

Review

Fermentation-Based Strategies for the Feed Industry: Nutritional Augmentation, Environmental Sustainability

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Abstract

Global agriculture faces unprecedented challenges, including a projected population of 10 billion by 2050, declining arable land, and the urgent need to phase out antibiotic growth promoters (AGPs) to stem antimicrobial resistance (AMR). This review evaluates fermentation technology as a sustainable solution to the “food–feed–fuel” three competing land uses. We systematically compare solid-state fermentation (SSF) and submerged fermentation (SmF), highlighting their quantitative advantages: SSF offers 2–3× higher volumetric productivity and 70–90% lower water usage for solid wastes (e.g., soybean meal, wheat bran), while SmF provides superior process control for high-value products (e.g., single-cell protein). Key molecular mechanisms are discussed, including enzymatic degradation of anti-nutritional factors (up to 95% phytate and 98.8% tannin removal), mycotoxin detoxification (60–80% reduction), and biosynthesis of bioactive compounds (e.g., vitamin B12 enrichment up to 15-fold). Fermented feeds benefit many livestock species, particularly in organic and high-density farming systems, improving growth performance, gut health, and disease resistance while reducing environmental footprints. Advanced technologies such as AI-driven digital twins, CRISPR-based strain engineering, and precision fermentation are explored to overcome bottlenecks, including heat dissipation, strain stability, and process control. Despite challenges in scale-up, economics, and divergent global regulations (EU, USA, China, Southeast Asia, and Africa), fermentation is a critical biotechnological paradigm for circularity—the circular bioeconomy—and long-term food security. Future research should prioritize cost-effective large-scale implementation and the harmonization of regulatory frameworks.

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1. Introduction: Converging Crises in Modern Animal Nutrition

Fermentation connects nutrition with industrial microbiology. It converts low-value substrates (such as agricultural wastes, industrial by-products, and food waste) into nutrient-rich, bioactive feed ingredients [1–3]. Fermentation processes can be categorized into two main types relevant to the feed industry: utilization of acceptable food by-products, such as whey from cheese production as a starter for further dairy ferments

or animal feeds, focusing on waste minimization; and valorization of agricultural waste, such as wheat straw, coffee husks, or palm kernel cake, into feed via microbial degradation of lignocellulose and nutrient enrichment [4]. These processes harness microbial enzymes to break down complex substrates, thereby improving digestibility and bioactivity. By enlisting microbes to upgrade feed, fermentation acts as a “biorefinery” on a small scale, increasing protein digestibility by 12–28% [5], adding essential micronutrients (e.g., vitamin B12) [6], and degrading anti-nutritional factors (ANFs), such as phytate and tannins [7,8].

This appeal has captured attention as well as investments: the fermented feed market is booming [9–11]. For context, global agro-industrial waste generation is approximately 2.5 billion tons annually [4,12]. Table 1 presents global market projections for the fermented feed industry through 2035, highlighting a pronounced shift toward biotechnology-driven solutions. The data reveal robust growth in high-tech segments, with Fermentation-Derived Protein and Microbial Fermentation Technology showing the highest Compound Annual Growth Rates (CAGRs) at 11.1% and 8.2%, respectively. In contrast, the traditional global poultry feed base, while commanding the highest market valuation (~\$233 billion in 2024), is projected to grow at a conservative rate of 1.8%.

Table 1. Global market metrics and growth projections for fermented feed segments.

Market Segment	Base Value * (Year)	Projected Value * (Year)	CAGR (%)	Ref.
Broad Fermented Feed Market	19.8 (2025)	32.0 (2035)	4.9	[13]
Fermented Feed Ingredients	36.71 (2024)	70.39 (2030)	11.42	[14]
Microbial Fermentation Tech	37.50 (2024)	89.25 (2035)	8.2	[15]
Fermentation-Derived Protein	7.2 (2025)	18.5 (2034)	11.1	[16]
Global Bean Products Market	18.5 (2024)	35.9 (2033)	6.8	[17]
Single-Cell Protein (SCP)	15.1 (2023)	45.0 (2030)	16.9	[18]
Insect-based Bio-protein	0.88 (2025)	3.18 (2032)	17.4	[19]
Global Poultry Feed Base	233 (2024)	259 (2030)	1.8	[20]
Poultry Phytogenic Additives	1.05 (2024)	1.48 (2030)	6.04	[20]
Agricultural Waste Market	20.20 (2025)	32.86 (2032)	7.2%	[21]

* Billion US dollars. CAGR: Compound Annual Growth Rate; Ref.: References.

Emerging categories such as single-cell protein (SCP) (projected to exceed \$45 billion by 2030) and agricultural waste valorization (7.2% CAGR) underscore the industry’s strategic pivot toward sustainable, non-conventional protein sources and circular economy models to address future feed demands. Table 2 outlines key global drivers: population growth (~9.7 billion by 2050), which necessitates a 70% increase in protein production and drives the search for high-efficiency alternatives; environmental limits (livestock ~ 14.5% of GHG), constraints further mandate reducing the livestock sector’s carbon footprint, and the phasing out of antibiotic growth promoters (AGPs) to combat the antimicrobial resistance (AMR) crisis. These factors, underpinned by a projected market growth to approximately \$47 billion by 2035, highlight the transition of fermentation from a niche technology to a central pillar of sustainable animal nutrition.

Table 2. Global drivers and strategic imperatives for fermented feed adoption.

Driver Category	Key Statistic/Indicator	Implications for Feed Industry	Ref.
Demographics	Population to hit 9.7B by 2050; protein demand +70%	Urgent need for alternative, high-efficiency protein sources.	[22]
Climate Impact	Livestock contributes 14.5% of global GHG emissions	Mandate to lower carbon footprint via waste valorization (circular economy).	[23]

Table 2. Cont.

Driver Category	Key Statistic/Indicator	Implications for Feed Industry	Ref.
AMR Crisis	10M deaths/year by 2050; \$ 100T economic loss	Regulatory bans on AGPs require bioactive replacements (e.g., probiotics).	[24]
Health Gap	Post-AGP mortality +15–25% in piglets	Need for feeds that actively boost gut immunity and barrier function.	[25]
Microbiome	Gut flora contributes approximately 30% to the host’s energy harvest	Focus shifts to “feeding the microbiome” to unlock host performance.	[26]
Market Growth	Market to reach ~\$ 47B by 2035 (8.2% CAGR)	High investment potential for scalable fermentation technologies.	[27]

AMR Crisis: Antimicrobial Resistance Crisis; \$: US dollar; M: million; B: billion; Ref.: References.

2. Fundamentals of Fermentation: Process Engineering and Microbial Ecology

Industrial production of fermented feed primarily operates through two distinct modalities: solid-state fermentation (SSF) and submerged fermentation (SmF). The substrate’s rheology, microbial metabolism, and economics guide the choice.

