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EXPLORING THE ETHICAL IMPLICATIONS OF APPLYING BIOENGINEERING IN AGRICULTURE AND MEDICINE

UMAR Fatima Adamu*[1]; MUHAMMAD Hajara Ladan[1]; MAHARAZU Khadija Kubau[1]; ALIYU Yahaya[1]; ADAM, Usman Ahmed[2]
[1] Department of Microbiology, Kaduna State University, Kaduna, Nigeria
[2] Department of Library and Information Science, Kaduna State University, Kaduna, Nigeria
umarfatimaadamu@gmail.com* | usadams@kasu.edu.ng | https://orcid.org/0000-0002-1353-4904

Abstract

Bioengineering has revolutionized agriculture and medicine, offering unprecedented opportunities for improvement. This article explores the ethical implications of bioengineering in agriculture and medicine, highlighting the complex moral questions that arise from these advancements. In agriculture, bioengineering enhances crop resilience and productivity, contributing to food security, yet it raises concerns about ecological balance, biodiversity loss, and the socioeconomic impacts on smallholder farmers. In medicine, technologies such as gene editing offer innovative treatment options but prompt critical discussions about consent, equity, and the potential for genetic discrimination. The need for comprehensive ethical frameworks is emphasized, incorporating diverse stakeholder perspectives to ensure responsible innovation. Additionally, the responsibilities of scientists regarding safety and efficacy, as well as the broader societal implications of these technologies, are examined. Addressing these ethical dimensions is essential for fostering informed dialogue and policies developments which balance technological progress with ethical integrity, promoting equitable and sustainable outcomes in both fields.

Keywords: *Bioengineering, ethics, agriculture, medicine, GMOs, gene editing*

Introduction

The rapid advancement of bioengineering in agriculture and medicine has sparked significant debate regarding its ethical implications. As technological innovations enable the modification of organisms at the genetic level, they promise to enhance food security and improve health

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outcomes. In agriculture, genetically modified organisms (GMOs) are engineered to increase crop productivity, enhance nutritional value, and improve resistance to pests and diseases, addressing critical challenges related to a growing population and climate change (Lemaire, 2020). However, these developments raise important ethical concerns, including biodiversity loss, potential health impacts, and the monopolization of seed markets by large corporations (Benson *et al*., 2021).

Similarly, in medicine, bioengineering techniques such as CRISPR and synthetic biology hold transformative potential for treating genetic disorders and personalizing medical care. Yet, they provoke discussions about the morality of creating "designer babies," informed consent, and the risk of exacerbating health inequalities (Smith, 2019; Faizal et al., 2024). This exploration aims to critically examine these ethical dimensions, analyzing how the intersection of technology, society, and the environment shapes our understanding of bioengineering's role in the future. By fostering a critical dialogue on the balance between innovation and potential societal risks, this article seeks to ensure that bioengineering advancements align with ethical considerations

Ethical Implications of Bioengineering in Agriculture

Genetic Modification and Food Security

The integration of bioengineering, particularly genetic modification (GM), into agriculture is increasingly viewed as a key strategy to address global food security challenges. As the world population is projected to reach approximately 9.7 billion by 2050 (United Nations, 2019), enhancing food production sustainably is critical. While GM crops offer significant benefits, they also raise complex ethical concerns that merit thorough examination.

Benefits of Genetic Modification

Genetic modification and modern biotechnology offer significant benefits to agriculture by improving crop productivity, resilience, and nutritional value. Recent advances have enabled the creation of genetically modified (GM) crops that yield more harvest per hectare and grow more efficiently than conventional varieties, addressing food security under increasing population pressure and shrinking arable land (Workineh, 2024). These technologies also bolster pest and disease resistance by incorporating traits that allow crops to withstand insect attacks, pathogens, and weeds reducing reliance on chemical pesticides and lowering environmental contamination risks (Ullah et al., 2024).

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In addition, biotechnology can enhance nutritional content, enabling biofortified crops with improved vitamin, mineral, or macronutrient profiles, which helps mitigate malnutrition and micronutrient deficiency in vulnerable populations (Anupama, 2025).

