes, with improved production, environmental benefits and disease resistance. In contrast, significantly greater economic support to drive the development of bio-engineered animals for biomedical uses. The commercialisation of agricultural biotechnology is hindered by several key factors. These include the high costs and lengthy timelines associated with regulatory approval processes, as well as challenges related to consumer acceptance. Potential investors remain cautious, largely due to the historically lower levels of public support for genetic engineering in agriculture compared to its acceptance in medical contexts, such as the production of recombinant insulin. Concerns are particularly heightened regarding the genetic modification of animals for food production, where ethical and safety concerns are more prominent [21].

The regulation of genetically engineered food animals in the United States is primarily overseen by the Food and Drug Administration (FDA). It regulates transgenic animals as "new animal drug" provisions of the Food, Drug, and Cosmetic Act (FDCA). Under this framework, primary regulatory emphasis is to ensure that the introduced genetic material (considered the "drug") is safe for the animal, effective in achieving its intended function, and that any resulting food products from the treated animals are safe for human consumption (FAO/WHO, 2003). Although regulatory review of genetically engineering in animals is required, the FDA has not yet provided official guidelines detailing the specific information necessary for this review process. As a result, commercialisation of such animals stays ambiguous and underdeveloped [39].

2.5.2. Fish

Increased fish yield: Scientists have altered the gene responsible for growth hormones in tilapia, a commonly farmed fish that has the potential for higher yields and improved availability of fish protein in local diets. No genetically modified food animals are accepted for sale in USA. However, fish with improved growth rates represent the most advanced application nearing commercial release for human consumption, with multiple species undergoing regulatory evaluation in at least three countries. Genetically engineered Atlantic salmon is designed to grow at a significantly faster rate than conventional salmon, although it does not exceed its final size when raised under identical conditions [40]. The projected increase in global fish demand suggests that genetically modified (GM) fish may play a significant role in both

developed and developing countries. Atlantic salmon engineered for accelerated growth—through the insertion of a growth hormone gene from Chinook salmon is considered the first genetically modified animal to enter the food market. These transgenic salmon reports five times faster growth with reduced production time along with increased food availability. Genetic engineering has been applied to enhance growth rates in at least eight additional farmed fish species. Experimental introduction of growth hormone genes has also been made in fish species such as *Grass carp*, *Rainbow trout*, *Tilapia*, and *Catfish* [32].

To overcome practical challenges in aquaculture, research has increasingly concentrated on enhancing disease resistance in farmed fish. For example, Atlantic salmon have been genetically modified to express lysozyme cDNA from rainbow trout. Lysozyme has antimicrobial properties that can combat pathogens affecting fish, including *Vibrio*, *Aeromonas* and *Yersinia*. Additionally, silkworm cecropin, is being studied for use in catfish. Warm-water species like common carp and tilapia are vulnerable to cold temperatures, leading to substantial losses during winter due to their lack of ability to withstand cold. Thus, it is proposed to modify the lipid molecular composition to enhance membrane dynamics. Another approach involves transferring antifreeze genes from cold-adapted fish species to those that are more vulnerable to cold temperatures. Although freeze-resistant strains of Atlantic salmon have been developed, the levels of antifreeze proteins they produce are insufficient to significantly lower the freezing point of their blood [41].

2.5.3. Livestock and Poultry

Increased nutrient absorption by livestock: Researchers are developing animal feed formulations aimed at improving the absorption of phosphorus by livestock. This modification reduces the amount of phosphorus excreted in animal waste, helping mitigate groundwater pollution. Although genetically modified (GM) livestock and poultry products are not yet commercially available, several promising applications are under investigation. Introduction of growth-enhancing genes in porcine species, for more leaner and tender meat. Although this research began more than a decade ago, the commercialisation of these pigs has not occurred because of some morphological and physiological changes that arose in the animals. In addition, numerous modifications to milk production have been proposed. These range from adding new proteins to milk to manipulating existing endogenous proteins to enhance nutritional or functional qualities [42].