2.1. Modalities of Fermentation

2.1.1. Solid-State Fermentation (SSF)

SSF involves growing microbes on moist solid substrates with little free water, mimicking the natural niche of many fungi and some bacteria. It excels at converting lignocellulosic residues (e.g., wheat bran, soybean hulls) and yields high enzyme productivity [3].

SSF has 70–90% less water usage and 40–60% lower energy consumption than SmF [28]. Solid substrates heat and cool faster than liquid (improving control but risking hot spots), so SSF typically runs at ~0.9–0.98 water activity (Aw): enough moisture for fungi but low enough to suppress bacteria [29]. This reduces sterilization needs and capital costs, reflecting nature’s efficiency in the process.

In SSF, the solid material serves as both a support and a food source. Typical substrates include wheat bran, soybean meal, coffee husks, and pelletized poultry manure, which often require pretreatment (e.g., steaming) to expose cellulose and increase surface area [30,31]. For example, life cycle assessments show that producing cellulase enzymes from coffee husks is more environmentally friendly via SSF than via SmF [32].

Bioreactor Engineering: SSF systems present unique engineering challenges (oxygen delivery, heat removal). Engineers apply fluid dynamics models (Darcy’s law for air flow, heat transfer equations) to balance bed height and airflow [33]. To address this, advanced reactor designs are used.

Packed-Bed Bioreactors: These all use forced aeration through the static bed to remove metabolic heat. Mathematical models based on Darcy’s law for pressure drop and heat transfer coefficients enable optimization of bed height and maintenance at physiological temperatures [34,35].

Rotating Drum Bioreactors: Periodically tumble solids for mixing and heat loss [36]; however, vigorous tumbling can shear fungal hyphae—a trade-off in design choice [37].

Tray Bioreactors: Shallow layers with passive airflow, low-tech and straightforward, but can be labor-intensive and cause temperature and moisture gradient problems, so they are suitable only for small-scale or specialty applications [38,39].

Fluidized-bed reactors: Improve heat dissipation by 20–30% via air circulation, validated in pilot scales [40].

2.1.2. Submerged Fermentation (SmF)

SmF immerses microbes in liquid broth, offering precise control of pH, temperature, and oxygen via impellers, spargers, and sensors [41]. It is mainly used for high-value products (e.g., purified enzymes, vitamins, single-cell proteins (SCPs)) where contamination cannot be tolerated (e.g., pure enzyme or SCP production) [42]. Modern SmF bioreactors employ “soft sensors” (digital twins) to predict metabolic states and adjust conditions in real time [43]. For example, under the microaerobic conditions with cobalt supplementation, yeast broth cultures in SmF will reach ~150 g L⁻¹ biomass—a very crowded culture [44–46].

Resource Intensity: SmF achieves such precision that it is the default production platform for high-value products (e.g., enzymes or single-cell protein) and for pure microbial metabolites. However, SmF is resource-intensive: a simple fermentation may use ~5–10 L water per kg of product [47,48], and thick broths demand ~2–3 kW/m³ for agitation [49–51].

Sequential Fermentation: Hybrid SSF–SmF systems combine the advantages of both modalities; for instance, SSF first hydrolyzes solids into sugars, which feed an SmF stage to produce target metabolites. This leverages SSF’s waste valorization with SmF’s precision, aligning well with circular economy goals [52–54].

2.1.3. Comparison of SSF and SmF

SSF is particularly applicable for solid agro-wastes (e.g., wheat bran), offering cost advantages of \$0.5–1 per kg product compared to SmF’s \$2–5 per kg for liquid substrates. Table 3 compares SSF and SmF: SSF yields 3–5× more enzyme titers with ~70% less water and 50% less energy, ideal for bulk feed/enzyme production. SmF, using liquid medium, provides process uniformity but requires intensive aeration/agitation. Each has scale-up challenges: SSF must address heat/mass transfer, while SmF faces shear stress and contamination risk, so the choice depends on the product and economics.

Table 3. Comparative analysis of fermentation modalities.

Feature/Parameter	Solid-State Fermentation (SSF)	Submerged Fermentation (SmF)	Key Microbial Agents	Ref.
Water Activity ¹	Low (moist solid, no free water)	High (liquid broth)	Fungi (<i>Aspergillus</i> , <i>Trichoderma</i>)	[55–57]
Enzyme Yield ²	Very High (3–5× vs. SmF)	Moderate to high	<i>A. niger</i> (phytase: 30,000 U/g)	[56,58,59]
Energy/Water Use ³	Low (−70% water, −50% energy) *	High (aeration-/agitation-intensive)	<i>Bacillus subtilis</i> , LAB	[60,61]
Process Control	Difficult (temp/pH gradients)	Excellent (homogeneous)	<i>Candida utilis</i> (SCP > 150 g/L)	[62]
Scale-Up Issues	Heat removal, mass transfer	Shear stress, contamination risk	<i>Trichoderma reesei</i>	[63]
Primary Output	Bulk fermented feed, enzymes	Pure metabolites, amino acids	<i>Lactobacillus plantarum</i>	[64]

* Energy savings based on 2020–2025 data. ¹ Moisture activity (low: <0.9 Aw; medium: 0.9–0.95; high: >0.95); ² enzyme yield (low: <50 g/kg; medium: 50–100 g/kg; high: >100 g/kg), and energy use. ³ Energy use: (low: <1 kWh/kg product; medium: 1–3 kWh/kg; high: >3 kWh/kg); water use: (low: <2 L/kg dry product; medium: 2–5 L/kg; high: >5 L/kg).

2.2. Mathematical Modeling of Fermentation Kinetics

Optimizing fermentations often relies on mathematical models. Classical Monod kinetics can be inadequate in SSF, where substrate diffusion and inhibition complicate growth.

Kinetic Models:

Modified Monod kinetics, for instance, the Logistic–Monod hybrid model (Equation (1)), which accounts for the carrying capacity of the solid matrix (X_{max}) and the threshold substrate concentration (S) required for maintenance energy [65,66].

$$\mu = \mu_{max} \frac{S}{K_s + S} \left(1 - \frac{X}{X_{max}} \right) \quad (1)$$

Heat transfer models are also used in engineering; mathematical models (Equation (2)) dealing with radial temperature distribution have been validated in 5 m³ pilot plants. These models integrate metabolic heat generation equations with convective and conductive heat removal terms to predict bed temperatures with high accuracy [67].

$$Q_{met} = \mu XV \Delta H \quad (2)$$

Similarly, the Luedeking–Piret model (Equation (3)) links product formation to both the growth rate (α) and the biomass concentration (β). Guiding the optimal harvest time when both microbial biomass (for single-cell protein, SCP) and metabolites (e.g., organic acids) are valued [68,69].

$$\frac{dP}{dt} = \alpha \frac{dX}{dt} + \beta X \quad (3)$$

Such mathematical tools are key milestones to scale up and make improvements. Models help narrow conditions, but empirical tuning remains essential.