Importantly, genetic engineering contributes to environmental resilience: through gene editing and stress-tolerance traits, crops can survive and remain productive under drought, salinity, and other abiotic stresses — a critical advantage in the context of climate change and unpredictable weather (Patil et al., 2024; Okeke, 2024). Altogether, these benefits show how GM and biotech crops can play a pivotal role in achieving sustainable agriculture, food security, and improved public health.

Ethical Concerns

Despite these benefits, genetic modification in agriculture raises several ethical concerns:

1. Biodiversity Loss

   The widespread adoption of GM crops can reduce genetic diversity within agricultural systems. Monocultures, resulting from the dominance of a few genetically modified varieties, increase vulnerability to pests and diseases, potentially destabilizing ecosystems (Qaim, 2020).

2. Corporate Control and Economic Inequality

   The biotechnology sector is largely controlled by a handful of multinational corporations, raising ethical concerns about corporate governance over the food supply. This concentration of power can exacerbate economic disparities, with smallholder farmers facing high costs for patented seeds and increased dependency on these corporations (Lemaire, 2020).

3. Health and Safety Concerns

   Regulatory agencies often assert the safety of GM foods for consumption, yet public skepticism persists regarding their long-term health effects. Concerns about allergenicity and unintended consequences of genetic modifications continue to fuel debates, emphasizing the ethical obligation to ensure food safety and address public apprehensions (Benson *et al*., 2021).

4. Ethical Treatment of Animals

   In livestock agriculture, genetic engineering raises ethical questions about animal welfare. Modifications aimed at improving production traits may inadvertently lead to health issues

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in animals, prompting discussions about the moral implications of prioritizing productivity over animal well-being (Carter, 2024).

5. Socio-Economic Impacts

   The introduction of GM crops can produce diverse socio-economic effects that vary by region. While some farmers benefit from increased yields, others may face challenges related to market access and changes in traditional farming practices (Benson *et al*., 2021).

Environmental Impact and Ecosystem Balance

Bioengineering in agriculture, particularly through genetic modification (GM), has revolutionized crop production, promising enhanced productivity and resilience against pests and diseases. However, the ethical implications of these technologies especially their environmental impacts and long-term consequences for ecosystem balance are critical areas of concern.

Environmental Impact of Genetic Modification

1. Biodiversity Loss
2. Altered Ecosystem Interactions
3. Soil Health and Microbial Communities
4. Chemical Dependence and Resistance

Long-Term Consequences

1. Ecosystem Stability

   The long-term ecological impacts of GM crops can threaten ecosystem stability. Reduced biodiversity undermines ecosystems' abilities to adapt to environmental changes, such as climate variability and the introduction of invasive species (Kelvin and Gideon, 2025).

2. Health Risks

   The ecological consequences of GM agriculture can extend to human health. Increased reliance on pesticides and herbicides raises concerns about chemical residues in food and potential health risks associated with long-term exposure (Benson *et al*., 2021).

3. Socio-Economic Implications

   The environmental impacts of GM crops can also lead to socio-economic challenges. Smallholder farmers may face increased costs related to herbicide applications and pest management changes due to GMOs (Verdezoto-Prado et al., 2025).

4. Intergenerational Equity

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The principle of intergenerational equity emphasizes the responsibility to maintain ecological integrity for future generations. The long-term environmental impacts of bioengineering raise critical questions about our duties to future populations.

Consumer Rights and Transparency in Informed Choice

The advancement of bioengineering, particularly through genetic modification (GM), has fundamentally transformed agricultural practices and food production. However, this transformation raises significant ethical concerns regarding consumer rights and the transparency necessary for informed choice. As genetically modified organisms (GMOs) become increasingly prevalent in the global food supply, ensuring that consumers can make informed decisions about what they eat is paramount. Ethical dimensions of consumer rights have been explored in the context of bioengineered foods, focusing on the necessity of transparency and the ethical responsibilities of stakeholders to provide accurate information.