2.6. Microorganisms for Food Applications

Lack of commercially available produces that contain live genetically modified microorganisms (GMMs). Other microorganisms being researched for food applications include starter cultures and lactic acid bacteria for fermented products such as bakery goods and cheese production. Research and development efforts have also focused on reducing infections caused by pathogenic microorganisms and enhancing the nutritional value and flavour of foods. Efforts have also been directed toward genetically modifying ruminant microorganisms to

enhance livestock protection against toxic or harmful components present in their feed. Biotechnology is also being applied to develop probiotics, live microorganisms that, when consumed in adequate amounts as part of food, provide health benefits to the host [10].

2.7. Role GM Microorganisms

Genetically modified microorganisms (GMMs) can be utilised as food ingredients, processing aids, dietary supplements, and veterinary chemicals to improve the nutritional quality of food, preserve it, and enhance the productivity of animals [9,43]. In these applications, GMMs are typically inactivated in the final product. GMMs have been commercially used for over a decade for various purposes, including the production of alpha-amylase in bread-making to improve dough quality, glucose isomerase for converting glucose to fructose in sweetener production, and chymosin in cheese-making to facilitate milk coagulation. Most microorganisms used in food processing are derived from those traditionally used in food biotechnology. Genetically modified microorganisms (GMMs) are also authorised in several countries for the production of micronutrients such as vitamins and amino acids, which are used in food and dietary supplements. One example is the use of GM bacteria for the production of carotenoids, which are utilised as food additives, colourants, or dietary supplements [9,43]. *Bacillus subtilis*, a generally recognised as safe (GRAS) organism, was genetically modified with carotenoid biosynthesis genes from *Staphylococcus aureus*, enabling it to produce C30 carotenoids such as 4,4'-diapolycopene, 4,4'-diaponeurosporene, and glycosylated carotenoid acids [44]. Genetically engineered products such as bovine somatotropin, which increases milk production, have been produced and made commercially available in various countries for over a decade. Protein engineering involves the modification of enzymatic amino acid sequences. However, this technique is not widely applied for production of enzymes. Research and development to change enzymatic characterization such as temperature or pH stability is of priority. While protein engineering has not been widely used in enzyme production thus far, research and development in this area aims to enhance enzymatic processing, which can often replace traditional chemical reactions. This shift frequently leads to reduced energy consumption and chemical waste [45,46].

3. Conclusion and Recommendations

Biotechnology plays a key role in human and animal medicine besides food processing. Over the past five decades, breakthroughs in genetics have facilitated the creation and commercialisation of GMOs with traits surpassing traditional species boundaries. These traits have the potential to significantly enhance food production. GM soybeans dominate the planting of GM crops, followed by GM maize and GM cotton. GM crops are believed to be cultivated on approximately 4% of the arable land area globally. Agronomic traits represent the most commonly incorporated characteristics in GM crops.

Agronomic traits are expected to remain the primary focus in the development of new GM crop varieties. However, there is a growing trend toward incorporating modifications that enhance quality and nutritional characteristics, albeit in a smaller proportion. In animal biotechnology, fast-growing GM salmon and genetically modified livestock with enhanced protein production are among the most advanced projects nearing commercialisation. In contrast, most other transgenic animals intended for food use remain in the early research and development stages. Enzymes produced using GM microorganisms have been widely used as food-processing aids in a range of processed foods for more than a decade. However, till date, live genetically modified food microorganisms have not been commercially introduced.

Based on the above conclusion and available literature, the recommendations are as follows:

- ✓ Protect the most food-insecure segments of the population by implementing targeted interventions to ensure access to adequate and nutritious food.
- ✓ Create a modern, efficient, and diversified agricultural sector aligned with the associated water and energy infrastructure.
- ✓ Optimize the production and supply mix to align with current and projected needs, leveraging distinctive strengths while also promoting nutritional education for high-risk groups
- ✓ The entire food security supply chain should be structured to ensure consistent, affordable access to sufficient, nutritious, and safe food that supports a healthy lifestyle.
- ✓ Utilize the resource base efficiently and sustainably, establishing outcome-based benchmarks that align with both regional and global standards.
- ✓ Measures to ensure food security include improving access to food by poor households.
- ✓ Targeted productivity enhancement programs will be implemented for farmers and livestock owners operating below subsistence levels, with a focus on increasing the production of essential food items, particularly in remote areas.