2.3. Microbial Host Systems and Strain Engineering

The core of fermentation involves organisms, each with unique strengths. Filamentous fungi like *Trichoderma reesei* and *Aspergillus niger* are essential for feed enzymes. *T. reesei* produces cellulases and hemicellulases crucial for degrading feed components for animals. Both *Trichoderma* and *Rhizopus* show weak preservative activity; thus, research should focus on their enzymatic roles. Even old strains like *T. reesei* can be genetically modified—knocking out regulators such as *cre1* and overexpressing activators like *xyl1*—to boost cellulase production [70–72]. *A. niger* is also essential for phytase enzymes that release phosphorus from plant meals [32,73]. Custom-built fungi can enhance feed breakdown, but engineered organisms should be cautiously regulated due to public and political concerns about GMOs (as discussed below).

Lactic acid bacteria (LAB), including *Lactobacillus plantarum* and *Pediococcus*, are common in fermented feed. They produce lactic acid, lowering pH to inhibit spoilage and protect against pathogens. Recent genomic advances have revealed new traits; for instance, genes for esterase and tannase in *Lactobacillus plantarum* enhance their ability to degrade tannins and utilize phenolic compounds, improving feed nutrition and taste [74–76]. Many LAB synthesize exopolysaccharides (EPS) during fermentation, which act as prebiotics and may enhance the animal's intestinal epithelium integrity [77–81].

Yeasts like *Saccharomyces cerevisiae* or *Yarrowia lipolytica* are popular for protein and lipid production and ferment sugars well. An example of co-fermentation combined *Rhizopus* with *Propionibacterium freudenreichii*, resulting in vitamin B12 production on plant substrates (e.g., lupin meal) to create a vegan, vitamin B12-fortified feed [82–85].

Safety and Regulation: Microorganisms are central to fermentation, determining the scope of biochemical transformations. Classic fungal strains like *Trichoderma reesei* and *Aspergillus niger* are essential feed enzyme producers. These microbial technologies face safety limits; even “naturally occurring” microorganisms require testing, with GMMs subjected to stricter protocols. Most regulations demand testing for DNA residues or microbial contaminants, often requiring levels of undesirable organisms to be below 10 CFU per gram [86–89].

Regulatory frameworks differ across regions but prioritize safety. EU regulations are especially strict, reflecting high-risk standards. Details on regional regulations are in Section 7.

3. Molecular Mechanisms of Nutritional Enhancement

Fermentation serves a purpose far beyond mere feed preservation; it functions as a nutritive enhancer by modifying and optimizing the molecular profile of nutrients in feed.

3.1. Degradation of Anti-Nutritional Factors (ANFs)

Plant-based feedstuffs contain anti-nutritional factors (ANFs) that impair nutrient digestibility. Fermentation can break down many ANFs, boosting digestibility by ~12–28%. This makes fermentation a powerful strategy to improve feed quality by removing ANFs while enriching nutrients [57].

3.1.1. Phytate Hydrolysis

Phytate (inositol hexakisphosphate) is a major non-absorbable anti-nutritional factor (ANF) in plant feeds, which binds essential minerals (P, Ca, Zn), making them unavailable to animals. Microbial phytases produced during fermentation sequentially hydrolyze phytate, removing phosphate groups stepwise ($IP_6 \rightarrow IP_5 \rightarrow IP_4 \rightarrow \dots \rightarrow$ inositol) [90,91]. As a result, fermentation can achieve up to ~95% phytate reduction, releasing minerals and preserving proteins/vitamins [92,93]. This lowers the need for costly phosphate supplements. However, phytases have saturation limits: extremely high phytate (or novel mycotoxins) may exceed enzyme capacity [8,94]. In practice, combining strains (e.g., *Bacillus subtilis* + *A. niger*) has achieved ~95% phytate breakdown at pilot scale, demonstrating that near-complete degradation is feasible with optimal strains and conditions [40].

However, the magnitude of this benefit remains contingent on the fermentation conditions and the microbial strain employed. Notably, not all solid-state fermentation processes yield an identical phytase profile. Thus, although the reported data demonstrate that near-complete phytate breakdown is feasible, achieving this outcome consistently at an industrial scale will require careful selection of microbial strains and precise control of the fermentation process.

3.1.2. Tannin Biodegradation

Tannins are complex polyphenols that precipitate proteins and inhibit digestion. Certain microbes (e.g., *L. plantarum*) produce tannase enzymes that cleave tannins into smaller compounds (gallic acid and glucose) [95–97]. Fermentation can dramatically reduce tannins by up to ~98% in some feeds, improving protein availability by ~15% [98–100]. The released gallic acid acts as an antioxidant [101–103].

However, fermentation of high-tannin feeds requires robust strains to ensure completeness; incomplete tannin removal could still impair monogastric nutrition. Careful strain and process design are essential.

3.1.3. Detoxification of Gossypol and Glucosinolates

Protein-rich meals like cottonseed (with gossypol) and rapeseed (glucosinolates) contain natural toxins. SSF can detoxify these; for example, *Candida utilis* or *Aspergillus oryzae* can bind or degrade free gossypol, cutting it by >80% while increasing protein via microbial biomass [104–106]. Fermented rapeseed can reduce glucosinolates by 70–85%, improving thyroid health in pigs [107,108]. Feeding trials show that fermented rapeseed meal causes fewer stress effects than raw meal [57,109]. Thus, fermentation is a practical detox step for these meals, turning otherwise valuable ingredients into safe feed.

3.2. Bioenzymatic Detoxification of Mycotoxins

Mycotoxins (e.g., aflatoxin B1 (AFB1), zearalenone (ZEN), deoxynivalenol (DON)) are dangerous fungal toxins. Fermentation offers a precise mitigation: specific microbial enzymes (e.g., laccases, esterases) can degrade toxin structures, for instance, fungal laccases oxidize aflatoxin B1 [110], and certain esterases cleave zearalenone [111]. In practice, fermentations using *Bacillus* strains or engineered yeasts can reduce AFB1, ZEN, and DON by ~60–80%, while leaving proteins and vitamins intact. For example, *Bacillus* species enable multi-toxin reduction with ~70% efficacy at scale [55,111,112]. However, very high or unexpected toxin loads may exceed enzymatic capacity. Therefore, fermentation-based detox should be part of a comprehensive feed safety plan, not a sole solution.

3.3. Synthesis of Bioactive Compounds and Micronutrients

Fermentation does not merely eliminate undesirable feed components; instead, it enriches feeds with a variety of beneficial novel constituents through microbial biosynthesis.

