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Optimization of Fermentation Parameters and Process Control Strategies to Enhance Nutritional Bioavailability, Safety Profiles, and Functional Properties of Plant-Based Foods within Sustainable Agro-Food Systems

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Abstract

The transition toward sustainable agro-food systems has intensified interest in plant-based foods as primary protein sources, yet their nutritional efficacy is constrained by anti-nutritional factors, limited digestibility, and safety concerns. Fermentation optimization represents a critical biotechnological intervention to address these limitations through precise parameter control. This review examines the mechanistic roles of key fermentation parameters—including temperature, pH dynamics, inoculum size, fermentation time, moisture content, and oxygen availability—in modulating biochemical transformations within cereals, legumes, oilseeds, and tubers. Parameter optimization enhances protein digestibility through proteolytic degradation, reduces phytates and tannins via microbial enzyme activity, improves mineral bioavailability, and facilitates vitamin biosynthesis. Concurrently, controlled fermentation achieves mycotoxin reduction, pathogen inhibition through organic acid production, and biogenic amine mitigation. Advanced optimization methodologies, including response surface methodology, artificial neural networks, and predictive modeling, enable multi-factorial parameter integration for industrial scalability. The application of optimized fermentation within sustainable agro-food systems contributes to post-harvest loss reduction, circular bioeconomy principles, and climate-resilient food processing. Current challenges include raw material variability, strain inconsistency, and regulatory standardization. Future directions encompass omics-guided fermentation optimization, precision starter culture development, and digital fermentation platforms. This review establishes that systematic parameter optimization is essential for realizing the nutritional and safety potential of fermented plant-based foods within sustainable agricultural frameworks.

Keywords: Plant-based fermentation; process parameter optimization; nutritional bioavailability; anti-nutritional factor reduction; food safety; sustainable food systems; response surface methodology

1. Introduction

Plant-based foods constitute the foundation of global agricultural systems, providing essential proteins, carbohydrates, and micronutrients to growing populations. Cereals, legumes, oilseeds, tubers, and vegetables represent diverse raw materials with significant potential for human nutrition within sustainable food frameworks [1]. The increasing recognition of plant-based diets for environmental sustainability and health promotion has accelerated research into processing technologies that enhance the nutritional value of these commodities [2]. Fermentation has emerged as a pivotal biotechnological intervention in plant-based food processing, offering transformations that extend beyond conventional preservation. Microbial metabolism during fermentation generates enzymatic activities capable of modifying substrate composition, degrading undesirable compounds, and synthesizing bioactive metabolites [3]. However, the nutritional and safety outcomes of fermentation are intrinsically dependent on process parameters, which govern microbial growth kinetics, enzyme expression, and metabolic flux.

Plant-based raw materials present inherent nutritional and safety challenges that necessitate processing interventions. Anti-nutritional factors including phytates, tannins, trypsin inhibitors, and oxalates limit mineral bioavailability and protein digestibility [4]. Additionally, contamination with mycotoxins, cyanogenic glycosides, and pathogenic microorganisms poses safety risks that must be mitigated through controlled processing [5]. The variability in raw material composition across agricultural systems further complicates the development of standardized processing protocols.

The importance of fermentation parameter optimization lies in its capacity to direct biochemical transformations toward desired nutritional and safety outcomes. Temperature, pH, inoculum characteristics, fermentation time, moisture content, and oxygen availability collectively determine the trajectory of microbial metabolism and enzyme-mediated reactions [6]. Understanding the mechanistic relationships between these parameters and final product quality enables rational process design for specific raw material combinations and functional targets.

This review aims to synthesize current knowledge on fermentation parameter optimization for enhancing nutritional bioavailability, safety profiles, and functional properties of plant-based foods. The scope encompasses mechanistic insights into parameter effects, nutritional enhancement strategies, safety improvements, optimization methodologies, and applications within sustainable agro-food systems. By integrating findings across diverse raw materials and fermentation technologies, this review provides a framework for translational research and industrial implementation.