ACKNOWLEDGEMENTS

We are thankful to Prof. Dr. R. K. Narayan for going through the manuscript and give his suggestions. This manuscript is dedicated to all scientists who pioneered contributions in the field of biotechnology.

Contribution of Authors

All authors contributed during the preparation and submission of the manuscript.

Conflict of Authors

The authors declare that there are no conflicts of interest.

Source of Funding

No financial support was received from any organization.

References

- [1] WHO (World Health Organization). Global prevalence of vitamin A deficiency in populations at risk 1995–2005. *WHO Global Database on Vitamin A Deficiency*, 2009. [Available at: <http://whqlibdoc.who.int/publications/2009/9789241598019eng.pdf>].
- [2] Persley L., Lai L.X., Kang J.X., Li R.F., Wang J.D., Witt W.T., Yong H.Y., Hao Y.H., Wax D.M., Murphy C.N., Rieke A., Samuel M., Linville M.L., Korte S.W., Evans R.W., Starzl T.E., Prather R.S., Dai Y.F., Generation of cloned transgenic pigs rich in omega-3 fatty acids. *Nature Biotechnology*, 24: 435–436, 2000.
- [3] Clive J., Gupta K., Safe use of biotechnology. In: Persley G.J. (Ed.), *Biotechnology for Developing Country Agriculture: Problems and Opportunities: 2020 Vision*, Focus 2, Brief 6 of 10, 2010.
- [4] Cohen J.I., Managing agricultural biotechnology: Addressing research program needs and policy implications, Wallingford, UK, 2009.
- [5] Conway G., Ruttan V., The doubly green revolution: Food for all in the 21st Century. *Penguin Books*, London, 1999.
- [6] Dyson T., World food trends and prospects to 2025. *Proceedings of the National Academy of Sciences*, 96: 5929–5936, 2009.
- [7] Pal A., Chakravarty A.K., Disease resistance for different livestock species. *Genetics and Breeding for Disease Resistance of Livestock*, 2020: 271–296, 2020.
- [8] Beyers L., Ismaël Y., Piesse J., Thirtle C., Can GM-technologies help the poor? The efficiency of Bt cotton adopters in the Makhathini Flats of KwaZulu-Natal. *ISNAR Consultation on Biotechnology and Rural Livelihood*, The Hague, 2001.
- [9] CEC (Commission of the Communities), Economic impacts of genetically modified crops on the agrifood sector: A first review. *Working Document Rev. 2, Directorate General for Agriculture*, 2002.
- [10] FAO/WHO (Food and Agriculture Organization/World Health Organization). Evaluation of data on ractopamine residues in pig tissues. *Joint FAO/WHO Expert Committee on Food Additives (JECFA)*. Meeting Report, 2001. [Available at: www.fao.org/docrep/012/i1618e/i1618e00.pdf].
- [11] Adato M., Meinzen R., Dick R., Assessing the impact of agricultural research on poverty using the Sustainable Livelihoods Framework. *International Food Policy Research Institute Discussion Paper*, 89 or 128, 2009.
- [12] Clark E.A., Factoring in the Environment for Decisions on Biotechnology in Agricultural Production. *NAEC Workshop Presentation*, Ottawa, Canada, 2008.
- [13] Thompson E., Echelard Y., Ziomek C.A., Meade H.M., Production of recombinant therapeutic proteins in the milk of transgenic animals. *Biopharm International*, 19: 36–40, 2003.
- [14] USDA (U.S. Department of Agriculture), APHIS (Animal and Plant Health Inspection Service), Petition for determination of non-regulated status: Arctic™ Apple (Malus × domestica), Events GD743, and GS784. *USDA-APHIS Report*, 2012. [Available at: <http://www.aphis.usda.gov/brs/aphisdocs/1016101p.pdf>].
- [15] NRC (National Research Council). Impact of genetically engineered crops on farm sustainability in the United States. *National Academies Press*, Washington, DC, 2010. [Available at: <http://dels.nas.edu/resources/static-assets/materials-based-on-reports/reports-in-brief/genetically-engineered-crops-report-brief-final.pdf>].
- [16] FDA (Food and Drug Administration), Questions and Answers on Food from Genetically Engineered Plants. *FDA Food Biotechnology*, 2013. [Available at: <http://www.fda.gov/Food/FoodScienceResearch/Biotechnology/ucm346030.htm>].
- [17] UNF., FAO/WHO., Modern Biotechnology and Human Health and Development: an evidence - based study. *UN/WHO Report*, 2012.
- [18] Lillico S.G., Sherman A., McGrew M.J., Robertson C.D., Smith J., Haslam C., Barnard P., Radcliffe P.A., Mitrophanous K.A., Elliot E.A., Sang H.M., Oviduct-specific expression of two therapeutic proteins in transgenic hens. *Proceedings of the National Academy of Sciences of the United States of America*, 104: 1771–1776, 2007.