Consumer Rights and Informed Choice

1. The Right to Know
2. Transparency in Food Production
3. Regulatory Frameworks and Labeling Policies

Ethical Challenges in Ensuring Informed Choice

1. Misinformation and Public Perception

   The rapid spread of misinformation, particularly through social media, complicates the landscape of consumer choice regarding GM foods. Misunderstandings and unfounded fears can shape public perception, leading to resistance against biotechnology (carter, 2024).

2. Economic Barriers to Choose

   The economic implications of consumer choices are significant. Non-GM products often come at a premium, potentially limiting access for lower-income consumers. This raises ethical concerns regarding equity in food choices; if healthy, non-GM options are unaffordable for certain segments of the population, their right to informed choice is undermined (Shu Ishida & Tsutomu Sawai, 2024)

3. Corporate Influence and Ethical Marketing

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The role of large agricultural corporations in shaping public perception of GMOs raises ethical questions about corporate influence on consumer rights. Companies may prioritize profit over the ethical obligation to provide clear and unbiased information about their products (Holt *et al*., 2018). The potential for conflicts of interest necessitates scrutiny and vigilance to ensure that consumer rights are not overshadowed by corporate interests.

Ethical Implications of Bioengineering in Medicine

In many places throughout the world, medical bio-engineering still awaits formal recognition as a profession. Its intrinsically multi and interdisciplinary characteristics partly account for that delay. This is aggravated by the lack of precise ethical rules that delineate and delimit the professional responsibility of biomedical engineers (Singh *et al.*, 2022). In recent years, biomedicine has witnessed rapid advancements in applying synthetic biology. While these advancements have brought numerous benefits to patients, they have also given rise to a series of safety concerns.

Gene Therapy and Genetic Editing

Gene therapy and genetic engineering are two close technologies that involve altering the genetic material of organisms. Gene therapy seeks to alter genes to correct genetic defects and thus prevent or cure genetic diseases. Genetic engineering aims to modify the genes to enhance the capabilities of the organism beyond what is normal.

Potential Benefits:

Gene therapy holds promise for treating genetic disorders and diseases. Techniques like CRISPR can potentially eliminate hereditary conditions and improve health outcomes. Below are some of the benefits:

1. Treatment of genetic diseases.
2. Cancer therapies
3. In the future, genetic therapies may be used to prevent, treat, or cure certain inherited disorders, such as cystic fibrosis, alpha-1 antitrypsin deficiency, hemophilia, beta thalassemia, and sickle cell disease.
4. Genetic therapies that are currently approved by the FDA are available for people who have Leber congenital amaurosis, a rare inherited condition that leads to blindness. CAR T-cell therapy is FDA approved for people who have blood cancers, such as acute lymphoblastic leukemia (ALL) and diffuse large B-cell lymphoma.

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Ethical Dilemmas

The burgeoning field of genome editing technologies such as CRISPR-Cas9 has led bioethicists to engage in profound moral inquiries regarding their application in reproductive contexts (National Academies of Sciences Engineering and Medicine 2017). Discussions have focused on genetic modification of embryos to prevent disease or disability and ostensibly improve future quality of life. The potential permissibility or even necessity of such interventions (Faizal et al., 2024) has sparked concerns about the unintended consequences of gene editing compared with the seemingly more ethical alternative of embryo selection (Vazquez M, 2020).

The central ethical dilemma thus shifts from a binary choice whether to use such biotechnologies to a nuanced choice between available biotechnologies. McMahan and Savulescu (2024) shed light on this debate by arguing that decisions regarding technological options should be based on two distinct ethical reasons: person-affecting and impersonal. After showing that neither category alone can fully address the ethical desirability of gene editing or embryo selection, they propose the “two-tier” view comprising both lines of ethical considerations. In this view, person-affecting reason should take precedence over impersonal reasons, thereby reconciling ethical tensions by recognizing that gene editing may benefit embryo-derived individuals, whereas selecting against a disability-causing embryo may be ethically objectionable for impersonal reasons (Shu Ishida & Tsutomu Sawai, 2024).