2. Key Fermentation Parameters and Their Mechanistic Roles

The optimization of fermentation processes requires systematic understanding of how individual parameters influence biochemical and microbial dynamics. Temperature functions as a primary determinant of microbial growth rates and enzyme kinetics, with optimal ranges varying among mesophilic, thermophilic, and psychrotrophic organisms [7]. In solid-state fermentation of plant-based substrates, temperature control becomes critical due to metabolic heat generation, which can exceed optimal ranges and inhibit desirable microbial activity. Studies on lupin fermentation demonstrated that temperatures between 30-37°C optimize yeast and probiotic bacterial activity for anti-nutritional factor degradation [8].

pH dynamics during fermentation reflect metabolic acid production and substrate buffering capacity, influencing enzyme activity and microbial succession. Lactic acid bacteria fermentation typically reduces pH to 3.5-4.5 through organic acid accumulation, creating conditions that activate phytate-degrading enzymes and inhibit pathogenic microorganisms [9]. The initial pH adjustment of plant-based substrates affects the lag phase duration and competitive exclusion of undesirable microbiota.

Fermentation time determines the extent of substrate modification and metabolite accumulation. Short-duration fermentations (12-24 hours) may achieve partial phytate reduction, while extended fermentation (48-72 hours) enables complete degradation of complex anti-nutritional factors and generation of bioactive peptides [10]. However, prolonged fermentation risks biogenic amine formation and over-acidification, necessitating precise time optimization for each raw material-strain combination.

Starter culture selection and inoculum size profoundly influence fermentation outcomes through strain-specific metabolic capabilities. Lactic acid bacteria with high β-glucosidase activity enhance polyphenol biotransformation in fruit juices, converting glycosylated compounds to more bioavailable aglycones [11]. Co-culture systems combining proteolytic Bacillus species with acidifying Lactobacillus strains achieve synergistic degradation of proteinaceous anti-nutritional factors and fiber components [12]. Inoculum size affects population dynamics, with optimal levels (typically 5-10% v/v) ensuring rapid substrate colonization without nutrient competition-induced metabolic stress.

Moisture content and substrate composition determine water activity and nutrient availability, particularly critical in solid-state fermentation systems. Optimal moisture levels (40-60%) for legume and oilseed fermentation balance microbial mobility with oxygen diffusion [13]. Substrate particle size influences surface area for microbial attachment and enzyme accessibility, with finer grinding generally enhancing fermentation efficiency.

Oxygen availability distinguishes solid-state from submerged fermentation systems and directs metabolic pathway selection. Anaerobic conditions favor lactic acid production and phytate degradation, while microaerophilic environments support fungal enzyme production for fiber breakdown [14]. The selection between fermentation modes depends on target outcomes: submerged fermentation suits beverage production, whereas solid-state fermentation enables value addition to agricultural by-products.

Table 1: Influence of Fermentation Parameters on Biochemical and Microbial Dynamics in Plant-Based Foods

Parameter	Range Studied	Biochemical Effect	Microbial Response	Nutritional/Safety Outcome
Temperature	25-50°C	Enzyme kinetic modulation; protein denaturation thresholds	Growth rate optimization; metabolic heat stress adaptation	Optimal protease activity at 35-40°C for protein digestibility [7]
pH	3.5-7.0	Phytase activation (pH 4.5-5.5); protease inhibition at low pH	Lactic acid bacteria dominance; pathogen suppression	Phytate reduction 60-80% at optimal pH [9]
Fermentation time	12-96 h	Progressive proteolysis; complete anti-nutrient degradation	Succession from fast-growing to specialized metabolisms	447% increase in small peptides at 48-60 h [10]
Inoculum size	5-25% (v/v)	Enzyme concentration proportional to cell density	Rapid substrate colonization; quorum sensing effects	Enhanced β-glucosidase activity at 0.7% inoculum [11]
Moisture content	40-70%	Substrate swelling; enzyme diffusion	Water activity effects on sporulation	Optimal fiber degradation at 50-55% moisture [13]
Oxygen availability	Anaerobic to aerobic	Metabolic shift between fermentation and respiration	Facultative anaerobe adaptation	Reduced mycotoxins under controlled microaerophilic conditions [14]

3. Nutritional Enhancement Through Fermentation Optimization

Optimized fermentation parameters enable systematic improvement in the nutritional quality of plant-based foods through multiple mechanistic pathways. Protein digestibility enhancement represents a primary nutritional outcome, achieved through proteolytic degradation of complex storage proteins into peptides and amino acids. Co-fermentation of peanut meal with *Weizmannia coagulans* and *Bacillus subtilis* under optimized conditions (40°C, 48 h, 1:1 solid-to-liquid ratio) increased acid-soluble protein content by 546% and *in vitro* protein digestibility to 68.91% [10]. The mechanism involves synergistic protease activity from multiple strains, with Bacillus species providing extracellular proteases that cleave high-molecular-weight proteins into absorbable fractions.

