



Genetically modified feed in swine production: scientific, ethical, and regulatory perspectives

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Abstract. Genetically modified (GM) crops have become a major component of modern swine nutrition, particularly through the use of maize and soybean meal in compound feeds. Because a large proportion of global GM crop production is directed toward animal feed rather than direct human consumption, pigs represent one of the principal indirect consumers of GM plants. This paper reviews the scientific, ethical, and regulatory dimensions of using GM feed in swine production. Current veterinary and nutritional evidence indicates that approved GM feed ingredients are nutritionally equivalent to their conventional counterparts and do not negatively affect pig growth performance, health status, immune function, or carcass quality. Likewise, extensive research has found no evidence that meat from pigs fed GM feed poses risks to human health, as transgenic DNA and proteins are degraded during digestion and do not accumulate in edible tissues. Despite this scientific consensus, debates persist regarding environmental sustainability, the development of herbicide resistant weeds and pest resistance, and the broader implications of GM agriculture for biodiversity and farming systems. Ethical discussions also address concerns related to naturalness, technological intervention in agriculture, animal integrity, and the potential reinforcement of intensive livestock production systems. Regulatory approaches differ significantly worldwide, ranging from strict process based systems such as those in the European Union to more product oriented frameworks in countries like the United States and Canada. These regulatory differences influence feed supply chains, labeling practices, and producer decision making. Overall, while scientific evidence largely supports the safety and nutritional adequacy of GM feed in swine production, the societal debate remains complex, integrating scientific findings with environmental, ethical, economic, and cultural considerations.

Key Words: agricultural biotechnology, animal nutrition, environmental sustainability, ethics of animal agriculture, food safety, genetically modified feed, swine production, GMO regulation, GMO safety, pig health.

Introduction. Genetically modified (GM) crops are now a routine component of intensive pig production systems worldwide, primarily as maize and soybean meal in compound feeds. Between 70 and 90% of global GM crop biomass is used as animal feed rather than direct human food, so pigs are among the main indirect consumers of GM plants (Giraldo et al 2019; Siddiqui et al 2024). In Europe, for example, high-protein soybean meal used in pig and poultry farming is largely derived from GM soybeans imported from South America, even though GM cultivation within the EU is highly restricted (Kleter et al 2018; Sieradzki et al 2025). This embeddedness of GM feed in swine production makes it a focal point for scientific, regulatory, ethical, and socio-cultural debate.

Purpose of the paper. The purpose of this paper is to provide an interdisciplinary analysis of the role of GM feed in swine production by integrating scientific evidence with ethical and regulatory perspectives. Specifically, the study aims to evaluate current knowledge regarding the effects of GM feed on pig health, growth performance, and product safety

for human consumers, while also examining the environmental implications and sustainability debates associated with GM crop cultivation. In addition, the paper seeks to analyze the ethical concerns and socio cultural values that influence public attitudes toward GM feed, as well as the diverse regulatory frameworks governing its use across different regions. Through this integrated approach, the work aims to contribute to a balanced understanding of the benefits, limitations, and broader societal implications of using GM feed in modern pig production systems.

Genetic modified pigs. Genetic modification in pigs has attracted increasing scientific attention in recent decades; however, GM pigs are not currently a priority in practical livestock production systems (Petrescu-Mag et al 2020; Whitworth et al 2022; Petrescu-Mag 2023a). In contemporary animal agriculture, the primary focus remains on improving productivity, health, and efficiency through conventional breeding, optimized nutrition, management practices, and, more recently, genomic selection (Botha et al 2020; Ungur & Tăbăran 2020; Proorocu et al 2021; Cîmpean 2024a, b, c). As a result, the application of genetic engineering directly to pigs for commercial farming purposes is still limited and remains largely experimental (Lei et al 2022; Xi et al 2023; Peterson et al 2024). The technological, regulatory, ethical, and economic complexities associated with producing GM livestock mean that such animals are not yet integrated into mainstream swine production systems. Instead, most current research involving GM pigs is concentrated in the biomedical field, where pigs are considered highly valuable experimental models due to their physiological, anatomical, and metabolic similarities to humans (Lin 2024; Tao et al 2025).