Following are some other important objections:

- Genetic engineering is against the natural or supernatural order.
- Genetic engineering is dehumanizing because it will create nonhuman, alienated creatures.
- If the changes are not integrated with other DNA already in the nucleus, the changes may not carry over to new cells and the person may have to undergo more therapy later
- Changing reproductive cells may cause events not seen until years later, and undesirable effects may have already been passed on to the patient’s children

Access and Equity

As cited by the Global Biotechnological Ethics perspectives 2024; Biotechnology advancements offer incredible potential to improve global health, but access remains

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unequal. Ethical concerns arise from disparities in resource allocation, exploitation of vulnerable populations, health disparities and global implications etc.

Health Disparities

Health disparities refer to the significant differences in health outcomes and access to healthcare that exist among different population groups, often influenced by factors like socioeconomic status, geography, ethnicity, and education. These disparities highlight the inequities in health and healthcare that can lead to poorer health outcomes for certain groups compared to others, emphasizing the need for tailored treatments and equitable access to healthcare services (Vazquez M, 2020). Furthermore, many programs devote consequential resources to developing cultural competency training to promote the deliverance of culturally sensitive healthcare by faculty, staff, as well as current and future healthcare providers (Rodriguez *et al*., 2023).

Causes of global health disparities

1. Economic factors
2. Political factors
3. Social determinants of health
4. Intellectual property rights and patents

Global Implications

The disparities in health outcomes revealed and exacerbated during the recent pandemic (Sirleaf and Clark, 2021) are the latest manifestation of longstanding global health inequity. Farmer *et al.*, 2016 pointed out that global health equity is often discussed in conversations on development as a policy goal, a field of research, an ethical imperative, a health sciences discipline, and is even the overarching theme of a university.

A global perspective requires a lens through which the outcomes for all are equally valued, regardless of national borders, gender, age, race or ethnicity, tribe, class, ability, sexual orientation, or income or other social and economic stratifies. At core, a global lens requires us to assess need and priorities at a supranational level. Taking such a lens is akin to conceptualizing the earth as a single country, in which all citizens are viewed as interconnected and interdependent, having the same fundamental rights. With this lens in mind, we turn to health. The World Health Organization

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(WHO) defines health as "…a state of complete physical, mental, and social wellbeing and not merely the absence of disease or infirmity."

Informed Consent and Autonomy

The practice of informed consent has historical roots in various disciplines and plays a critical role in medicine as we are entering the era of patient as a consumer and doctor as a service provider (Vazquez M, 2020). Informed consent means an agreement, compliance or permission given voluntarily without any compulsion (Carter, 2024).

Requirements for Valid Informed Consent

The practice of medicine is extraordinarily complex and difficult, with little margin for error. In most situations the doctor cannot act without a patient's "informed consent." In order for patients' consent to be "informed" and thus valid, they must be able to make a well-informed logical decision. If they agree to the treatment, understanding what it involves, they have given informed consent. Informed consent was practically non-existent till the time COPRA [Consumer Protection Act] came into existence. This is seen as more of a legal requirement than the ethical moral obligation on part of the doctor towards his patient (Bansal and Singh, 2017). Informed consent is meant to force the doctor to give the patient the knowledge that will make patient to promote individual autonomy and freedom of choice (Stone A.A., 2019).

Respecting Autonomy

The concept of autonomy has been integral to the debate of what constitutes humankind since the time of Plato and Aristotle (Takala, 2021) with rationality being the thread running through scholars' thinking. The concept of patient autonomy however only gained recognition during the 1950s, together with a greater sense of the need for truth and justice in patient care (Jones D.G., 2020).

Case Studies

Examples of Ethical Issues

Bioengineering applications in agriculture and medicine has raise various ethical concerns, including the intellectual property rights and patenting of life forms (Carter, 2024), environmental and health risks associated with genetically modified organisms (GMOs) (Fernandez-Cornejo *et al.*, 2020*)*, unequal access to benefits and potential exacerbation of social inequalities (Howard, 2019), animal welfare concerns in animal testing and xenotransplantation (Lynch *et al.*, 2017) and informed consent and privacy issues in genetic engineering (Carter, 2024).