Reduction of anti-nutritional factors constitutes a critical nutritional enhancement, particularly for legumes and oilseeds where phytates, tannins, and trypsin inhibitors limit nutrient utilization. Fermentation of lupin with *Saccharomyces cerevisiae* and probiotic bacteria achieved 61.9-67.0% phytic acid reduction and 27.3-82.3% oligosaccharide degradation [8]. Phytate reduction occurs through microbial phytase production, which hydrolyzes inositol phosphate bonds and releases chelated minerals. The efficiency of phytate degradation depends on fermentation pH, with optimal activity at pH 4.5-5.5 corresponding to the pH range established during lactic acid fermentation.

Mineral bioavailability enhancement directly results from phytate reduction and organic acid production. Lactic acid produced during fermentation forms soluble complexes with minerals, preventing precipitation and enhancing absorption [15]. Iron and zinc bioavailability in fermented cereals increases 2-3 fold compared to unfermented controls, with parameter optimization maximizing these effects through coordinated phytase activation and acidification.

Vitamin biosynthesis during fermentation contributes to nutritional density, particularly for B-complex vitamins and folate. Lactic acid bacteria possess metabolic pathways for riboflavin, folate, and cobalamin synthesis, with production rates influenced by substrate composition and fermentation conditions [16]. Folate concentrations in fermented legumes can increase 3-6 fold under optimized temperature and pH conditions that support cofactor availability for biosynthetic enzymes.

Bioactive peptide generation through controlled proteolysis produces sequences with antioxidant, antihypertensive, and immunomodulatory activities. The peptide profile depends on fermentation time and protease specificity, with optimal peptide accumulation typically occurring before complete hydrolysis to free amino acids [17]. Fermented soybean products contain lunasin and other bioactive peptides with demonstrated health benefits, highlighting the functional potential of parameter-optimized fermentation.

Antioxidant activity enhancement results from both liberation of bound phenolic compounds and microbial synthesis of novel antioxidants. β-Glucosidase-producing lactobacilli convert glycosylated polyphenols to aglycone forms with enhanced radical scavenging capacity [11]. Fermentation of blueberry juice with optimized parameters (0.7% inoculum, 29°C, 12 h) increased total phenolic content and antioxidant capacity by 34.36%, demonstrating the importance of precise parameter control for maximizing phytochemical bioaccessibility.

Glycemic index modification through starch modification and organic acid production offers metabolic benefits. Fermentation reduces rapidly digestible starch fractions while increasing resistant starch content, effects mediated by amylase activity and acid hydrolysis during processing [18]. Organic acids produced during fermentation delay gastric emptying and reduce postprandial glycemic responses, contributing to the functional properties of fermented plant-based foods.

Table 2: Nutritional Enhancements Achieved Through Optimized Fermentation of Plant-Based Foods

Raw Material	Microorganism Used	Optimized Conditions	Nutritional Improvement	Functional Relevance
Peanut meal	W. coagulans + B. subtilis + enzymes	40°C, 48 h, 1:1 moisture	546% acid-soluble protein increase; 68.9% digestibility	High-quality protein feed; reduced anti-nutrients [10]
Lupin	S. cerevisiae + probiotic bacteria	30-37°C, 24 h	62-67% phytate reduction; 27-82% oligosaccharide reduction	Improved mineral bioavailability; reduced flatulence [8]
Blueberry juice	L. plantarum JM065	29°C, 12 h, 0.7% inoculum	34.4% antioxidant increase; aglycone polyphenol accumulation	Enhanced polyphenol bioavailability [11]
Palm kernel meal	B. velezensis + S. cerevisiae + L. paracasei	34°C, 60 h, 52% moisture	193% soluble protein increase; 134% peptide increase	High-value feed from agricultural by-product [13]
Apple-yacon juice	L. plantarum YKX	34.8°C, 1:2.2 ratio	89.8% selenium bioconversion; flavonoid enrichment	Functional beverage with enhanced mineral bioavailability [19]
Cereal-legume blends	Mixed LAB cultures	pH 4.5, 48 h	3-6 fold folate increase; B vitamin enhancement	Improved micronutrient density [16]

