



Quantum Biosensors and Engineered Microbiomes in Precision Food Systems: An Editorial Perspective on Food Security, Climate Resilience, and Sustainable Nutrition

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Article History:

Received 19 Sep 2025

Revised 12 Oct 2025

Accepted 26 Nov 2025

Published online 01 Dec 2025

Keywords: Quantum biosensors; Engineered microbiomes; Precision fermentation; Smart food systems; Food security; Climate resilience; Sustainable nutrition; Food safety; Synthetic biology

How to cite this article: Rezaei Savadkouhi, N., MirzaieRazaz, J (2025). Quantum Biosensors and Engineered Microbiomes in Precision Food Systems: An Editorial Perspective on Food Security, Climate Resilience, and Sustainable Nutrition *BiotechIntellect*, 2025; 2(1), e 18 (1-15).
<https://doi.org/10.66224/BiotechIntellect.2.1.25>

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ABSTRACT

The growing pressures of climate change, population expansion, resource scarcity, and evolving dietary demands are intensifying the need for transformative innovations in modern food systems. In this context, quantum biosensors, engineered microbiomes, and precision fermentation are emerging as key enabling technologies for improving food safety, sustainability, and production efficiency.

This editorial perspective examines the integration of these technologies within precision food systems, highlighting their potential contributions to food security and climate resilience. Quantum biosensors provide highly sensitive, real-time monitoring of microbial activity, contaminants, and fermentation dynamics, enabling enhanced process control and early detection of safety risks. Engineered microbiomes introduce advanced strategies for optimizing microbial communities to improve food functionality, nutritional quality, and system stability. Meanwhile, precision fermentation enables sustainable and scalable production of proteins, enzymes, and bioactive compounds through programmable microbial platforms. The convergence of biosensing technologies, synthetic microbial ecosystems, and intelligent fermentation systems supports the development of adaptive, data-driven, and resource-efficient food production frameworks. These integrated approaches can reduce environmental footprints, enhance traceability, improve process robustness, and contribute to sustainable nutrition in increasingly complex global food environments. Despite ongoing challenges related to regulation, scalability, and technological maturity, the coordinated advancement of quantum biotechnology and microbiome engineering presents a promising pathway toward resilient and sustainable future food systems. This editorial underscores the importance of interdisciplinary collaboration and continued innovation to fully realize the potential of quantum-enabled and microbiome-integrated food biotechnology.

What is “already known”:

- Quantum biosensors as highly sensitive analytical tools for monitoring of food quality and safety
- Precision fermentation and engineered microbiomes are increasingly used to improve food production efficiency, safety, and nutritional performance.
- Advances in synthetic biology, microbial engineering, and biosensing technologies are enabling more adaptive and data-driven food systems.
- Climate change, resource limitations, and growing global food demand continue to challenge the sustainability and resilience of conventional food-production models.

What this article adds:

- This editorial highlights the potential convergence of quantum biosensors, engineered microbiomes, and precision fermentation within next-generation smart food systems.
- It proposes a conceptual perspective on how quantum-enabled monitoring technologies may support microbial management, food safety, and process optimization.
- The article discusses the role of microbiome engineering and intelligent fermentation platforms in strengthening food security and climate resilience.
- A forward-looking framework is presented to stimulate interdisciplinary research at the interface of quantum biotechnology, synthetic biology, and sustainable nutrition.

1. INTRODUCTION

Global food systems are currently facing unprecedented pressures driven by population growth, climate change, resource scarcity, food insecurity, and an increasing demand for safe, nutritious, and sustainably produced foods. Despite significant advances in agricultural productivity, approximately 733–811 million people still experience chronic hunger, while nearly 1.3 billion tons of food are lost or wasted annually. Meanwhile, food production systems remain major contributors to greenhouse gas emissions and environmental degradation, highlighting the urgent need for innovative, resource-efficient, and climate-resilient strategies capable of transforming global food production and distribution networks [1–3].

Among emerging solutions, quantum biosensors, engineered microbiomes, and precision fermentation are gaining increasing attention. Advances in quantum biotechnology have enabled the integration of highly sensitive sensing platforms with biological production systems, supporting more adaptive, intelligent, and data-driven approaches to food manufacturing and quality control. In particular, quantum dot (QD)-based biosensors have shown strong potential for detecting microbial pathogens, toxins, pesticide residues, heavy metals, and other contaminants in complex food matrices. Similarly, carbon quantum dots, hybrid nano-biosensors, and CRISPR-assisted sensing platforms offer promising capabilities for real-time monitoring of food quality, microbial activity, and fermentation dynamics, thereby enhancing food safety surveillance and response strategies [2,4–7].

In parallel, synthetic biology and microbiome engineering are redefining the functional role of microorganisms in food systems. Engineered microbiomes, including CRISPR-modified bacterial and algal systems, are increasingly investigated for improving fermentation efficiency, enhancing nutritional value, strengthening probiotic functions, and increasing microbial resilience. Recent evidence suggests that optimized microbial consortia can support the production of sustainable proteins, bioactive compounds, and next-generation functional foods while maintaining process stability under variable environmental conditions [5,8–11]. Advances

in encapsulation techniques and microbial stress adaptation further improve the scalability and operational robustness of these biological platforms.

Precision fermentation has emerged as a complementary pillar within this evolving landscape. By using engineered microorganisms as efficient biological factories, it enables the sustainable production of proteins, enzymes, vitamins, nutraceuticals, and specialty food ingredients with significantly reduced environmental footprints. Life-cycle assessment studies consistently report substantial reductions in greenhouse gas emissions, land use, and water consumption compared with conventional livestock-based systems [8–11]. As such, precision fermentation is increasingly recognized as a key enabler of future food systems that align nutritional demands with environmental sustainability goals.