- [19] NRC (National Research Council), Animal biotechnology: Science-based concerns. *National Academies Press*, Washington, D.C, 2002.
- [20] Shakweer W.M.E., Krivoruchko A.Y., Dessouki S.M., Khattab A.A., A review of transgenic animal techniques and their applications. *Journal of Genetic Engineering and Biotechnology*, 21(1): 55, 2023.
- [21] FDA (Food and Drug Administration), Regulation of genetically engineered animals. *FDA Consumer Updates*, 2012. [Available at: <http://www.fda.gov/ForConsumers/ConsumerUpdates/ucm048106.htm>].
- [22] FDA (Food and Drug Administration), Animal cloning. *FDA Safety and Health*, 2008. [Available at: <http://www.fda.gov/AnimalVeterinary/SafetyHealth/AnimalCloning/default.htm>].
- [23] Edgerton M.D., Increasing crop productivity to meet global needs for feed, food, and fuel. *Plant Physiology*, 149 (1): 7–13, 2009.
- [24] Peng J., Richards D.E., Hartley N.M., Murphy G.P., Devos K.M., Flinham J.E., Beales J., Fish L.J., Worland A.J., Pelica F., Sudhakar D., Christou P., Snape J.W., Gale M.D., Harberd N.P., ‘Green revolution’ genes encode mutant gibberellin response modulators. *Nature*, 400: 256–261, 2009.
- [25] Juma C., Gupta A., Safe use of biotechnology. In: Persley G.J. (Ed.), *Biotechnology for Developing Country Agriculture: Problems and Opportunities, 2020 Vision*, Focus 2, Brief 6 of 10, International Food Policy Research Institute, Washington DC, USA, 2010.
- [26] Sharma K.K., Lavanya M., Recent developments in transgenics for abiotic stress in legumes of the semi-arid tropics. In: Ivanaga M. (Ed.), *Genetic Engineering of Crop Plants for Abiotic Stress*, *JIRCAS Working Report*, 23: 61–73, 2002.
- [27] Smart C., Thomas H., Hosken S., Schuch W.W., Drake C.R., Grierson D., Farrell A., John A., Greaves J.I., Regulation of senescence. *Patent Application EP*, 719341, 2006.
- [28] James C., Smart H., Thomas S., Hosken W.W., Schuch C.R., Drake D., Grierson A., Farrell I., John J.A., Greaves J., Regulation of senescence. *Patent Application EP*, 719341, 2004.
- [29] Potrykus D.E., Richards N.M., Hartley G.P., Murphy K.M., Devos J.E., Flinham J., Beales L.J., Fish A.J., Worland F., Pelica D., Sudhakar P., Christou J.W., Snape M.D., Gale N.P., Harberd N.P., ‘Green revolution’ genes encode mutant gibberellin response modulators. *Nature*, 400: 256–261, 1999.
- [30] World Health Organization (WHO) and United Nations Children’s Fund (UNICEF). (2005). Genetically Modified Foods and Their Impact on Global Food Security. WHO/UNICEF Report.
- [31] Schmitdt R.R., Kasinathan P., Hamir A.N., Castilla J., Sathiyaseelan T., Vargas F., Sathiyaseelan J., Wu H., Matsushita H., Koster J., Kato S., Ishida I., Soto C., Robl J.M., Kuroiwa Y., Production of cattle lacking prion protein. *Nature Biotechnology*, 25: 132–138, 2007.
- [32] FAO/WHO (Food and Agriculture Organization/World Health Organization), Evaluation of data on ractopamine residues in pig tissues. *Joint FAO/WHO Expert Committee on Food Additives (JECFA)*, Meeting Report, 2003. [Available at: www.fao.org/docrep/012/i1618e/i1618e00.pdf].
- [33] Potrykus J.T., Cook M.A., McNiven G.F., Richardson A.M., Sutterlin A.M., Growth rate, body composition and feed digestibility/conversion of growth-enhanced transgenic Atlantic salmon (*Salmo salar*). *Aquaculture*, 188: 15–32, 2000.
- [34] Lehrer S.B., Bannon G.A., Risks of allergic reactions to biotech proteins in foods: Perception and reality. *Allergy*, 60(5): 559–564, 2005.
- [35] Newell M.C., Barry M., Nutritionally improved agricultural crops. *Plant Physiology*, 147: 939–953, 2008.
- [36] Crawford A.W., Wang C., Jenkins D.J., Lemke S.L., Estimated effect on fatty acid intake of substituting a low - saturated, high - oleic, low - linolenic soybean oil for liquid oils. *Nutrition Today*, 46 (4): 189–196, 2011.
- [37] TIHGMC (The International Human Genome Mapping Consortium), A physical map of the human genome. *Nature*, 409: 934–941, 2001.
- [38] IFT (Institute of Food Technologists), Antimicrobial Resistance: Implications for the Food System. *Comprehensive Reviews in Food Science and Food Safety*, 5 (3): 71–137, 2006.