3.3.1. Functional Peptides and Peptidomics

Modern peptidomic analysis (LC-MS/MS) has revealed that fermented feeds contain thousands of peptide species, with a generalized increase in bioactive peptides by 20–40% observed across studies. Most of these short protein fragments are not merely nutritional; many exhibit bioactivity. In soybean meal fermented by *Bacillus* species or lactic acid bacteria (LAB), proteases break down the storage proteins (e.g., glycinin and β -conglycinin) into shorter oligopeptides (2–20 amino acids). Specific sequences, such as Val-Pro-Pro (VPP) and Ile-Pro-Pro (IPP), familiar in human nutrition, are ACE (angiotensin-converting enzyme) inhibitors and can modulate immunity [113].

Nrf2-KEAP1 activation: Specific fermentation-derived peptides can activate the antioxidant Nrf2-KEAP1 pathway. Under basal conditions, Nrf2 is sequestered by its regulatory protein KEAP1 and remains inactive. However, specific fermentation-derived peptides bind directly to KEAP1, triggering a conformational change that releases (or “unmasks”) Nrf2. Once liberated, Nrf2 translocates to the cell nucleus, where it acts as a transcription factor to induce the expression of target genes. These genes, in turn, enhance the animal’s intrinsic antioxidant defense system, strengthening its ability to counteract oxidative stress [114]. In high-density farming systems, fermented soybean meal supplementation reduces oxidative stress in piglets by 25%. In other words, feeding piglets fermented soybean meal primes their cellular antioxidant machinery to mitigate oxidative stress [115].

Not all peptides offer benefits, as their efficacy depends on proper digestion and absorption. However, fermentation enriches the feed’s peptide profile with bioactive compounds—substances that may not be obtainable through conventional processing. These bioactive peptides, in turn, can support animal health and growth.

3.3.2. Vitamin B12 Enrichment

Vitamin B12 (cobalamin) is not naturally produced by plants, so animals must obtain it from fishmeal or dietary supplements. Fermentation can enable the in situ synthesis of vitamin B12 directly within animal feed. Certain microorganisms, particularly *Propionibacterium freudenreichii*, possess the complete “cob” biosynthetic pathway: a complex cascade of over 30 enzymes required for vitamin B12 production. In an optimized co-culture (often with a fungus and added cobalt under microaerobic conditions), these microbes can produce very high B₁₂ levels. For instance, fermented lupin-based feed contained ~1230 ng/g B₁₂—nearly 15 times the unfermented control [6,116]. Achieving this requires strict oxygen control to maintain the O₂-sensitive cobamide pathway [117]. The result is plant feed intrinsically rich in B₁₂, potentially eliminating the need for external supplements.

3.3.3. Exopolysaccharides (EPS)

Many lactic acid bacteria produce exopolysaccharides (EPS) during fermentation. These polysaccharides remain in the feed and act as prebiotics. In aquaculture, diets containing LAB-derived EPS have been shown to strengthen gut barriers—e.g., increasing gut tight junction integrity by ~30% [118–120]. This boosts resistance to pathogens. However, EPS levels must be controlled: too much EPS increases feed viscosity, and different EPS have varying benefits. Ongoing research aims to identify the most beneficial EPS for each animal species.

Table 4 summarizes these quantitative enhancements; e.g., *Bacillus*/*Aspergillus* fermentation can raise protein digestibility from ~67% to ~89%, phytate degradation to 95%, tannin reduction to 98.8%, vitamin B₁₂ levels 15-fold, and significant mycotoxin and antioxidant improvements. These mechanisms underscore fermentation’s role in valorizing agro-industrial substrates for sustainable feed production.

Table 4. Quantitative mechanisms of nutritional enhancement.

Mechanism	Target Substrate	Key Microorganism(s)	Quantitative Outcome	Ref.
Proteolysis	Soybean Meal	<i>Bacillus subtilis</i> , <i>Aspergillus</i>	Digestibility 67% → 89%; peptides	[121–123]
Phytate Degradation	Corn/Legumes	<i>Lactobacillus buchneri</i>	Phytate reduction up to 95.5%	[92,124]
Tannin Hydrolysis	Sorghum/Corn Paste	<i>Lactobacillus plantarum</i> A6	Tannins reduction 98.8% (4.2 → 0.05 mg/g)	[125,126]
Vitamin B12 Synthesis	Lupin/Wheat Bran	<i>P. freudenreichii</i> + <i>Rhizopus</i>	B12 level 1230 ng/g (15-fold increase)	[125,127]
Mycotoxin Detox	Contaminated Grains	<i>Lactobacillus</i> , yeast	Aflatoxin B1 −67%; zearalenone −54%	[128]
Antioxidant Boost	Herbal Residues	<i>Bacillus</i> , <i>S. cerevisiae</i>	SOD activity +28%; GSH-Px +32%	[129–131]

→: Symbol for “change in value”.

4. Sustainability and the Circular Bioeconomy

Fermentation contributes to the circular bioeconomy by converting organic waste into high-value resources.

4.1. Valorization of Food Waste and By-Products

Globally, food waste totals 1.3 billion tons annually. Fermentation can valorize 20–30% of this discarded organic biomass, effectively recovering a substantial share of otherwise wasted resources for agricultural and aquacultural feed production [132–134]. For example, brewer’s spent grain (BSG)—often low-grade feed—can be upgraded by SSF: fermentation raises its protein content (~27% → 31%) and lowers fiber by 22%, producing a high-protein, digestible ingredient for poultry and swine. This repurposing can save ~\$30 per ton and diverts BSG from disposal [135,136].

Similarly, other residues (coffee husks, palm kernel cake, cassava peels) can be fermented. Coffee husks (~200 million t/year) see ~80% toxin removal by *Aspergillus niger* fermentation, releasing polysaccharides and antioxidants [3,137]. Fermented cassava peels, with cyanide removed, become safe for cattle [138]. These examples highlight fermentation’s role in reclaiming diverse waste streams.

Overall, fermentation reduces feed–food competition by ~30–50% in intensive farming by using waste instead of human-edible crops. This supports food security by enabling animal protein production with less arable land [139–141].

Yet challenges remain; waste streams are typically heterogeneous, necessitating sorting or pretreatment. Moreover, large-scale use of such waste requires compliance with food safety standards; even fermented waste must meet feed safety regulations to eliminate potential pathogens or toxins. AI-enabled sorting can reduce waste stream heterogeneity by 25%, providing a viable mitigation strategy [142].

4.2. Novel Protein Sources: Insects and Algae

Fermentation also facilitates the utilization of unconventional proteins, which are inherently difficult to digest. This is particularly relevant for proteins derived from waste streams—for instance, insects reared on BSG—where fermentation further enhances the bioavailability of these otherwise indigestible proteins.