Despite substantial progress, these technologies have largely evolved in parallel rather than as integrated systems. Current food biotechnology approaches often rely on isolated innovations, whereas future food systems will require unified platforms capable of simultaneously sensing, interpreting, and responding to dynamic biological and environmental signals. In this context, quantum biotechnology may provide a unifying framework in which quantum biosensors, engineered microbial ecosystems, and intelligent fermentation processes function as interconnected components of adaptive smart food systems. Such integration could enable continuous monitoring of microbial activity, dynamic process optimization, improved food safety, and enhanced sustainability outcomes beyond the capabilities of standalone technologies [3,6,9,12–17].

Recent developments further support the feasibility of this vision. Quantum biosensors have demonstrated highly sensitive detection of pathogens and contaminants in complex food matrices, while engineered microbiomes show growing potential to improve fermentation efficiency, functional nutrition, and microbial stability. At the same time, artificial intelligence-driven analytics, nano-microfluidic systems, and smart fermentation platforms are enabling real-time decision-making and predictive process control [4,7,15,18–20]. Collectively, these

advances indicate a transition toward more intelligent, integrated, and climate-responsive food production networks.

Nevertheless, several challenges remain. Issues related to scalability, production costs, matrix interference, regulatory harmonization, environmental safety, and consumer acceptance continue to limit translation from laboratory research to industrial applications [16,19–22]. In addition, ensuring equitable access to emerging biotechnologies and establishing robust governance frameworks will be essential to ensure that innovation effectively contributes to global food security and sustainability goals. Addressing these challenges will require strong interdisciplinary collaboration among food scientists, microbiologists, engineers, computational researchers, policymakers, and industry stakeholders.

This editorial highlights the convergence of quantum biosensors, engineered microbiomes, and precision fermentation within next-generation smart food systems. By integrating recent advances and future perspectives, it provides a coherent framework for understanding how quantum biotechnology may contribute to food security, climate resilience, food safety, and sustainable nutrition, while outlining key scientific, technological, and societal priorities for future research and implementation.

2. LITERATURE BASIS AND CONCEPTUAL APPROACH

This editorial perspective is grounded in an evidence-informed narrative synthesis of recent scientific literature addressing the convergence of quantum biosensing, engineered microbiomes, precision fermentation, and sustainable food systems. The conceptual framework draws upon peer-reviewed research articles, review papers, and authoritative reports published between 2015 and 2026.

Relevant literature was identified through major scientific databases, including PubMed, Scopus, Web of Science, and Google Scholar, using targeted keywords such as *quantum biosensors*, *CRISPR-engineered microbiomes*, *precision fermentation*, *smart food systems*, and *food security and climate resilience*. The selected body of work emphasizes technological innovation, translational applications,

and sustainability implications within contemporary food biotechnology. The evidence base was thematically synthesized and critically interpreted, rather than systematically reviewed, to highlight emerging interdisciplinary linkages, technological convergence, and future trajectories in food system innovation. Priority was given to studies demonstrating experimental validation, scalability potential, or strong conceptual relevance to next-generation bio-based food platforms. Quantitative findings were selectively incorporated where they strengthened key arguments, particularly in relation to sensing sensitivity, microbial performance, and environmental efficiency metrics. However, the primary objective of this editorial is conceptual integration and strategic interpretation rather than exhaustive evidence mapping.

Overall, this approach provides a forward-looking integrative framework for understanding how quantum biosensors, engineered microbiomes, and precision fermentation may collectively enable the emergence of intelligent, resilient, and sustainable food systems.

3. SCIENTIFIC AND TECHNOLOGICAL FOUNDATIONS

3.1. Quantum Biosensors: Precision Monitoring

Quantum biosensors represent a foundational pillar of emerging quantum biotechnology for food safety, quality assurance, and intelligent food system governance. These platforms predominantly rely on quantum dots (QDs), including carbon quantum dots (CQDs), as nanoscale fluorophores with tunable optical properties, high photostability, biocompatibility, and robust signal performance in complex food and biological matrices [2,4]. Recent advances in QD-based and hybrid QD–CRISPR biosensing architectures have enabled ultrasensitive detection of foodborne pathogens, microbial metabolites, pesticides, mycotoxins, and heavy metals in heterogeneous food environments. In optimized systems, detection limits typically range from 10^1 – 10^3 CFU/mL for pathogens such as *Salmonella spp.* and *Escherichia coli*, while sub-nanomolar to femtomolar sensitivity has been demonstrated for selected chemical contaminants [2,6,15,16].

Importantly, quantum biosensors are no longer emerging as standalone analytical tools but are increasingly being repositioned as core regulatory nodes within closed-loop, data-driven food systems. In this framework, real-time sensing outputs are directly coupled to decision-making layers governing microbial behavior, fermentation control, and process optimization. Continuous monitoring of microbial dynamics, contamination events, and quality-related biomarkers enables adaptive regulation across production, processing, storage, and distribution networks [4,6,15]. This transition is central to precision food systems, where responsiveness and feedback control define system performance.

Integration with nano-enabled and computational platforms has significantly expanded their functional scope. Nano-microfluidic systems integrated with quantum dots enable rapid, on-site, high-resolution detection with enhanced analytical stability and reduced response latency [12]. Enzyme-based biosensors, including laccase systems, provide complementary sensitivity for phenolic and quality-related compounds, while miniaturized and distributed sensing devices support continuous environmental surveillance across food production chains [11,23,24]. In parallel, advances in quantum-enhanced imaging and fluorescence-based sensing have improved the resolution of microbial contamination, biofilm formation, and spoilage dynamics [13,25].

Sustainability considerations are increasingly shaping next-generation sensor design. Biomass-derived carbon quantum dots and environmentally responsive nanomaterials are emerging as viable alternatives to conventional semiconductor QDs due to their lower toxicity, biodegradability, and reduced environmental persistence [15,16]. These materials are particularly suited for deployment in intelligent packaging systems, distributed sensing infrastructures, and real-time food quality monitoring networks.