- [39] FDA (Food and Drug Administration), Genetically engineered animals. *Development Approval Process*, 2012 b [Available at: <http://www.fda.gov/AnimalVeterinary/DevelopmentApprovalProcess/GeneticEngineering/GeneticallyEngineeredAnimals/default.htm>].
- [40] Du S.J., Gong Z., Fletcher G.L., Shears M.A., King M.J., Idler D.R., Hew C.L., Growth enhancement in transgenic Atlantic salmon by the use of an "all fish" chimeric growth hormone gene construct. *Nature Biotechnology*, 10: 176–181, 2002.
- [41] Das S, Ray MK, Panday D, Mishra PK. Role of biotechnology in creating sustainable agriculture. *PLOS Sustainability and Transformation*, 13; 2 (7): 2021.
- [42] Martínez A, Abanto M, Días NB, Olate P, Pérez Nuñez I, Díaz R, Sepúlveda N, Paz EA, Quiñones J. Recent Trends in Food Quality and Authentication: The Role of Omics Technologies in Dairy and Meat Production. *International Journal of Molecular Sciences*, 6;26(9): 4405, 2025.
- [43] Capper J.L., Castañeda - Gutiérrez E., Cady R.A., Bauman D.E., (rbST) use in dairy production. *Proceedings of the National Academy of Sciences (PNAS)*, 105(28): 9668 - 9673, 2008.
- [44] Maeda I., Genetic modification in *Bacillus subtilis* for production of C30 carotenoids. *Methods in Molecular Biology (Clifton, N.J.)*, 892: 197–205, 2012.
- [45] Imran M, Tausif MA, Waseem M. Effect of Bovine Somatotropin Administration on Mastitis Incidence and Body Condition Score in Dairy Buffaloes. *Insights in Animal Science*, 1(2): 18-24, 2024.
- [46] Vickram AS, Shofia SI, Palanivelu J, Karishma S, Yaashikaa PR. A comprehensive analysis and exploration of the recent developments in the utilization of genetically modified microorganisms for the remediation of hazardous dye pollutants. *Groundwater for Sustainable Development*, 13: 101315, 2024.
- [47] Pal M, Patel AS, Bariya AR, Godishala V, Kandi V. A review of biotechnological applications in food processing of animal origin. *Am J Food Sci Technol*, 5(4): 143–8, 2017.



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