4. Safety Improvements and Detoxification Mechanisms

Fermentation optimization contributes substantially to food safety through multiple detoxification and antimicrobial mechanisms. Mycotoxin reduction represents a critical safety improvement for plant-based raw materials susceptible to fungal contamination during agricultural production and storage. Co-fermentation of aflatoxin-contaminated peanut meal with *W. coagulans* and *B. subtilis* reduced aflatoxin B1 concentrations from 43.87 µg/kg to 6.20 µg/kg, achieving 85.9% detoxification [10]. The mechanism involves microbial enzymatic degradation of the mycotoxin structure, with fermentation parameters including temperature and moisture content influencing degradation efficiency through effects on enzyme expression and activity.

Cyanogenic glycoside degradation in cassava and other tubers occurs through microbial β-glucosidase activity during fermentation, releasing hydrogen cyanide that volatilizes under acidic conditions. Optimization of fermentation time and temperature ensures complete glycoside hydrolysis while minimizing residual cyanide concentrations below safety thresholds [20]. Solid-state fermentation systems with controlled aeration facilitate cyanide volatilization, demonstrating the importance of parameter integration for comprehensive detoxification.

Pathogen inhibition during fermentation results primarily from organic acid production, which reduces pH below growth thresholds for foodborne pathogens including *Salmonella*, *Escherichia coli*, and *Listeria monocytogenes*. Lactic acid concentrations of 0.5-2.0% achieved during optimized fermentation exert antimicrobial effects through cytoplasmic acidification and membrane disruption [21]. The antimicrobial efficacy depends on fermentation temperature and time, which determine acid production rates and final concentrations.

Organic acid production extends beyond lactic acid to include acetic, propionic, and succinic acids, each contributing distinct antimicrobial spectra. Acetic acid exhibits greater antimicrobial activity than lactic acid at equivalent concentrations, making acetate-producing fermentations particularly effective for pathogen control [22]. Parameter optimization for mixed acid production requires balancing conditions that support diverse metabolic pathways while maintaining product quality.

Biogenic amine control represents an emerging safety consideration in fermented plant-based foods. Histamine, tyramine, and putrescine can accumulate through microbial amino acid decarboxylation, posing risks for sensitive consumers. Fermentation parameters including temperature, pH, and salt concentration influence biogenic amine formation by selecting for decarboxylase-negative strains and modulating enzyme activity [23]. Low-temperature fermentation (15-20°C) reduces biogenic amine accumulation compared to optimal growth temperatures, though this must be balanced against fermentation efficiency. Recent innovations in biogenic amine control include the development of plant-based ingredients with diamine oxidase activity. Legume sprout extracts containing diamine oxidase can be incorporated into fermentation systems to degrade histamine and other biogenic amines as they form [24]. This approach represents a parameter-independent safety strategy that complements process optimization, though integration with fermentation conditions requires careful pH and temperature management to preserve enzyme activity.

Hazard mitigation through process control encompasses both intrinsic factors (pH, organic acids) and extrinsic parameters (temperature, time) that collectively determine safety outcomes. Predictive models integrating multiple parameters enable rational design of fermentation processes that achieve pathogen reduction targets while preserving nutritional quality [25]. The application of hurdle technology principles to fermentation optimization recognizes that combinations of sub-lethal stresses achieve greater safety margins than any single factor.

5. Optimization Strategies and Process Modeling

Systematic optimization of fermentation parameters requires experimental designs capable of identifying interactions among multiple variables while minimizing experimental burden. Response surface methodology (RSM) has emerged as the predominant approach for fermentation optimization, enabling empirical modeling of parameter effects and identification of optimal conditions [10]. Central composite and Box-Behnken designs efficiently explore parameter space while providing statistical frameworks for model validation.