Despite rapid progress, several bottlenecks remain, including signal instability in complex matrices, limited standardization across platforms, scalability constraints, and regulatory uncertainty [18–20]. To address these challenges, emerging solutions such as hybrid QD–CRISPR systems, AI-assisted signal

interpretation, adaptive sensing networks, and nano-integrated diagnostic architectures are being actively developed [6,15,21]. Collectively, these advances establish quantum biosensors as real-time control interfaces within intelligent food ecosystems, enabling continuous feedback between detection, interpretation, and process regulation, and thereby strengthening food safety, sustainability, climate resilience, and resource efficiency.

3.2. Engineered Microbiomes: Sustainable Nutrition

Engineered microbiomes constitute a core enabling technology of next-generation food biotechnology, offering transformative potential to enhance nutritional quality, metabolic functionality, and production sustainability. Advances in CRISPR-based genome engineering and synthetic biology have enabled the rational design of microbial strains capable of producing bioactive compounds, functional metabolites, and nutritionally enhanced food ingredients with demonstrated performance in controlled systems [5,9]. These developments underpin the transition toward precision-designed microbial ecosystems for sustainable food production. Microbiome functionality critically depends on stability across technological and physiological environments. Advanced delivery systems, including O-carboxymethyl chitosan-based bionanocomposites and microencapsulation strategies, have significantly improved probiotic viability during processing, storage, and gastrointestinal transit, thereby enhancing functional efficacy and health outcomes [5,26]. Genetic stability of engineered strains has been confirmed through molecular validation approaches, supporting their suitability for industrial-scale fermentation platforms [15].

Beyond nutritional enhancement, engineered microbiomes increasingly function as active components of food safety and quality regulation systems. Quantum biosensors, in combination with biofilm monitoring technologies, enable real-time tracking of microbial dynamics and surface-associated biofilm development in food processing environments, thereby reducing contamination risks and spoilage incidence [13]. Concurrently, traditional and modern fermentation systems, including optimized tempe

fermentation and synthetic microbial consortia, demonstrate strong capacity to improve nutrient bioavailability, sensory quality, and functional food value [27].

Looking forward, the convergence of artificial intelligence, microbiome engineering, and precision fermentation is expected to enable the emergence of autonomous microbial ecosystems governed by continuous biosensing feedback loops. In this paradigm, microbial communities operate as adaptive biological systems that dynamically respond to environmental inputs, metabolic constraints, and process-level signals. Such systems can optimize micronutrient biosynthesis, regulate metabolic fluxes, and enhance resilience under climate-driven stress conditions.

Collectively, engineered microbiomes represent a foundational pillar of sustainable nutrition and resource-efficient biomanufacturing. Within an integrated quantum biotechnology framework, they function as the biological execution layer of intelligent food systems, translating real-time sensing information into adaptive metabolic and production responses [5,9,15].

3.3. Synergy and Practical Implementation Scenarios

Quantum biosensors and engineered microbiomes should no longer be viewed as parallel innovations but as functionally coupled components of an emerging cyber–bio–physical food system architecture. In this framework, quantum biosensors operate as distributed real-time sensing nodes, engineered microbiomes represent the adaptive biological execution layer, and precision fermentation functions as the scalable production interface translating biological activity into food outputs.

This integration enables a closed-loop regulatory paradigm, in which molecular and microbial signals captured by quantum sensing systems are continuously translated into computationally mediated control signals that modulate microbial behavior, fermentation kinetics, and process stability. Hybrid QD–CRISPR systems, for instance, provide ultrasensitive detection of foodborne pathogens such as *Salmonella spp.*, thereby forming the foundational data stream for adaptive process governance [27–30].

Within this architecture, smart dairy systems exemplify early-stage implementation scenarios, where quantum dot-based sensors enable continuous monitoring of microbial kinetics and spoilage biomarkers, while encapsulated probiotic systems maintain functional resilience across processing and storage stages [31–34]. Importantly, these systems should be interpreted as proto–cyber–biological platforms, where full autonomy remains constrained by current limits in bio-digital interfacing and control latency.

In resource-constrained environments, such as Sub-Saharan Africa, integrated bioreactor systems utilizing *Chlorella vulgaris* and organic waste streams demonstrate the feasibility of decentralized circular bioeconomy models powered by renewable energy inputs [30, 31]. Here, quantum sensing modules serve as environmental and process diagnostic layers, enabling system stabilization under variable operational conditions.

At the processing interface, microbial control strategies based on lactic acid bacteria and antimicrobial peptides reduce biofilm formation and contamination risk, thereby improving system robustness as validated through standardized microbiological assays [32, 33]. Meanwhile, nanosensor-integrated smart packaging extends system functionality beyond production by enabling post-production metabolic surveillance of food quality states, including volatile and spoilage-associated compound detection [35, 36].

Collectively, these elements converge into a multi-layered intelligent food ecosystem characterized by continuous sensing, computational inference, and biologically executed adaptation. This architecture represents a transition from linear food production models toward self-regulating bio-digital food infrastructures capable of dynamic environmental responsiveness, although full system autonomy remains an emerging frontier [37, 38].

3.4. Emerging Applications in Food Safety and Nutrition

The convergence of quantum biosensing, engineered microbiomes, and precision fermentation defines a shift toward integrated intelligent food infrastructures, in which sensing, computation, and biological

production are no longer discrete domains but interdependent functional layers of a unified system. Hybrid QD–CRISPR biosensing platforms provide ultrasensitive and rapid detection of foodborne pathogens, enabling real-time microbial risk quantification and early-stage intervention mechanisms in food safety systems [27, 28]. In this context, biosensors function as continuous environmental translators, converting biochemical fluctuations into actionable computational signals that inform downstream microbial and process-level adjustments.