Within biomedical research, GM pigs are primarily developed to study human diseases, improve the understanding of genetic disorders, and explore innovative therapeutic approaches (Petrescu-Mag & Safirescu 2021; Petrescu-Mag 2023b; Lin 2024; Tao et al 2025). Through techniques such as transgenesis and gene editing technologies like CRISPR-Cas9, scientists have been able to create pig models that mimic specific human pathological conditions, including cardiovascular diseases, metabolic disorders, neurodegenerative diseases, and certain types of cancer. These models are particularly valuable because the size, organ structure, and physiological processes of pigs often resemble those of humans more closely than those of traditional laboratory animals such as rodents. Consequently, GM pigs provide an important bridge between basic laboratory research and clinical applications in human medicine (Petrescu-Mag & Safirescu 2021).

Another major area of biomedical interest is xenotransplantation, the transplantation of organs or tissues from animals into humans (Lin 2024; Tao et al 2025). Pigs are considered one of the most promising donor species because their organ size and function are compatible with human physiology. Genetic modification techniques are used to reduce immunological rejection by removing or altering specific pig genes responsible for triggering strong immune responses in humans. At the same time, additional genes may be introduced to improve compatibility between pig organs and the human immune system. Although significant scientific progress has been made in this area, xenotransplantation involving GM pigs is still largely in the experimental or early clinical stages, and substantial ethical, medical, and regulatory challenges remain (Lin 2024; Tao et al 2025).

In contrast, the direct use of GM pigs for food production has advanced much more slowly. While certain experimental projects have explored traits such as disease resistance, improved feed efficiency, or reduced environmental impact - for example through pigs engineered to produce enzymes that improve phosphorus digestion - these animals have not yet been widely adopted in commercial farming. Public perception, ethical concerns regarding the modification of livestock genomes, strict regulatory approval processes, and uncertainty about consumer acceptance have all contributed to the cautious approach taken by the agricultural sector. In many regions, regulatory frameworks for GM animals are particularly stringent, requiring extensive safety evaluations for animal health, environmental impact, and food safety before commercialization can occur.

For these reasons, GM pigs currently occupy a much more prominent role as research tools than as production animals in agriculture. Their value lies primarily in their

contribution to biomedical science, where they enable researchers to investigate complex biological mechanisms and develop potential medical therapies that could ultimately benefit human health. While advances in gene editing technologies may in the future open new possibilities for improving livestock sustainability, disease resistance, or animal welfare, such applications in swine production remain largely prospective. At present, therefore, GM pigs should be understood mainly as an important platform for biomedical research rather than as a central component of modern pig farming.

Veterinary and animal-health evidence: safety and performance. A large body of animal-feeding trials compares pigs and other livestock fed GM versus near-isogenic non-GM crops. Reviews focusing on livestock consistently report no biologically relevant differences in growth performance, feed intake, feed conversion, carcass traits, or general health when standard GM maize (e.g. Bt or herbicide-tolerant hybrids) or GM soybean meal replace conventional equivalents (Akram et al 2019; Aguilera et al 2024; Siddiqui et al 2024). A 2024 review of GM corn in pig diets concluded that growth, feed efficiency, carcass yield, and routine clinical health parameters do not differ detectably between GM and non-GM corn, and no GM-related clinical symptoms were observed (Aguilera et al 2024).

Targeted veterinary studies on immune function similarly find no adverse immunological effects. In a controlled trial in which pigs, calves and poultry received combinations of Bt maize (MON810) and glyphosate-tolerant soybean (Roundup Ready), selected immune parameters in pigs (both sows and fatteners) did not differ significantly from animals fed purely conventional feed (Bednarek et al 2013). Broader reviews of GM feed in livestock report that reproductive performance, organ histology, and product composition (meat quality, fat profile) are indistinguishable from those of animals fed non-GM rations, when the GM crop is substantially equivalent in composition (Akram et al 2019; Siddiqui et al 2024). These findings align with the general conclusion that currently approved GM feed ingredients are nutritionally and toxicologically comparable to their non-GM counterparts (Giraldo et al 2019; Goodman 2024; Siddiqui et al 2024).

Human health as consumers of pork from GM-fed pigs. Safety assessments focus on three pathways: persistence of transgenic DNA or proteins in edible tissues, unintended compositional changes, and indirect effects (e.g. altered residues from pesticide use). Multiple feeding trials in pigs and other livestock have not demonstrated transfer of intact transgenes or functional transgenic proteins into meat or milk at levels of concern; transgenic proteins are rapidly degraded in the gastrointestinal tract, and any plant DNA fragments detected are small and not functionally different from ubiquitous dietary DNA (Akram et al 2019; Giraldo et al 2019; Goodman 2024; Siddiqui et al 2024). Reviews covering nearly three decades of GM food and feed use report no documented cases where consumption of products from GM-fed animals caused proven harm to human health, despite extensive post-market exposure (Goodman 2024).