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Ethical Dilemmas surrounding Genetically Modified Crops

The following are agriculturally based case studies that illustrate these concerns:

1. Genetic modification of Corn for Drought Resistance

A genetically modified corn variety known as DroughtGard, developed by Monsanto Company in 2012 has sparked debate. DroughtGard is engineered to produce a drought-related protein, reducing water loss and improving yields in water-scarce environment (Monsanto, 2019). Analysis of patent and regulatory frameworks governing Genetically Modified crop development revealed that DroughtGard increased yields by 10-15% in drought conditions (Monsanto, 2019), difficulty in assessing the GM seeds and benefiting from the technology by small scale farmers (Howard, 2019) and it leads to increased use of herbicide and decreased in crop diversity (Fernandez-Cornejo *et al*., 2020). Critics argue that the widespread adoption of DroughtGard could lead to environmental, social, and health impacts, including increased herbicide use (Fernandez-Cornejo *et al*., 2020), gene flow into non-target species (Lucht, 2015), limited access to GM seeds due to patenting issues (Kleinman & Kinchy, 2017), unequal distribution of benefits (Howard, 2019), and potential human health risk such as allergic reactions and altered nutritional content (Lynch *et al*., 2017).

2. Golden Rice: A Bioengineered Solution to Vitamin A Deficiency

Golden Rice a bioengineered crop enriched with beta-carotene, a precursor to vitamin A. Developed by the International Rice Research Institute (IRRI) and funded by the Bill and Melinda Gates Foundation, aim to address vitamin A deficiency in developing countries, raises ethical concerns regarding intellectual property rights (Takala, 2021), environmental impact (Carter, 2024), social justice (Howard, 2019), and human health risks (Lynch *et al*., 2017), but has demonstrated effectiveness in field trials (IRRI, 2020), improved vitamin A intake in children (Tang *et al.,* 2019), and received regulatory approval in the Phillipines and Bangladesh (IRRI, 2020)

3. Bioengineered Pest-Resistant Crops: The Bt Cotton

Bt cotton, engineered with the *Bacillus thuringiensis* (Bt) gene to produce a toxin lethal to certain pests, was developed by Monsanto (now Bayer) to reduce pesticide use and increase yields (Monsanto, 2019). However, its adoption raises ethical concerns, including environmental impacts such as pesticide-resistant pests and unintended effects on non-target species (Fernandez-Cornejo *et al*., 2020), equitable access to seeds and benefits distribution

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(Howard, 2019), potential human health risks like allergic reactions and nutritional changes (Lynch *et al*., 2017), and intellectual property rights issues related to patenting and ownership (Kleinman & Kinchy, 2017). Despite these concerns, field trials demonstrated Bt cotton's effectiveness in reducing pesticide use and increasing yields (Monsanto, 2019), and studies showed decreased pesticide poisoning among farmers (Gideon, 2024). Bt cotton has received regulatory approvals in several countries, including the United States, India, and China (ISAAA, Ultimately, Bt cotton highlights bioengineering's potential to improve agriculture, but its implications require careful consideration and addressing through regulatory frameworks and public engagement.

The following are Medical Bioengineering based case studies that illustrate these concerns:

1. Gene Editing for Sickle Cell Disease: CRISPR Technology

Sickle cell disease (SCD), a genetic disorder affecting hemoglobin production, has been targeted through gene editing, with CRISPR/Cas9 successfully editing the responsible HBB gene in human embryos (Li *et al*., 2017) and correcting the sickle cell mutation in patient-derived stem cells (Verdezoto-Prado et al., 2025). However, ethical considerations for SCD gene editing include risk-benefit analysis (Nieminen *et al*., 2018), alternative therapies like bone marrow transplants and gene therapy (Bekesiene *et al*., 2017), and uncertainty surrounding long-term consequences (Atia et al., 2024).