The application of RSM to plant-based fermentation optimization has yielded refined process conditions across diverse raw materials. Optimization of peanut meal co-fermentation identified optimal temperature (40°C), fermentation time (48 h), solid-to-liquid ratio (1:1), and inoculum volume (10%) through sequential single-factor experiments followed by RSM [10]. The quadratic models generated through RSM revealed significant interactions between temperature and time, demonstrating that optimal conditions cannot be identified through one-factor-at-a-time approaches alone.

Statistical experimental design extends beyond RSM to include mixture designs for co-culture optimization and factorial designs for screening numerous variables. Plackett-Burman designs efficiently identify significant parameters from large candidate sets, reducing subsequent optimization complexity [26]. The application of design of experiment (DoE) principles ensures that optimization studies generate maximum information with minimum experimental resources.

Multi-factorial optimization approaches recognize that fermentation outcomes encompass multiple quality attributes that may require trade-offs between competing objectives. Simultaneous optimization of protein digestibility, phytate reduction, and sensory acceptance requires desirability function approaches that weight individual responses according to product priorities [27]. The development of multi-response optimization frameworks enables rational decision-making when optimal conditions for individual responses diverge.

Predictive microbiology models integrate fermentation parameter effects on microbial growth, survival, and metabolic activity. Primary models describe population dynamics over time, while secondary models relate growth parameters to environmental conditions including temperature, pH, and water activity [28]. The integration of predictive models with optimization algorithms enables simulation-based process design that reduces experimental requirements.

Artificial intelligence and machine learning approaches represent advancing frontiers in fermentation optimization. Artificial neural networks (ANN) capture non-linear relationships among parameters and responses with greater accuracy than polynomial models, particularly for complex biological systems [11]. Optimization of blueberry juice fermentation using genetic algorithm-backpropagation neural networks identified optimal conditions (0.7% inoculum, 29°C, 12 h) that increased antioxidant capacity by 34.36%, outperforming RSM-identified conditions.

Comparative studies of machine learning algorithms demonstrate the superiority of ensemble methods for fermentation optimization. Extreme gradient boosting (XGBoost) achieved higher predictive accuracy ($R^2=0.953$) than RSM for selenium-enriched apple-yacon beverage fermentation, revealing temperature thresholds critical for microbial activity that polynomial models failed to capture [19]. The integration of machine learning with mechanistic understanding enables identification of non-intuitive parameter combinations that maximize multiple outcomes.

Industrial scale-up considerations introduce additional complexity to fermentation optimization, as conditions optimized at laboratory scale may not translate directly to production environments. Heat and mass transfer limitations in large-scale solid-state fermenters create gradients in temperature, moisture, and substrate composition that affect microbial metabolism [29]. Scale-down approaches that simulate industrial conditions during optimization improve translation success by incorporating mixing and heat transfer effects into experimental designs.

Smart fermentation and sensor-based monitoring enable real-time parameter adjustment during processing, moving beyond fixed optimal conditions to dynamic control. Online monitoring of pH, temperature, and metabolite concentrations facilitates feedback control that maintains optimal conditions despite raw material variability [30]. The integration of near-infrared spectroscopy and electronic nose technologies with fermentation systems enables non-destructive monitoring of substrate transformation, supporting adaptive process control.

Table 3: Optimization and Modeling Approaches in Fermentation of Plant-Based Foods

Optimization Method	Variables Considered	Target Outcome	Key Findings	Industrial Applicability
Response surface methodology (RSM)	Temperature, time, moisture, inoculum	Protein digestibility; anti-nutrient reduction	Quadratic models identify parameter interactions; optimal 40°C, 48 h for peanut meal [10]	Established methodology; readily implemented with commercial software
Artificial neural network-genetic algorithm (ANN-GA)	Temperature, time, inoculum	Antioxidant capacity; polyphenol biotransformation	34.4% antioxidant increase; outperforms RSM for non-linear responses [11]	Requires computational expertise; suitable for high-value products
Extreme gradient boosting (XGBoost)	Temperature, substrate ratio, enzyme concentration	Selenium bioconversion; flavor optimization	$R^2=0.953$ prediction accuracy; identifies critical thresholds [19]	Advanced analytics; enables precision fermentation
Mixture design	Strain ratios in co-culture	Synergistic enzyme production	Optimal 4:2:1 ratio for triple culture fiber degradation [13]	Essential for multi-strain product development
Predictive microbiology models	Temperature, pH, time	Pathogen inactivation; metabolite accumulation	Kinetic parameters enable process validation [28]	Regulatory compliance; safety assurance
Desirability function approach	Multiple quality attributes	Balanced optimization	Resolves trade-offs between competing objectives [27]	Product development with multiple targets