Insect Meal: Black soldier fly larvae (BSFL) and mealworms (*Tenebrio molitor*) are high-quality alternative protein sources. Incorporating insect meal in organic poultry farming yields a 10% growth rate increase [143]. However, their chitinous exoskeletons restrict nutrient digestibility, but fermenting insect meal with *Bacillus* or LAB partially degrades chitin to chitosan (a prebiotic) and releases amino acids [144,145]. Fermented insect feeds also yield antimicrobial peptides that inhibit pathogens (e.g., *Salmonella*) and mitigate key feed safety risks [146,147]. In practice, fermentation increases insect protein digestibility by 15–20% and suppresses pathogenic microbes, easing insect meal use in feeds [148–150].

Microalgae: Algae such as *Chlorella* and *Spirulina* are rich in protein and fatty acids, but have rigid cell walls. Fermentation or enzymatic pretreatment breaks cell walls and releases nutrients [151–153]. For example, feeding fermented algae significantly increases omega-3 absorption in animals. On a large scale, algal fermentation still faces economic challenges, as the cultivation and drying of algae entail considerable costs. However, the integration of a fermentation step into the algal biorefining process boosts nutrient yields by 25%. It reduces the production cost to \$0.8 per kilogram, thereby driving a substantially more efficient overall system [154,155].

4.3. Life Cycle Assessment (LCA) and Environmental Footprint

LCAs confirm fermentation's sustainability benefits. Fermented feeds can reduce carbon footprints by ~35–50% and water use by ~50–90% compared to conventional feeds [156]. For example, organic systems using fermented by-products show ~40% GHG cuts versus soy feeds, and insect-based feeds have much lower footprints than fishmeal [134,157]. Similarly, precision fermentation of pure proteins uses <1% of agricultural land (and ~90% less water) compared to livestock [158]. Hybrid SSF–SmF processes further shrink environmental impacts (~45% less footprint) [52,54].

Emission mitigation: Fermentation may also lower livestock emissions. In vitro studies found 25–40% reductions in ruminant methane with fermented feed additives, though in vivo trials are mixed due to microbial adaptation. In some cases, methane emissions even rebounded or increased when additives were administered long term, as the ruminant rumen microbiome adapts and develops the ability to degrade the additives themselves [159–162]. This “methane paradox” underscores that ruminal fermentation in ruminants is a dynamically evolving and highly adaptive system. Sustainable emission reductions, therefore, can only be achieved through dynamic, variable strategies, such as feeding additives in rotation, or combining additive adjustments with other dietary modifications to outpace microbiome adaptation. Notably, such rotational feeding strategies yield a sustained 20–30%

reduction in methane emissions over the long term in high-density ruminant production systems [163].

Crucially, fermentation is not automatically sustainable in every case. Comprehensive, system-wide LCA is needed to ensure environmental gains in one area (e.g., fertilizer use) are not offset by losses in another (e.g., energy for fermentation).

Table 5 presents the economic and environmental benefits of fermenting agro-industrial substrates for sustainable feed production. SSF of brewer’s spent grains with *Bacillus* and *Aspergillus* spp. reduces feed cost by 16.3% per kg gain, increases CP by 4%, and NDF by 22%, while diverting waste. Liquid fermentation of bakery waste saves \$30–45/ton and cuts methane emissions by 8–12%. Anaerobic/silage fermentation of banana biomass saves \$18–25/ton, raising protein from 8.5% to 14.2% with probiotic enrichment. Fermentation of olive mill wastewater yields a low-cost antioxidant additive, increasing polyphenols 3.2-fold and lowering ecotoxicity. SSF enzyme production from residues reduces carbon footprints by 35–50%. These results highlight fermentation’s dual role in cost reduction and environmental protection in the circular bioeconomy.

Table 5. Economic and environmental valorization metrics.

Substrate/Resource	Fermentation Strategy	Economic Impact	Environmental/Nutritional Gain	Ref.
Brewer’s Spent Grains	SSF with <i>Bacillus</i> / <i>Aspergillus</i>	Feed cost/kg gain reduced by 16.3%	CP ↑ 4%; NDF ↓ 22%; waste diverted	[164,165]
Food Waste (Bakery)	Liquid Fermentation (pig feed)	Cost saving \$30–45/ton	Methane emissions ↓ 8–12%; avoids landfill	[166,167]
Banana Biomass	Anaerobic/Silage	Cost saving \$18–25/ton	Protein 8.5% → 14.2%; probiotic enrichment	[168–171]
Olive Mill Wastewater	<i>L. plantarum</i> + Yeast	Low-cost antioxidant additive	Polyphenols ↑ 3.2×; reduced eco-toxicity	[172,173]
Agro-Ind. Residues	Enzyme Production (SSF)	Low-cost enzyme source	Carbon footprint ↓ 35–50% vs. conventional	[174]

↑: Symbol for “increase/rise”; ↓: Symbol for “decrease/decline”; →: Symbol for “change in value”.

5. Clinical Applications and Performance Outcomes

Experimental trials highlight fermentation’s effects on animal performance.

5.1. Swine Production: Navigating the Weaning Transition

The weaning period is a critical stress point in swine production. Stress, dietary changes, and immature gastrointestinal tracts typically lead to diarrhea and poor growth performance.

Growth and Health: Piglets fed fermented diets show ~15–25% higher average daily gain and ~15–25% lower mortality [175].

Digestive Benefits: Fermentation acts as pre-digestion, breaking down proteins, starches, and fiber, improving nutrient absorption and feed efficiency [176–178].

Immune Modulation: Fermented feeds suppress inflammation (e.g., downregulating the TLR4/NF-κB pathway and lowering IL-1β, TNF-α levels), freeing energy for growth [179].

However, the picture is not entirely positive. The positive effects rely heavily on the consistency of the fermentation process, the quality of probiotic cultures, and the overall formulation of the diet.

5.2. Poultry Production: Growth Performance and Immunity

In poultry production, fermented feeds are widely utilized to enhance bone development, regulate immune function, and boost production efficiency.

Fermented feed improves poultry performance by increasing phosphorus uptake by 15–25%, mainly through the degradation of anti-nutritional phytate by phytase during fermentation. This enhances nutrient bioavailability, allowing broilers to absorb more phosphorus and calcium [180,181].

Layer efficiency: In dense hen flocks, ammonia emissions drop by 25%. Long-term fermented wheat bran supplementation boosts egg production and improves eggshell quality, likely due to better intestinal feed tolerance and reduced chronic stress via *NF-κB* downregulation [182,183].

Transcriptomics analysis of the chicken gut shows fermented feeds boost nutrient transporter genes (like *PepT1*) and upregulate immune genes like IgA, increasing immune activity 2–3 times, while lowering stress-related genes and other regulatory effects [184,185].

Gut Microbiota: In the chicken cecum, fermented feeds alter the composition of the microbiota in organic production systems with beneficial genera (e.g., *Lactobacillus* and *Bifidobacterium*) being enriched, which in turn strengthens the intestinal barrier [180,186,187].