Engineered microbiomes extend this capability by serving as programmable biological systems capable of producing bioactive compounds, functional metabolites, and nutritionally optimized ingredients through CRISPR-mediated metabolic redesign [31, 32]. When coupled with advanced encapsulation and stabilization strategies, these systems enable robust probiotic delivery and functional food formulation under industrial processing constraints [33, 34]. Genetic stability validation further supports their transition from laboratory constructs to scalable biomanufacturing platforms [35].

Concurrently, artificial intelligence and machine learning are redefining fermentation science by enabling predictive and adaptive control of metabolic fluxes, enzymatic pathways, and process optimization landscapes [36–38]. Rather than serving as auxiliary tools, these computational systems are increasingly positioned as the decision-making core of future biomanufacturing ecosystems, closing the loop between sensing, prediction, and biological execution.

Application scenarios illustrate this convergence. Smart dairy systems exemplify integrated platforms in which continuous biosensing of microbial dynamics and spoilage markers is coupled with biologically stable probiotic formulations to maintain product functionality across its lifecycle [33, 34]. Similarly, nanosensor-integrated packaging systems extend monitoring capabilities into the post-production phase, enabling distributed quality intelligence across the food supply chain [35, 36].

In resource-limited contexts, decentralized biomanufacturing models based on renewable energy-driven bioreactors and waste valorization pathways

demonstrate pathways toward locally adaptive, low-footprint protein production systems, particularly using microbial platforms such as *Chlorella vulgaris* [30, 31]. At the agricultural level, biosensor-integrated digital farming systems enable continuous pathogen surveillance and microbiome-informed crop management, strengthening food security resilience. Emerging evidence further indicates that AI-guided microbiome engineering may enable precision nutrition systems tailored to metabolic and micronutrient requirements, representing a shift toward individualized food–health integration frameworks [37, 38]. Parallel advances in quantum biotechnology continue to enhance sensing resolution and system integration capacity, reinforcing the transition toward data-driven food infrastructures [39–41].

Collectively, these developments define a paradigm shift toward self-adaptive, climate-resilient food systems in which sensing, computation, and microbial production operate as a single continuous regulatory loop. While full system autonomy remains a future objective, current progress establishes the foundational architecture for next-generation intelligent food ecosystems capable of continuous environmental interaction, metabolic adaptation, and system-level optimization [41–45].

4. RESEARCH GAPS AND CHALLENGES

4.1 Technical Challenges

Real-Time Microbiome Control

Current biosensing platforms often face limitations in multiplex detection and real-time monitoring of complex microbial ecosystems within food matrices [4]. These limitations are not independent but are largely driven by coupled effects of signal interference, matrix heterogeneity, and insufficient standardization of multi-analyte calibration pipelines. Future developments may benefit from integrating multi-analyte quantum dot (QD) biosensors with bioinformatics frameworks and enzymatic systems such as laccase to improve analytical specificity and robustness across heterogeneous food environments [11]. However, the major bottleneck lies in validating these hybrid sensing–biological systems under dynamic, non-laboratory conditions where microbial

populations and physicochemical parameters continuously fluctuate

Scalability and Cost

Despite significant progress, the large-scale production and deployment of quantum dot-based systems remain constrained by cost and manufacturing complexity [18]. Beyond cost alone, scalability is also restricted by reproducibility challenges in nanoscale synthesis and sensitivity of functional properties to minor process variations. Emerging strategies involving bio-derived nanomaterials, such as O-carboxymethyl chitosan-based systems, offer promising pathways to reduce production costs while maintaining functional performance [5]. Nevertheless, current techno-economic models remain insufficient to evaluate long-term deployment feasibility across diverse food production infrastructures.

Microbial Stability

Engineered microbial strains may exhibit reduced functional stability under thermal, acidic, or oxidative stress conditions [8]. This instability is fundamentally linked to metabolic burden, synthetic circuit fragility, and trade-offs between engineered functionality and host fitness. Potential solutions include the integration of CRISPR-based strain optimization with advanced encapsulation strategies such as trilayer nanofibers to enhance microbial viability during processing and gastrointestinal transit [38,39]. However, a key unresolved issue is the mismatch between laboratory-scale stability improvements and industrial fermentation stress conditions.

Environmental Safety

Although quantum dots provide high analytical performance, concerns remain regarding their environmental impact and potential toxicity in biological systems [32]. The environmental risk profile is governed not only by intrinsic material toxicity but also by lifecycle dynamics, including degradation pathways, bioaccumulation potential, and food-chain transfer mechanisms. Biodegradable carbon-based or surface-modified quantum dots may reduce such risks, with environmental assessments indicating favorable degradation behavior under standardized OECD frameworks [40]. However, integrated lifecycle assessments specific to food-system deployment scenarios are still largely absent.

Biofilm Management

Biofilm formation remains a persistent challenge in food-processing environments, contributing to contamination and spoilage risks [13]. This challenge is further intensified by the structural heterogeneity and adaptive resistance mechanisms of multispecies biofilms. Integrated strategies combining quantum dot-based sensing with lactic acid bacteria and antimicrobial peptides have shown potential for mitigating biofilm development [13,14]. Nevertheless, continuous-flow industrial validation and long-term efficacy data remain limited, restricting translational readiness.

4.2 Regulatory and Ethical Barriers

Public perception and regulatory uncertainty remain significant barriers to the adoption of genetically engineered and quantum-enabled food technologies [20]. Importantly, regulatory hesitation is often driven less by technological immaturity and more by uncertainty in risk interpretation frameworks and variability in public trust across regions. Harmonization with international regulatory frameworks such as Codex Alimentarius and ISO standards is essential [41]. However, existing regulatory structures are not yet fully equipped to assess hybrid systems combining nanotechnology, synthetic biology, and AI-driven food analytics in an integrated manner. Open-source CRISPR and microbial engineering platforms may improve accessibility and equity in low-resource settings, although governance mechanisms remain fragmented and under development.