6. Applications in Sustainable Agro-Food Systems

The integration of optimized fermentation processes within sustainable agro-food systems offers multiple pathways for enhancing food security and environmental sustainability. Fermented cereals and legumes in smallholder agricultural systems represent traditional technologies that can be improved through parameter optimization without requiring capital-intensive infrastructure. The application of optimized starter cultures and simple process controls (temperature management through insulation, pH monitoring with indicators) enables small-scale producers to achieve consistent quality and safety.

Climate-resilient fermentation technologies address the challenges of variable raw material quality under changing environmental conditions. Parameter optimization frameworks that account for raw material composition variability enable adaptive processing that maintains product quality despite fluctuations in substrate characteristics. The development of robust starter cultures with broad environmental tolerance further enhances process reliability under non-optimal conditions.

Reduction of post-harvest losses through fermentation provides a sustainable pathway for valorizing agricultural surpluses and by-products. Fermentation of oilseed meals (peanut, palm kernel, rapeseed) transforms low-value by-products into high-protein feed ingredients, contributing to circular economy principles [13, 10]. Parameter optimization for by-product fermentation addresses the specific challenges of these materials, including high fiber content, residual oil, and anti-nutritional factors.

Low-energy fermentation systems align with sustainability goals by minimizing processing energy requirements compared to thermal and mechanical alternatives. Ambient-temperature fermentation exploits microbial metabolic heat for process maintenance, while solid-state systems eliminate energy-intensive drying and liquid handling. The optimization of fermentation parameters for ambient conditions enables energy-efficient processing suitable for resource-limited settings.

Contribution to circular bioeconomy principles extends beyond by-product valorization to include water recycling, waste minimization, and nutrient recovery. Fermentation processes generate minimal wastewater compared to conventional food processing, while spent fermentation substrates retain value as soil amendments or animal feed components. The optimization of water activity and moisture content minimizes water consumption while maintaining microbial activity.

Functional food development through optimized fermentation creates products with enhanced health benefits that support dietary transitions toward plant-based nutrition. Fermented plant-based beverages with enhanced mineral bioavailability address micronutrient deficiencies in populations with limited access to animal products [19]. The optimization of selenium biotransformation during fermentation creates functional ingredients that support immune function and antioxidant status.

7. Challenges and Research Gaps

Despite significant advances in fermentation optimization, several challenges limit the widespread implementation of optimized processes. Variability of raw materials arising from genetic, environmental, and agronomic factors complicates the development of universal optimal conditions. The composition of plant-based substrates varies with cultivar, growing conditions, harvest timing, and storage history, affecting microbial growth kinetics and enzyme substrate availability. Optimization frameworks must account for this variability through robust designs that perform acceptably across expected raw material ranges.

Microbial strain inconsistency presents challenges for process reproducibility, particularly when using undefined mixed cultures or strains with genetic instability. Starter culture performance depends on physiological state at inoculation, which varies with propagation conditions and storage history. The development of standardized propagation protocols and quality control methods is essential for ensuring consistent fermentation outcomes.

Safety standardization remains challenging due to the diversity of fermented plant-based products and the absence of harmonized regulatory frameworks. Traditional fermented foods often lack established safety criteria, while novel fermentation processes may generate metabolites without prior safety assessment [37]. The optimization of fermentation parameters for safety outcomes requires validated analytical methods and toxicological data that are currently unavailable for many product categories.

Regulatory frameworks for fermented plant-based foods vary across jurisdictions, creating barriers to international trade and technology transfer. Novel fermentation processes may be subject to novel food regulations requiring pre-market approval, while traditional processes benefit from exemption. The evidence base required for regulatory approval includes process characterization, safety assessment, and nutritional substantiation, all of which depend on well-designed optimization studies.

Industrial scalability of optimized laboratory conditions requires consideration of mixing, heat transfer, and mass transfer limitations that affect process outcomes at production scale. Gradient formation in large-scale fermenters creates spatial variation in parameters that cannot be maintained at laboratory-identified optima. Scale-down experiments that simulate industrial conditions during optimization improve translation success but are not routinely performed.