On farms, success depends on costs. If fermented feed raises expenses without reliable benefits, adoption drops. Most positive effects are supported by controlled studies, with a cost–benefit ratio of 1.2 to 1.5 [175,180,188].

5.3. Aquaculture: The Fishmeal Replacement Challenge

Fermented feeds are transforming aquaculture, especially for shrimp. In high-density farming, fermented feed boosts survival rates by 20%, highlighting its value for sustainability and efficiency [189,190].

Plant-Based Alternatives: Existing trials use fermented plant meals to replace 30–50% of fishmeal in diets, such as fermenting soybean meal for largemouth bass, which reduces enteritis and intestinal issues compared to unfermented soybean meal [191,192]. By pre-digesting ANFS, fermentation allows high plant meal levels without stunting. In short, intestinal damage in largemouth bass from soybean meal can be entirely prevented through optimized fermentation protocols [193].

Shrimp immunity plays a crucial role in shrimp farming, showing a notable 25% boost in disease resistance in organic aquaculture systems that utilize optimized dietary strategies [194–196]. Shrimp fed solid-state-fermented diets show improved immune gene expression and disease-fighting proteins. One study found these shrimp survived White Spot Syndrome Virus (WSSV) challenges better than those on conventional feeds [58,189,197]. A multi-omics analysis of shrimp embryos (simultaneous transcriptomics and proteomics) further revealed that fermented feed supplementation induces protective physiological changes in the shrimp gut, which in turn bolsters overall shrimp disease resistance [198,199].

These results show fermented feeds could prevent disease in aquaculture. Early findings are promising, but extensive field trials are needed to confirm these benefits in commercial settings.

5.4. Ruminants: Optimization and Mitigation

In ruminants like cattle, sheep, and goats, the main goals of fermented feed are to improve fiber use and reduce greenhouse gases. In organic systems, fermented feeds boost fiber digestibility by 15% [200]. Fermented total mixed rations improve fiber digestibility in dairy cows, increase milk fat by 4%, and reduce DMI by 5%. Pre-digestion of cellulose and hemicellulose helps rumen microbes extract more energy, often leading to higher milk production or faster growth [162,201].

Methane: Lab trials show fermented feed additives cut enteric methane by 25–40%, but microbes adapt: long-term use may result in about 12% [202]. The rumen microbiome adapts; over weeks, microbes develop the ability to degrade additives, negating initial methane reductions. To maintain lower methane, a rotational or combined approach may be needed to disrupt microbial adaptation. Rotating additives achieved sustained ~20–30% methane cuts [203–207]. Fermented feeds improve digestibility, but their effect on emissions needs more long-term research.

Table 6 shows the outcomes of fermentation interventions in livestock and aquaculture. In weaned pigs, FSBM boosts ADG by 11.2%, cuts FCR by 6.8%, cuts diarrhea by 43%, and increases butyrate. For broilers, 10% probiotic-fermented feed raises ADG and weight by 11.3% and 11.4%, with better villus height and sIgA. Laying hens fed fermented feed lay 4.2 more eggs, emit 25% less ammonia, and have better egg quality. Dairy cows on fermented TMR produce more milk fat, have lower DMI, better feed efficiency, and digest NDF and CP more. Sheep fed hydroponic wheat have 12% less meat shear force, higher propionate, and a 1.42 cost–benefit ratio. In aquaculture, fermented plant proteins replace 30–50% fishmeal, reduce enteritis, and improve antioxidant status. Overall, fermentation improves animal nutrition in a circular bioeconomy.

Table 6. Summary of clinical outcomes by species.

Species	Intervention	Performance Metric (vs. Control)	Health/Physiological Marker	Ref.
Swine (Weaned)	Fermented Soybean Meal (FSBM)	ADG +11.2%; FCR −6.8%	Diarrhea incidence −43%; butyrate ↑	[175–177]
Broilers	Probiotic Fermented Feed (10%)	ADG +11.3%; body Wt +11.4%	Villus height +18%; sIgA ↑	[180,208,209]
Layers	Fermented Mixed Feed	Production +4.2 eggs/year	Ammonia emission −25%; Haugh unit +6.3	[210,211]
Dairy cows	Fermented TMR	Milk Fat ↑; DMI ↓ (Efficiency ↑)	Digestibility (NDF, CP) ↑	[26]
Sheep	Hydroponic Wheat/Fodder	Meat shear force −12%	Propionate ↑; cost–benefit ratio 1.42	[212]
Aquaculture	Fermented Plant Proteins	Replaces fishmeal (up to 30–50%)	Prevents enteritis; antioxidant status ↑	[213–215]

↑: Symbol for “increase/rise”; ↓: Symbol for “decrease/decline”.

6. Technological Frontiers

6.1. Artificial Intelligence in Bioprocess Control

Bioprocess scale-up has faced challenges like heat dissipation, contamination, and variability in living systems, limiting efficiency and reproducibility. AI and ML are advancing quickly to reduce variability and improve process control. By 2026, Bioprocessing 4.0, driven by digital technologies, is emerging [216].

Real-Time Optimization: AI with soft sensors monitors pH and oxygen, predicts microbes’ behaviors, and sends data on off-gas and acidity to forecast metabolic state. This enables automatic fine-tuning like adding nutrients or adjusting aeration, streamlining processes for better consistency and higher yields [217,218].

Digital twins are virtual replicas of fermentors and their biological contents. Engineers simulate multiple fermentation experiments on the digital twin before scaling up, conducting all testing in silico. This data-driven approach enables efficient, low-risk scale-up and reduces scale-up costs by 30–40% [219–221].

This AI system is beneficial during scale-up, as AI and digital twins are becoming essential tools that enable fermentation to be a predictable, scalable solution.

6.2. Genome Editing and Synthetic Biology

Meanwhile, native microbial hosts are undergoing advanced reprogramming. Synthetic biology enables precise regulation of metabolic pathways, while CRISPR gene editing customizes processes to boost product yields and system robustness [222,223].

CRISPR/Cas9 is used to engineer microbial “hyperproducers”—achieving 50% higher yields and 20% lower costs. For example, scientists created *T. reesei* cellulase hyperproducers by deleting repressor genes and overexpressing key enzymes, leading to unprecedented secretion levels [224,225]. This CRISPR reprogramming is not limited to fungi; similar strategies work with bacteria for amino acid production, unlike fungal cellulase engineering. *Corynebacterium glutamicum*, a key industrial amino acid producer, has had its metabolic pathways engineered to boost carbon flux toward amino acids like L-lysine and L-isoleucine, which are crucial for balancing nutrients in poultry and livestock feeds [226,227].

Strain Robustness: We can engineer microbes for stress resistance, creating strains tolerant to inhibitors and temperature changes. Editing chaperone and efflux pump genes produces variants that thrive in acidic or acetate-rich broth, conditions that would impair their parental strains [228–231]. This engineered strain robustness is a pivotal determinant of reliable industrial fermentation performance.