2. Xenotransplantation: a case study on pig-to-human heart transplantation

Xenotransplantation, the transplantation of organs from one species to another, raises complex ethical concerns, particularly with the use of pig hearts for human transplantation (Lynch *et al*., 2017; Sullivan *et al.*, 2018; Nieminen *et al.*, 2018). Key ethical dilemmas include animal welfare concerns, such as exploitation, suffering, and rights (Lynch *et al*., 2017), the risk of disease transmission from animals to humans (Fishman *et al*., 2018), questions about human dignity and moral implications (Sullivan *et al.*, 2018), and ensuring informed consent for patients (Nieminen *et al.,* 2018).

3. Synthetic Biology

A case study is the rVSV-ZEBOV vaccine, developed by the National Institutes of Health and Merck, has demonstrated efficacy against Ebola virus disease (Henao-Restrepo *et al*., 2017). However, its development and deployment raise ethical considerations, including risk-benefit analysis (Nieminen *et al*., 2018), consideration of alternative options (Kanduc, 2018), ensuring

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equitable distribution and access (Tantivess *et al.*, 2019), and community engagement in vaccine development and deployment (Afolabi *et al.*, 2019). Synthetic biology poses ethical dilemmas, including unintended consequences on human health and ecosystems (Kanduc, 2018), intellectual property concerns (Rai *et al.*, 2019), access and equity disparities (Tantivess *et al.*, 2019), and informed consent in clinical trials (Nieminen *et al.*, 2018).

The Role of Regulation and Oversight

Regulatory frameworks are essential for overseeing the development and application of bioengineering technologies. Agencies such as the U.S. Department of Agriculture (USDA), the Food and Drug Administration (FDA), and the Environmental Protection Agency (EPA) are tasked with evaluating the safety and efficacy of genetically modified organisms (GMOs) and biopharmaceuticals before they reach the market (Sullivan *et al.*, 2021).

1. Establishing Safety Standards
2. Monitoring and Enforcement
3 Engaging Stakeholders

Importance of Ethical Guidelines

1. Promoting Transparency
2. Addressing Social Equity

Stakeholder Engagement

Public engagement in regulatory processes is vital for addressing ethical concerns and for the successful regulation of bioengineering. Involving a diverse range of stakeholders including scientists, ethicists, farmers, and community members ensures that regulatory frameworks reflect societal values and ethical considerations (Takala, 2021).

1. Collaborative Decision-Making
2. Building Trust and Reducing Opposition

Case Studies

1. GMOs in Agriculture

   The regulation of GMOs illustrates the complex relationship between science, ethics, and public perception. In the European Union, stringent regulations have led to considerable public debate and resistance to GMO adoption, highlighting a precautionary approach

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(Graham *et al*., 2020). In contrast, the U.S. regulatory framework is more permissive, focusing on science-based risk assessments.

2. CRISPR and Genetic Editing

   The emergence of CRISPR technology has introduced new ethical dilemmas in both agriculture and medicine. Regulatory agencies are currently grappling with how to classify and oversee CRISPR applications, particularly regarding germline editing (Verdezoto-Prado et al., 2025)

Conclusion

The ethical implications of bioengineering in agriculture and medicine are intricate and multifaceted, encompassing critical issues such as food security, biodiversity, corporate control, consumer rights, and environmental sustainability. To navigate these complexities, it is essential to prioritize transparency, robust regulation, and inclusive dialogue among diverse stakeholders. The significance of ethical guidelines and stakeholder engagement within the framework of regulation and oversight cannot be overstated. As this field continues to evolve, these elements are vital for ensuring that innovations are safe, equitable, and socially responsible. By committing to ethical responsibility and promoting transparency, addressing social equity, and engaging various stakeholders, society can effectively harness the benefits of bioengineering while safeguarding public health and protecting ecosystems. Ultimately, a holistic approach is essential for fostering a sustainable and equitable future that respects both human and environmental welfare, guiding bioengineering toward outcomes that are beneficial for all.

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