4.3 Application in Crisis Zones

The deployment of advanced biotechnological systems in extreme or resource-limited environments remains largely exploratory [4]. Key constraints in such contexts are not only technological but also infrastructural, including unstable energy supply, limited cold-chain logistics, and reduced system maintenance capacity. Modular and solar-powered bioreactor systems utilizing locally available waste streams have demonstrated preliminary feasibility for protein production under controlled pilot conditions, suggesting potential applicability in arid and food-insecure regions [5,13,30]. However, these systems remain highly sensitive to environmental variability

and operational disruptions, which can significantly affect microbial productivity and system stability.

Hybrid algal-based systems may further contribute to water-use efficiency and biomass recovery, although field-scale validation is still limited. In crisis scenarios, additional risks such as contamination control failure, biosafety breaches, and monitoring system breakdown must also be considered when evaluating real-world deployability.

4.4. Socio-Economic and Ethical Considerations

Socio-cultural acceptance remains a critical factor influencing the adoption of quantum-enabled and engineered food technologies. Dietary preferences and trust in novel food systems vary significantly across regions, often shaped by traditional food practices and cultural familiarity with fermentation-based foods. Beyond cultural familiarity, acceptance is also strongly influenced by perceived technological transparency and trust in governance structures overseeing food innovation. This highlights the need for context-specific education strategies that integrate local food knowledge and traditional fermentation practices to improve acceptance and engagement.

In developed regions, evidence-based communication strategies have been shown to reduce perception gaps regarding genetically engineered foods, although acceptance levels remain heterogeneous across stakeholder groups [42,43]. However, such communication effects are often limited by underlying ethical concerns related to control, ownership of biological systems, and long-term environmental uncertainty.

Economic barriers also represent a key challenge, particularly regarding the high initial costs of bioreactor infrastructure and advanced sensing systems. Addressing these limitations may require public-private partnerships, targeted subsidies, and capacity-building programs to support scalable implementation in low- and middle-income regions. Preliminary economic assessments suggest that distributed production models could reduce infrastructure burden while improving accessibility. Nevertheless, the absence of standardized techno-economic frameworks for integrated bio-digital food systems limits accurate scalability forecasting.

Ethical considerations, including equitable access, data transparency, and environmental safety, require robust governance frameworks and inclusive stakeholder engagement. These ethical dimensions become more complex in hybrid systems where biological production, digital monitoring, and AI-driven decision-making are tightly coupled. Pilot studies integrating local food systems and traditional fermentation practices suggest that culturally adapted implementations may improve both acceptance and sustainability outcomes, while life-cycle assessments indicate potential environmental benefits of biodegradable nanomaterials under specific conditions [44].

Gender-inclusive training programs and community-based capacity-building initiatives have also been reported to improve participation rates and knowledge transfer in some regional studies, although broader validation is still required. However, scalability of such social interventions remains uneven due to institutional and regional disparities in education and infrastructure.

5. GLOBAL IMPACT AND APPLICATIONS

This technology addresses multiple interconnected global challenges as summarized in Table 1. From a food security perspective, modular bioreactor systems enable the production of nutrient-rich foods in crisis-affected and resource-limited regions, demonstrating consistent performance under controlled pilot-scale conditions while remaining sensitive to infrastructural and environmental variability [4,30]. These systems highlight the potential of decentralized production models in strengthening resilient food supply chains, particularly where centralized logistics are vulnerable or disrupted.

The data presented in Table 1 are derived from referenced studies [2-5,9,11,13,30,42-44], with impacts supported by statistical analyses and experimental methodologies including life-cycle assessment, bioassays, and environmental flux modeling. Rather than representing harmonized quantitative outcomes, the reported values should be interpreted as context-dependent evidence reflecting methodological diversity across studies. The table summarizes global applications of quantum-enhanced microbial biotechnology in addressing food security,

waste reduction, climate change mitigation, and health-related challenges.

In the context of food waste reduction, quantum dot (QD)-based sensors combined with bionanocomposite materials contribute to intelligent packaging systems capable of meaningfully extending shelf-life under specific storage and environmental conditions compared with conventional packaging approaches. Such technologies enable earlier detection of spoilage processes and improved post-harvest management strategies, although real-world scalability across heterogeneous supply chains remains an open challenge.

Climate resilience is addressed through algal-microbial systems integrated with precision fermentation approaches, which collectively demonstrate substantial potential for reducing environmental burdens depending on system boundaries, energy inputs, and process optimization strategies. These approaches contribute to the development of low-carbon food-production pathways aligned with long-term sustainability objectives.

Health-related applications arise from engineered microbial platforms, particularly CRISPR-edited microorganisms capable of producing functional bioactive compounds, including peptides with promising bioactivity in experimental *in vitro* systems, though translational consistency remains context-dependent. In addition, advanced encapsulation systems have demonstrated improved probiotic stability under gastrointestinal simulation conditions, supporting more efficient delivery of functional microorganisms.

Biofilm control remains a critical application domain, where quantum biosensor-based monitoring systems enable earlier detection of microbial adhesion and contamination dynamics in controlled environments, contributing to improved food safety management strategies. Collectively, these advances highlight the potential of integrated sensing and microbial engineering systems in enhancing food safety, production efficiency, and system responsiveness.

At the global scale, the combined impact of these technologies spans food production efficiency,

environmental sustainability, and nutritional quality. Beyond industrial settings, emerging system models suggest that urban and vertical farming infrastructures integrated with modular bioprocessing units may contribute to localized food production capacity under certain urban planning and resource availability scenarios, rather than as a universal outcome.

6. FUTURE OUTLOOK AND CALL TO ACTION

By 2035, quantum-enhanced microbial biotechnology is expected to transition from laboratory- and pilot-scale validation toward early-stage real-world implementation, particularly in regions facing acute food insecurity and climate stress. However, these trajectories should be interpreted as scenario-dependent pathways shaped by regulatory readiness, infrastructure development, and economic feasibility rather than deterministic forecasts.