Biological systems resist simplification: knocking out one gene can boost one pathway but hinder another. Balancing these changes needs more research and better algorithms. Still, microbial strain engineering advances quickly, and fermentation for feed benefits from these customized microbes.

6.3. Precision Fermentation

Another frontier is “precision fermentation,” where microbes act as cell factories to produce high-value molecules instead of bulk biomass. This method uses genetically engineered microbes to produce animal-identical proteins or additives [158,232,233]. This technology has enabled lab-scale production of heme, casein for cheese, and lactoferrin for infant formula, all identical to animal-derived versions but with a lower environmental footprint [234,235]. The microbial manufacturing approach is expanding into animal feed, with engineered yeast producing milk-identical lactoferrin and lysozyme that boost livestock gut health. These proteins, yielding 10–20 g/L at \$2–5 per kg, are much cheaper than dairy sources at \$10 per kg. They can replace 20–30% of traditional animal proteins in organic feed [235].

Precision fermentation is increasingly attractive from a sustainability view, supported by AI-optimized strains that cut microbial development time by 40%. It requires almost no land and much less water than livestock or crops. However, scale and cost remain barriers, with high production costs for pure proteins. As costs decrease, processes scale, and markets develop, precision-fermented products like custom enzymes or protective proteins will become mainstream, shifting from bulk ingredients to value-added additives supporting animal health [158].

6.4. Multi-Omics Integration

Multi-omics covers genomics, transcriptomics, proteomics, and metabolomics to create a detailed molecular fingerprint of fermentation at all biological levels.

Quality control with metabolomic fingerprinting (via LC-MS/MS) identifies and quantifies thousands of metabolites in feed, verifying active peptides and checking for undesirable compounds like residual toxins and biogenic amines [236,237].

Multi-omics offers deeper mechanistic insights by establishing causal relationships, not just correlations. Researchers can link genes or microbial transcripts to metabolite biosynthesis, aiding rational strain selection. For example, proteomic analysis might identify an enzyme linked to vitamin B12 production, and future strain development could involve overexpressing this enzyme [238,239]. Over time, accumulation of multi-omics data creates an “omics blueprint” to characterize fermentation ecology.

The development of fermented feed will shift from trial-and-error to data-driven design, increasing efficiency and effectiveness.

Table 7 summarizes the 2024–2025 emerging tech for feed fermentation, combining process, synthetic biology, and analytical science to boost efficiency, sustainability, and quality in the circular bioeconomy. AI/ML in process control optimizes fermentation parameters in real time with over 92% accuracy. CRISPR-Cas9 creates high-yield *Trichoderma reesei* strains with over 100 g/L enzyme titers. Synthetic bio toolkits like Easy-MISE reduce yeast strain development from 6 weeks to 8 days. LC-MS metabolomics profiles safety and fingerprints metabolites with over 200 compounds. Magnetic microparticles halve anaerobic digestion start-up time and increase methane by 40%. Metagenomics expands microbial diversity analysis in the rumen microbiome by 340%, aiding precision nutrition. These interdisciplinary technologies show potential to solve challenges in fermented feed production.

Table 7. Emerging technologies in feed fermentation.

Technology Domain	Innovation/Tool	Application/Benefit	Impact Metric	Ref.
Process Control	AI & Machine Learning	Real-time parameter optimization	Prediction accuracy > 92%	[44]
Strain Engineering	CRISPR-Cas9	Hyperproducing <i>T. reesei</i> strains	Enzyme titers > 100 g/L	[174]
SynBio Toolkit	Easy-MISE (Yeast)	Rapid strain construction (modular)	Dev time: 6 weeks → 8 days	[174]
Quality Control	Metabolomics (LC-MS)	Safety & metabolite fingerprinting	Detection of >200 metabolites	[240]
Materials	Magnetic Micro-particles	Enhanced anaerobic digestion	Start-up time –50%; CH ₄ +40%	[174]
Genomics	Metagenomics	Rumen microbiome analysis	340% increase in diversity map	[26]

→: Symbol for “change in value”.

7. Challenges and Regulatory Landscapes

While fermentation shows promise for animal feed, it faces substantial practical challenges.

7.1. Fragmented Global Regulations

A significant barrier to the commercialization and global deployment of genetically modified microbes (GMMs) and their products is the fragmented landscape of international regulatory frameworks, whose variations significantly affect GMM adoption across regions.

The European Food Safety Agency (EFSA) employs a stringent process-based regulatory framework for GMOs, leading to risk assessments that often delay approvals by 1–2 years [87,241]. Any feed additive from a GMM must undergo rigorous evaluation, and GMO labeling is mandatory if recombinant DNA is present. The EU uses a qualified presumption of safety (QPS) list to streamline approvals for known-safe microbes, but its regime remains among the strictest worldwide.

The United States Food and Drug Administration (FDA) adheres to a product-centric approach, emphasizing product safety over manufacturing processes. This methodology facilitates the expedited approval of non-GMO fermented feeds, with the majority of microbial products entering the market via the Generally Recognized as Safe (GRAS) pathway, which is generally more straightforward than the European Union route. Nonetheless, the introduction of new mandatory “bioengineered” labeling requirements has introduced additional complexity [242].

Japan’s regulatory approach to GMMs and their derivatives is heavily product-focused and similar to the FDA model. It is supported by strict food hygiene standards, comprehensive labeling requirements, and coordinated oversight across multiple agencies. Based on the Food Sanitation Act and Genetically Modified Food Labeling Standards, roles are clearly defined: the Ministry of Health, Labor and Welfare (MHLW) formulates policies and makes ultimate decisions on market access, while the Pharmaceuticals and Medical Devices Agency (PMDA), its technical partner, handles scientific safety assessments, provides pre-market advice, and ensures compliance with Good Manufacturing Practice (GMP) [243–245]. For feed-use GMMs and fermented feed products, the Ministry of Agriculture, Forestry and Fisheries (MAFF) oversees with the MHLW through case-by-case approval to ensure safety and standards [244,246,247].

China’s Ministry of Agriculture (MARA) updated biotech rules to match EU standards by requiring biosafety evaluations for feed-use GMMs. It balances biotech innovation, with R&D funding, and environmental impact studies, focusing on progress and risk mitigation [248].

Other Regions: Different regulatory regimes exist elsewhere. In Southeast Asia, Indonesia requires GMO labeling and trial costs of \$20 K–50 K. ASEAN has harmonized biotech regulations focusing on GMO safety assessments [243]. In Africa, Kenya follows Codex standards, with biosafety committees overseeing GMM evaluations. The African Union Model Law on Biosafety offers a framework, focusing on GMO risk assessments for feed production [249]. Brazil, a top GMO soybean producer, enforces its 2005 Biosafety Law through CNBS and CTNBio, requiring risk assessments with public input and labeling for foods over 1% GM [250,251].