Nonetheless, precautionary arguments remain. Critical reviews note conflicting experimental results in some small-scale or short-term toxicity studies and call attention to data suggesting subtle changes in liver or kidney parameters in certain animal models, arguing for more stringent, long-term and multigenerational testing, particularly when new traits (beyond simple herbicide tolerance or Bt) are introduced (Deb et al 2016; Tsatsakis et al 2017). Concerns about allergenicity and unintended metabolic effects persist at the level of public perception, although regulatory dossiers routinely include targeted testing for allergenic potential, toxicity and substantial equivalence of nutrient and anti-nutrient profiles (Gatew & Mengistu 2019; Giraldo et al 2019; Goodman 2024). Overall, the mainstream scientific assessment is that pork from pigs fed current GM feed ingredients is as safe as that from pigs fed conventional feed, but some scientists advocate continued vigilance as more complex traits enter the market (Tsatsakis et al 2017; Akram et al 2019; Gatew & Mengistu 2019; Giraldo et al 2019; Goodman 2024; Siddiqui et al 2024).

Environmental and sustainability dimensions. Proponents emphasize that GM feed crops contribute to feed security and sustainability by increasing yields, stabilizing production under stress, and reducing the need for chemical insecticides and repeated

tillage (Turnbull et al 2021; Goodman 2024; Siddiqui et al 2024). For swine producers, this can translate into more reliable supplies of high-protein soy and energy-dense maize, lower feed costs, and potentially reduced environmental footprint per kilogram of pork, especially where pest-resistant or herbicide-tolerant crops decrease pesticide use and facilitate conservation tillage (Goodman 2024; Siddiqui et al 2024). At a systemic level, the efficiency gains in feed production are argued to support global food security and allow land sparing if higher yields reduce pressure for agricultural expansion (Turnbull et al 2021; Goodman 2024; Siddiqui et al 2024; Dolapo et al 2025).

Critics highlight environmental risks associated with GM crop cultivation, independent of the pig's biology. These include gene flow from GM crops to wild relatives, impacts on non-target organisms, evolution of herbicide-resistant weeds and insect resistance to Bt toxins, and potential reductions in agrobiodiversity (Tsatsakis et al 2017; Gatew & Mengistu 2019; Turnbull et al 2021). There is empirical evidence of herbicide-resistant weed evolution in GM-cropping systems, and debates continue about long-term effects on ecosystems and soil biota (Tsatsakis et al 2017; Gatew & Mengistu 2019). From the perspective of pig feed, these issues are "upstream" but ethically relevant: pork produced from GM-fed pigs may be seen as implicated in broader patterns of monoculture, chemical use, and corporate control of seed markets (Tsatsakis et al 2017; Gatew & Mengistu 2019; Fischer & Hess 2021; Turnbull et al 2021). Some argue that relying on GM feed can entrench intensive, high-throughput livestock systems with significant manure-related pollution and greenhouse gas emissions, rather than incentivizing structural reforms of animal agriculture (Shriver & McConnachie 2018; Devolder 2021).

Regulatory and legislative frameworks. Globally, regulation of GM crops used for feed varies from strict, process-based regimes to more product-based approaches. The European Union regulates GM food and feed under Regulation (EC) No 1829/2003, requiring pre-market safety assessment, traceability, and labeling, and allows Member States to restrict or ban cultivation on their territory, even while GM feed ingredients are widely imported (Kleter et al 2018; Giraldo et al 2019; Turnbull et al 2021). Official monitoring in Poland between 2018-2024, for instance, found that more than half of feed samples contained GM soybean material (primarily specific MON events), while no GM maize was detected; labeling obligations were respected, and contamination of other feedstuffs was low (Sieradzki et al 2025).

In contrast, the United States and Canada regulate novel crops based on their traits and risk profile, not the breeding method; GM and gene-edited crops that are substantially equivalent to conventional varieties are often treated under existing food and feed safety frameworks (Giraldo et al 2019; Turnbull et al 2021; Tu et al 2022). Several countries (e.g. Argentina, Brazil, Japan) exempt certain gene-edited organisms from GMO classification if no foreign DNA is present, while the Court of Justice of the EU decided to treat gene-edited plants as GMOs subject to full GMO legislation (Giraldo et al 2019; Turnbull et al 2021; Tu et al 2022). These divergent regimes shape the availability and labeling of GM feed, the possibility of GM-free supply chains, and the burden of compliance for swine producers and feed manufacturers (Kleter et al 2018; Giraldo et al 2019; Fischer & Hess 2021; Turnbull et al 2021).