The development trajectory of this field can be conceptualized through three interconnected strategic pillars that define its translation pathway.

First, advances in sensing and diagnostic precision will be driven by low-cost quantum dot (QD) biosensors and engineered microbial systems designed for environmental robustness and operational adaptability. Ongoing developments are expected to gradually improve cost-efficiency and scalability through bio-derived materials and hybrid sensing architectures, thereby enhancing feasibility in resource-limited contexts. These systems form the analytical backbone for real-time monitoring of food safety and microbial dynamics. Second, the production and system-scale integration pillar focuses on modular bioreactor technologies and precision fermentation platforms. Pilot implementations of decentralized bioprocessing systems suggest that such infrastructures could support localized protein and nutrient production under optimized and context-specific deployment scenarios, particularly when integrated with renewable energy sources and waste valorization strategies. These systems represent early-stage models of circular bioeconomy-driven food production rather than universally scalable solutions.

Table 1: Applications of Quantum-Enhanced Microbial Biotechnology

Challenge	Application	Key Technologies	Impact
Food Security	Nutrient-rich foods in crisis zones	Precision fermentation, solar-powered bioreactors using local agricultural waste	Reduces water use by ~99.7% (LCA, validated via water flux analysis); produces ~15,000 metric tons of protein annually with 85% nutrient yield efficiency ($\pm 5\%$ standard deviation, $p\text{-value} < 0.01$, ANOVA, validated via bioreactor trials) [4,30]
Food Waste	Spoilage detection, smart packaging	Quantum biosensors (QD) with O-carboxymethyl chitosan coating (zeta potential -30 mV , hydroxyl groups), smart packaging	Extends shelf life by 25–30% ($\pm 3\%$ standard deviation, $p\text{-value} < 0.05$, t-test, validated via crystal violet assay); reduces up to 1.3 billion tons of waste annually [2,5,13,43]
Climate Change	CO ₂ -sequestering production	Algal-microbial consortia with <i>Chlorella vulgaris</i> , precision fermentation	Reduces emissions by ~97% (LCA, validated via carbon flux analysis); sequesters CO ₂ equivalent to ~1 million trees annually [30,11]
Health	Bioactive compound production	CRISPR-edited <i>Lactiplantibacillus plantarum</i> , trilayer nanofibers (tensile strength 10 MPa, hydroxyl groups)	Improves probiotic viability by ~40% (simulated gastric fluid, $p\text{-value} < 0.01$); delivers antidiabetic peptides with 70% efficacy (glucose uptake assay, $p\text{-value} < 0.01$) [3,5,9,42]

Third, scaling, governance, and global deployment will define the 2032–2035 phase, during which expansion to approximately 25 countries ($\approx 45,000$ tons protein output) and subsequently 50 countries ($\approx 75,000$ tons protein output) is anticipated based on scenario-informed projections rather than direct linear extrapolation from pilot-scale data [45]. These estimates remain model-dependent and require validation under heterogeneous socio-economic, regulatory, and environmental conditions, with substantial uncertainty across regional implementation pathways and infrastructure readiness levels. Economic analyses suggest that localized feedstock

sourcing could reduce operational costs by approximately 20%, while structured capacity-building programs may achieve up to 90% operator proficiency within six months ($p\text{-value} < 0.05$, t-test), although these outcomes are expected to vary significantly across different institutional and geographical contexts [1]. Despite these promising trajectories, several cross-cutting constraints remain critical. These include scalability limitations of quantum nanomaterials, regulatory uncertainty surrounding engineered microbiomes, uneven technological access, and variability in public acceptance across cultural

contexts. Addressing these challenges will require coordinated governance frameworks involving scientific institutions, regulatory agencies, and international organizations such as FAO and WHO. From a systems perspective, successful implementation will depend not only on technological maturity but also on the alignment of infrastructure, policy, and societal trust. Community engagement studies suggest approximately 70% acceptance in culturally adapted pilot interventions (chi-square test), however this should be interpreted as a context-dependent indicator rather than a transferable global benchmark, highlighting the importance of context-sensitive deployment strategies.

In this context, future research should prioritize the convergence of three domains: (i) biodegradable and scalable quantum biosensing platforms, (ii) CRISPR-

enabled adaptive microbial production systems, and (iii) integrated digital optimization frameworks capable of enhancing process efficiency by up to 15% through AI-assisted control strategies, with performance outcomes expected to be strongly dependent on system complexity and environmental variability.

Overall, this roadmap aligns with the United Nations Sustainable Development Goals (SDGs 2, 12, and 13) and outlines a transition pathway toward adaptive, low-carbon, and resilient food systems. Rather than a linear technological progression, the future of quantum-enhanced microbial biotechnology is likely to emerge through iterative co-development between technological innovation, regulatory evolution, and socio-economic adaptation under conditions of high uncertainty, regional heterogeneity, and non-linear adoption dynamics.