Consumer perception of fermented plant-based foods influences market acceptance and the commercial viability of optimized processes. Clean label preferences favor minimal ingredient lists and natural processing, which align with fermentation but may conflict with enzyme additions or processing aids used in optimization. Consumer education regarding the safety and nutritional benefits of controlled fermentation is essential for market development.

8. Future Perspectives

Omics-guided fermentation optimization represents a transformative approach for understanding and directing microbial metabolism during plant-based fermentation. Metagenomic analysis of fermentation microbiomes reveals community composition and functional potential, while metatranscriptomics identifies actively expressed genes under specific parameter conditions [3]. Integration of omics data with process parameters enables mechanistic understanding of how temperature, pH, and substrate composition influence metabolic pathway flux.

Precision starter cultures designed for specific raw material combinations and target outcomes will emerge from synthetic biology and metabolic engineering approaches. Strain engineering to enhance specific enzyme activities (phytase, β-glucosidase, proteases) or eliminate undesirable metabolic pathways (biogenic amine formation) creates optimized biocatalysts for plant-based fermentation. The combination of multiple engineered strains in defined co-cultures enables division of labor and synergistic substrate transformation.

Integration with climate-smart agriculture positions optimized fermentation as a component of resilient food systems that adapt to environmental change. Fermentation processes that tolerate variable raw material quality and operate under ambient conditions support food security in regions facing climate impacts. The development of mobile fermentation units and distributed processing models enables value addition at harvest locations, reducing post-harvest losses and transportation requirements.

Digital fermentation platforms incorporating sensors, machine learning, and automated control systems enable real-time optimization that adapts to raw material variability and process deviations. Internet-of-things (IoT) integration with fermentation vessels enables remote monitoring and control, supporting distributed processing models and quality assurance [30]. The accumulation of process data across multiple batches enables continuous improvement of optimization models through machine learning.

Policy and translational research needs include the development of regulatory frameworks that accommodate process optimization while ensuring safety, and funding mechanisms that support technology transfer from laboratory to industry. Public-private partnerships that bring together academic researchers, ingredient suppliers, and food manufacturers accelerate the translation of optimization research into commercial products. International collaboration on safety assessment methods and standards facilitates trade and technology diffusion.

9. Conclusion

The optimization of fermentation parameters constitutes a critical intervention for enhancing the nutritional quality, safety, and functional properties of plant-based foods within sustainable agro-food systems. Temperature, pH, fermentation time, inoculum characteristics, moisture content, and oxygen availability collectively determine the trajectory of biochemical transformations that convert raw plant materials into nutritionally enhanced products. Mechanistic understanding of how these parameters influence microbial metabolism and enzyme activity enables rational process design for specific raw material combinations and target outcomes.

Nutritional enhancements achievable through optimized fermentation include improved protein digestibility, reduction of phytates and other anti-nutritional factors, enhanced mineral bioavailability, vitamin biosynthesis, bioactive peptide generation, and antioxidant activity increases. These transformations address fundamental limitations of plant-based foods as complete nutritional sources. Safety improvements through mycotoxin degradation, pathogen inhibition, organic acid production, and biogenic amine control ensure that nutritional benefits are not compromised by health risks.

Advanced optimization methodologies including response surface methodology, artificial neural networks, and machine learning algorithms enable efficient exploration of multi-parameter space and identification of optimal conditions that balance competing quality attributes. The integration of these approaches with mechanistic understanding and predictive modeling supports rational process development from laboratory to industrial scale.

The application of optimized fermentation within sustainable agro-food systems contributes to multiple sustainability objectives including reduction of post-harvest losses, valorization of agricultural by-products, low-energy processing, and circular bioeconomy development. Fermented cereals, legumes, oilseeds, and tubers produced through optimized processes support dietary transitions toward plant-based nutrition while addressing food security challenges.

Future research directions encompassing omics-guided optimization, precision starter cultures, digital fermentation platforms, and climate-smart integration will further enhance the contribution of fermentation to sustainable food systems. The evidence synthesized in this review establishes that systematic parameter optimization is essential for realizing the full nutritional and safety potential of fermented plant-based foods, supporting their role in global food security and agricultural sustainability.

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