A solution to fragmentation is harmonizing QPS/GRAS lists, which can streamline approvals for non-GM microbial products by establishing consistent safety benchmarks across regions. Navigating fragmented regulations—such as designing strains to EU standards, compiling FDA data, and meeting regional specifics like Japan’s multi-agency oversight and labeling—presents a technical challenge similar to optimizing fermentation processes.

7.2. Economic and Scale-Up Barriers

Scaling up solid-state fermentation (SSF) for feed production is challenging. Packed-bed and rotary drum bioreactors help with heat and mass transfer, but no complete solution exists. Unlike brewing or pharmaceuticals, the fermented feed sector lacks standardized facilities and processes, leading to product variability [34,37]. This variability in nutritional quality causes inconsistent animal performance, which producers want to avoid, while farmers depend on ingredient consistency for proper nutrition and health. Scaling up requires innovative reactor engineering and industry standards for fermentation and quality control.

Economic feasibility drives adoption. Bioreactors cost \$50 K–\$500 K; substrates \$0.1–\$0.5/kg; energy \$0.2–\$0.5/kWh/kg, with pretreatment accounting for 20–30% of costs (\$0.1–\$0.3/kg). Despite an \$18.5B market projected by 2034, small-scale producers face high costs. Large-scale production reduces unit costs by 40–60%, to \$0.5–\$1/kg [134].

Techno-economic analyses reveal that bulk products like single-cell protein require significant cost reductions to compete with soy or fishmeal. Meanwhile, high-value niche products such as feeds with probiotics, peptides, or vitamins can fetch higher prices by reducing animal health and medication costs. This encourages large feed companies to adopt incremental fermentation for savings, while startups focus on niche additives.

Policy support boosts the economy. China's and the EU's subsidies lower entry barriers, while carbon credits or health subsidies monetize fermentation's hidden benefits like emissions cuts and reduced antibiotic use [252].

7.3. Antimicrobial Use Paradox

In fermentation, antimicrobials conflict with fighting antimicrobial resistance (AMR). Solutions like phage therapy and engineered microbial resistance have been suggested. [253–256]. Implementing these strategies has been shown to reduce antimicrobial use by 37–54% [257–259]

7.4. Market Trends and Industry Dynamics

The fermented feed market trends as top agribusinesses like DSM, Alltech, and Cargill pursue gains through fermentation expertise [260]. Meanwhile, startups like BiomEdit and Calysta explore new areas, such as customizing animal microbiomes and converting waste gases like methane and CO₂ into biomass [261]. Asia-Pacific leads in animal feed innovation growth, driven by expanding intensive farming in China, Japan, and Asia [13,262]. This trend shows a global pattern: Western economies lead in feed tech development, but Eastern producers quickly adopt new technologies due to operational needs. To remain competitive, feed companies must navigate regional differences and adapt their services and partnerships.

Table 8 presents a SWOT analysis of fermented feed technology in sustainable animal nutrition and the circular bioeconomy. Strengths include improved feed conversion, gut health, waste valorization, and reduced antibiotic use. Weaknesses involve artisanal variability, heat management issues in solid-state fermentation, and high startup costs. Opportunities include AI and CRISPR advances, carbon credit integration, and new substrates like insects and algae. Threats cover regulatory hurdles for GMMs, fragmented rules, and feed safety issues like mycotoxins. The analysis highlights the potential to solve food–feed–fuel challenges, but also barriers that need innovation.

Table 8. Strategic SWOT analysis of fermented feed technology.

Dimension	Key Factors/Observations	Ref.
Strengths	Proven FCE improvement; gut health support; waste valorization; reduced antibiotic need.	[6,263]
Weaknesses	High variability in artisanal production; scale-up heat issues (SSF); high initial CAPEX.	[264]
Opportunities	Precision fermentation (AI/CRISPR); carbon credit markets; new substrates (insects/algae).	[27]
Threats	Regulatory barriers for GMMs; inconsistent regulatory frameworks globally; feed safety (mycotoxins).	[97,265]

8. Conclusions

Fermentation technology has progressed from a basic preservation method to a sophisticated biotech platform that addresses pressing feed challenges. By transforming agricultural wastes into nutrients, lowering anti-nutritional factors (ANFs) and mycotoxins,

and producing bioactive compounds, fermentation enhances feed quality and promotes sustainability. Quantitative evidence demonstrates notable benefits, such as a 12–28% increase in protein digestibility, approximately 95% reduction in phytate levels, and substantial decreases in methane emissions in ruminants. Advanced methodologies, including AI-driven digital twins, CRISPR technology, and precision fermentation, tackle technical challenges such as heat removal, strain robustness, and variability. Nevertheless, obstacles remain, notably high capital expenditure and inconsistent international regulatory frameworks.

Future efforts should focus on (1) cost-effective, large-scale hybrid SSF–SmF systems with techno-economic analysis; (2) engineering durable, multifunctional microbial consortia; (3) standardizing global GMO regulations; and (4) conducting additional field trials in organic and high-density systems. Ultimately, fermentation-based strategies will be vital to a resilient, resource-efficient circular bioeconomy capable of feeding a growing population sustainably while minimizing environmental harm.

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Abbreviations

The following abbreviations are used in this manuscript:

ACE	Angiotensin-converting enzyme
ADG	Average daily gain
AFB1	Aflatoxin B1
AGPs	Antibiotic growth promoters
AI	Artificial intelligence
AMR	Antimicrobial resistance
ANFs	Anti-nutritional factors
Aw	Water activity
ASEAN	Association of Southeast Asian Nations
BSFL	Black soldier fly larvae
BSG	Brewer's spent grains
CP	Crude protein
CAGR	Compound Annual Growth Rate
DON	Deoxynivalenol
EPS	Exopolysaccharides
EFSA	Science, safe food, sustainability (EU)
FAO	Food and Agriculture Organization
FCE	Feed conversion efficiency
FCR	Feed conversion ratio
FDA	Food and Drug Administration (U.S.)
GHG	Greenhouse gas
GM	Genetically modified
GMM	Genetically modified microorganism

GMO	Genetically modified organism
GMP	Good Manufacturing Practices
GRAS	Generally Recognized as Safe
LAB	Lactic acid bacteria
LCA	Life cycle assessment
MAFF	Ministry of Agriculture, Forestry and Fisheries (Japan)
MHLW	Ministry of Health, Labor and Welfare (Japan)
MARA	Ministry of Agriculture and Rural Affairs (China)
NDF	Neutral detergent fiber
PMDA	Pharmaceuticals and Medical Devices Agency (Japan)
QPS	Qualified presumption of safety
SCP	Single-cell protein
SmF	Submerged fermentation
SSF	Solid-state fermentation
TMR	Total mixed rations
WSSV	White Spot Syndrome Virus
ZEN	Zearalenone

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