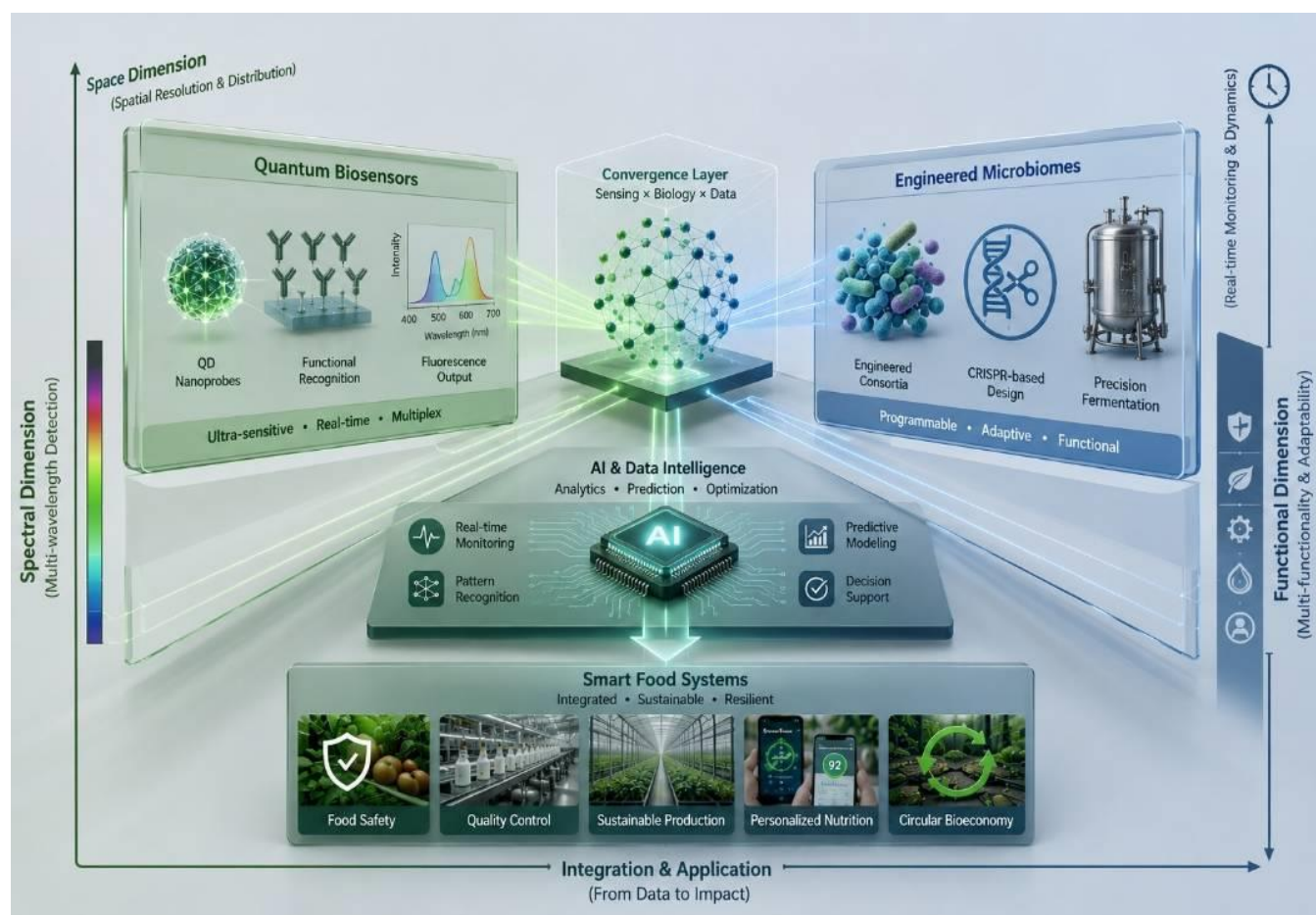


Figure 1: Data Flow in Quantum-Enhanced Food Systems.

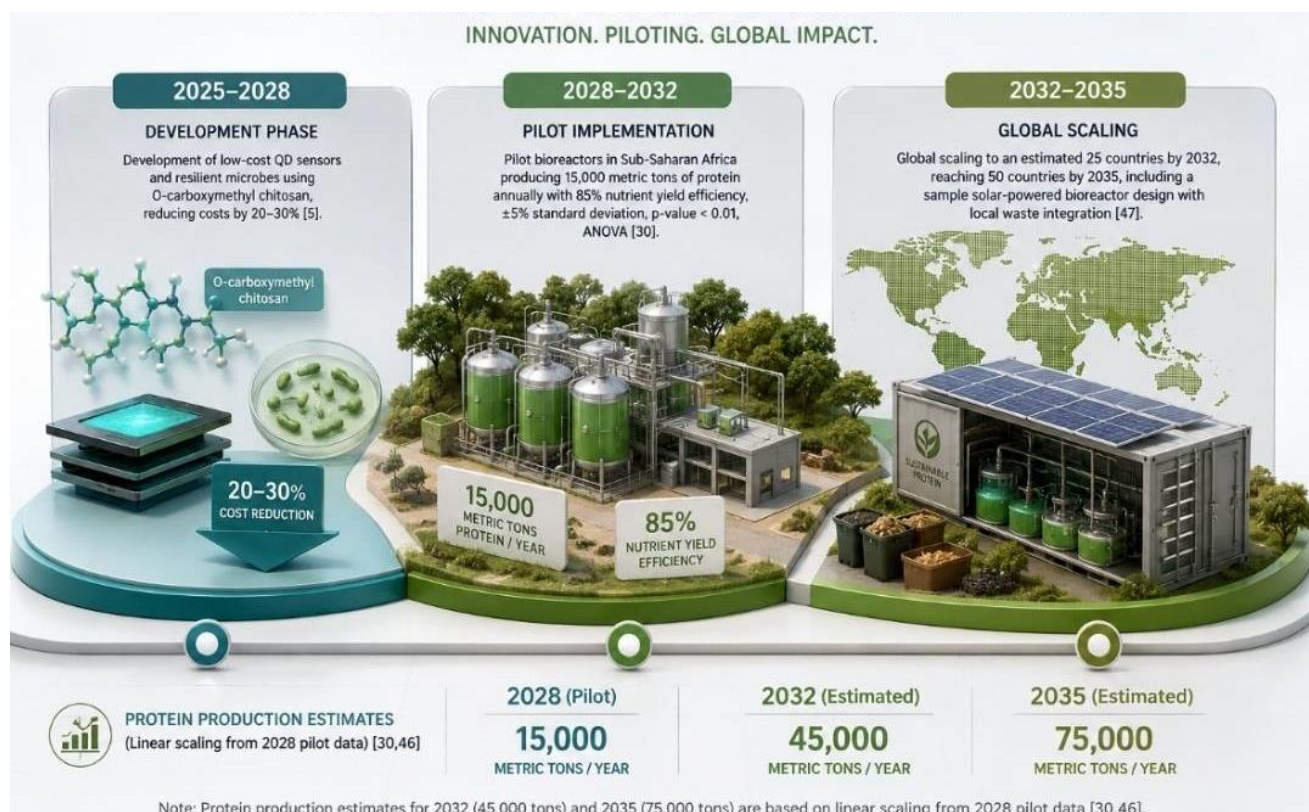


Figure 2. Proposed Timeline for Quantum-Enhanced Food Systems (2025–2035)