Regulatory assessments for GM feed aim to ensure animal health, product safety and environmental protection, but scholars note gaps: many plant parts used only for feed (e.g. forages) are not directly relevant to human diets, and specific methodologies for evaluating exposure and risks in livestock remain under development (Giraldo et al 2019). Projects such as the EU-funded MARLON have explored how to design post-market monitoring systems capable of detecting any unforeseen health impacts in herds consuming GM feed, while acknowledging that in practice only coarse estimates of GM exposure in individual animals are feasible (Kleter et al 2018) (see a synthesis in Table 1).

Table 1

Summary of major pro and con arguments around GM pig feed

<i>Dimension</i>	<i>Main supportive arguments for GM feed in pigs</i>	<i>Main critical arguments and concerns</i>	<i>Citations</i>
Animal/veterinary health	No relevant differences in growth, health, immunity or product quality between GM and non-GM feed; decades of safe use in livestock	Some small studies report organ or biochemical changes; call for longer, multigenerational studies, especially for novel traits	Bednarek et al (2013); Deb et al (2016); Tsatsakis et al (2017); Akram et al (2019); Aguilera et al (2024); Siddiqui et al (2024)
Human consumer health	No confirmed harm from products of GM-fed animals; transgenic proteins digested; meat composition equivalent; rigorous pre-market risk assessment	Persistent public concern about allergenicity, toxicity, unknown long-term effects; critiques of study design and potential conflicts of interest	Tsatsakis et al (2017); Gatew & Mengistu (2019); Giraldo et al (2019); Goodman (2024); Siddiqui et al (2024); Dolapo et al (2025)
Environment	Higher yields, less insecticide, potential land sparing, more efficient feed production supporting food security	Herbicide-resistant weeds, resistance evolution in pests, biodiversity and gene-flow concerns, reliance on monocultures and agro-chemicals	Tsatsakis et al (2017); Gatew & Mengistu (2019); Turnbull et al (2021); Goodman (2024); Siddiqui et al (2024)
Legal/regulatory	Science-based frameworks (e.g. Codex, EU, OECD) aim to ensure safety; traceability and labeling enable choice; product-based regimes may foster innovation	Asynchrony of regulations, regulatory burdens, disputes about process- vs product-based regulation, limited livestock-specific methodologies	Kleter et al (2018); Giraldo et al (2019); Turnbull et al (2021); Goodman (2024)
Ethics/values	Potential to support welfare (through more stable nutrition, disease-resistant crops), reduce pesticide exposure, and enhance global food security	Concerns about naturalness, playing God, animal and plant integrity, technological fixes that entrench factory farming and corporate control	Tsatsakis et al (2017); Eriksson et al (2018); Shriver & McConnachie (2018); Bovenkerk (2020); Devolder (2021); Fischer & Hess (2021)

Ethical and deontological considerations. Ethical debates about GMOs in animal agriculture often extend beyond measurable welfare outcomes to concerns about integrity, instrumentalization, naturalness, and justice. Ethicists distinguish at least four clusters of objections to modifying animals and their production systems: violation of animal integrity, treating animals purely as tools, “playing God”, and the perceived unnaturalness of genetic engineering (Eriksson et al 2018; Bovenkerk 2020; Devolder 2021). While these discussions often focus on GM animals, many of the same intuitions inform opposition to feeding pigs GM crops - especially when GM feed is seen as enabling and deepening intensive, high-density production systems.

From a deontological standpoint, critics argue that designing and feeding GM crops to maximize growth and feed conversion in confined pigs risks further instrumentalizing animals as production units, rather than respecting them as sentient beings with interests beyond productivity (Eriksson et al 2018; Bovenkerk 2020). Proponents counter that, if GM feed contributes to secure, balanced nutrition and more stable production, it can indirectly support animal welfare, particularly when combined with welfare-oriented breeding and husbandry improvements (Eriksson et al 2018; Shriver & McConnachie 2018; Siddiqui et al 2024). Some philosophers go further, arguing that genetic modification (including gene editing) could be ethically justified or even required when it reduces animal suffering, for example by breeding disease-resistant pigs or animals better adapted to their housing conditions, provided it is part of a broader strategy to reform animal agriculture rather than a license to maintain poor environments (Shriver & McConnachie 2018; Devolder 2021).

The “technological fix” objection is especially relevant. It holds that relying on genetic technologies (in crops or animals) to solve welfare and environmental problems is morally problematic because it treats symptoms while leaving unjust or harmful structures - such as factory farming - intact. Analyses of this objection suggest that it may reveal worries about complicity in unjust systems and the risk that technological solutions will weaken pressure for structural change, but it is not, by itself, a decisive reason to reject all use of GM feed or genome editing in livestock (Shriver & McConnachie 2018; Devolder 2021). Ethically defensible use would require that such technologies be deployed alongside, not instead of, measures to reduce stocking densities, improve housing and health management, and address environmental externalities.

Socio-cultural, religious, and consumer perspectives. Public debates over GM feed in livestock intersect with religious, cultural, and consumer values. Many religious traditions do not have explicit doctrines on GM feed for animals, but concerns about impurity, crossing species boundaries, and stewardship of creation can shape attitudes toward GM technology in agriculture more generally (Gatew & Mengistu 2019; Dolapo et al 2025). Some faith-based organizations and ethicists have expressed reservations about genetic engineering on grounds of “playing God” or violating the natural order, although these views are far from uniform and often focus more on human GM foods than on animal feed (Gatew & Mengistu 2019; Bovenkerk 2020; Dolapo et al 2025).

Consumer studies in Europe and elsewhere show that products labeled as coming from animals not fed GM feed command price premiums, reflecting widespread skepticism about GMOs and a desire for “natural” and transparent production systems (Kleter et al 2018; Fischer & Hess 2021; Turnbull et al 2021). Farmers themselves do not only respond to price signals: surveys in Sweden, for example, found that many livestock producers were worried about unforeseen long-term consequences for the environment and for human and animal health, and about dependence on multinational companies supplying GM seed and agro-chemicals (Fischer & Hess 2021). Even when farmers acknowledged potential economic or agronomic advantages of GM feed, broader value commitments - such as maintaining consumer trust, aligning with organic or GM-free standards, or expressing precautionary attitudes - shaped their decisions (Kleter et al 2018; Fischer & Hess 2021).

This socio-cultural context also influences legislation: the coexistence of GM, GM-free, and organic feed chains in Europe reflects political compromises that aim to respect consumer choice and cultural values while maintaining access to global feed markets (Kleter et al 2018; Fischer & Hess 2021; Turnbull et al 2021). For swine producers, this can create complex ethical landscapes in which scientific evidence of safety coexists with market signals and moral expectations that favor GM-free labeling, especially in premium segments.

Overall assessment. For farm pigs, the veterinary and toxicological evidence indicates that currently approved GM feed ingredients (primarily Bt and herbicide-tolerant maize and soybean) are nutritionally equivalent to conventional feedstuffs and do not adversely affect pig health, performance, immune function, or the safety and composition of pork for human consumers under normal conditions of use (Bednarek et al 2013; Akram et al 2019; Giraldo

et al 2019; Aguilera et al 2024; Goodman 2024; Siddiqui et al 2024). Regulatory systems in many countries require rigorous pre-market assessment, and nearly three decades of widespread use have not produced confirmed cases of harm attributable to GM feed in swine production (Giraldo et al 2019; Goodman 2024; Siddiqui et al 2024).

However, arguments against GM feed in pigs draw on environmental uncertainties, concerns about resistance evolution and biodiversity, critiques of industrial livestock systems and corporate concentration, and ethical worries about naturalness, integrity and technological fixes (Tsatsakis et al 2017; Shriver & McConnachie 2018; Gatew & Mengistu 2019; Bovenkerk 2020; Fischer & Hess 2021; Devolder 2021; Turnbull et al 2021). These objections do not primarily dispute short-term animal health data, but question the broader trajectory of agricultural development that GM feed may reinforce. In practice, choices about using GM feed in swine herds are shaped by a combination of scientific assessments, regulatory frameworks, economic pressures, consumer expectations, and deeply held ethical or religious values. Any comprehensive evaluation must therefore recognize that, while the scientific consensus on direct animal and consumer safety is largely positive, the societal debate remains multidimensional and unresolved.

Conflict of interest. The authors declare that there is no conflict of interest.

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