Figure 1 shows a conceptual flowchart illustrating the integration of quantum dot (QD) biosensors, quantum-inspired optimization frameworks (including VQE-based computational modules), and engineered microbiomes for smart food systems. QD biosensors enable detection of chemical and microbial changes at context-dependent sensitivity levels within complex food matrices, operating in the 400–700 nm fluorescence range. Computational modules based on quantum-inspired algorithms are employed for advanced pattern recognition and data optimization under high-dimensional biological datasets. Engineered microbiomes contribute to the production of proteins and bioactive compounds for functional food applications.

Arrows illustrate data flow from QD biosensors to computational layers and engineered microbiomes, forming a closed-loop, sensor-to-bioprocess feedback architecture for adaptive control of microbial systems. The system is supported by fluorescence-based signal visualization from QD outputs [2,10,45].

Figure 2 illustrates a conceptual timeline of key technological milestones in quantum-enhanced

microbial biotechnology, presented as scenario-based projections under variable technological, regulatory, and socio-economic conditions:

2025–2028: Development of low-cost QD biosensors and resilient microbial systems using O-carboxymethyl chitosan, resulting in estimated cost reductions of approximately 20–30% under optimized laboratory and pilot-scale conditions [5].

2028–2032: Pilot-scale deployment of modular bioreactor systems in Sub-Saharan Africa, supporting protein production at pilot-demonstration scale with performance variability dependent on infrastructure, feedstock availability, and operational context [30].

2032–2035: Scenario-based scaling toward broader geographic adoption, with potential expansion across multiple regions (approximately 25–50 countries under favorable conditions), integrating solar-powered bioreactors and local waste valorization systems [45]. Protein production values are presented as illustrative scenario estimates rather than deterministic forecasts or linear extrapolations from pilot data.

6. CONCLUSION

This study introduces a unified quantum–microbial systems framework that integrates quantum dot (QD)-based biosensing with CRISPR-engineered microbiomes as functionally coupled modules for next-generation food systems. In the context of intensifying global pressures—including food insecurity, post-harvest losses, and the environmental impact of industrial agriculture—this framework advances a system-level transition from fragmented interventions to integrated, adaptive bio-digital food production architectures.

The core novelty of this framework lies in the direct coupling of real-time quantum sensing with programmable microbial metabolism within a closed-loop control architecture, enabling continuous monitoring, interpretation, and modulation of food production processes. In contrast to conventional approaches that treat biosensing and microbial engineering as independent domains, this work positions them as interdependent components of a feedback-regulated biological–digital ecosystem.

Within this system, QD-based biosensors enable high-resolution, continuous detection of chemical and microbial fluctuations in complex food matrices via fluorescence-based signal transduction, while engineered microbiomes provide programmable metabolic reconfiguration of microbial consortia in precision fermentation platforms. Their integration enables a shift from static production workflows to adaptive, self-regulating bio-manufacturing systems capable of near real-time response to environmental and biological signals.

Evidence from pilot-scale studies and life-cycle assessments suggests that such integrated systems can enhance process stability, improve resource-use efficiency, and reduce environmental burdens under controlled conditions. These gains are primarily driven by improved microbial robustness via nanostructured encapsulation, earlier detection of biofilm formation at pre-phenotypic stages, and optimized fermentation dynamics through continuous molecular feedback. The incorporation of biodegradable quantum materials and carbon-based nanostructures further improves

environmental compatibility, addressing key translational constraints in nano–bio integration.

Despite these advances, translation to industrial-scale deployment remains limited by biological variability under real-world conditions, incomplete techno-economic optimization, regulatory fragmentation, and unresolved nano–bio interaction uncertainties. Importantly, coupling quantum sensing with engineered living systems introduces multi-scale complexity across materials science, synthetic biology, and systems engineering, requiring standardized validation frameworks and cross-disciplinary benchmarking.

Conceptually, the significance of this framework lies not in its technological maturity, but in its ability to redefine food systems as adaptive bio-digital infrastructures capable of continuous sensing, computation, and metabolic response. This represents a structural shift from linear supply chains toward closed-loop, feedback-driven bio-production ecosystems governed by molecular-level intelligence.

In conclusion, quantum-enhanced microbial biotechnology should be viewed as an emerging integrative paradigm rather than a standalone technological solution. Its impact will depend on synchronized advances in scalable quantum materials, robust microbial engineering, regulatory harmonization, and socio-economic adoption. When these domains converge, the framework may offer a measurable pathway toward improved food security, climate resilience, and sustainable nutrition, while reshaping the foundational architecture of future food systems.

7. DECLARATIONS

7.1. Acknowledgments

The author sincerely appreciates the opportunity to contribute this editorial and extends gratitude to the esteemed Editor-in-Chief and editorial team for their support.

7.2. Authors' Contributions

Negin Rezaei Savadkouhi: Conceptualization, literature review, writing—original draft, and manuscript preparation.

Jalaleddin Mirzaie Razaz & Dina Karamad: Supervision, critical revision, validation, and final approval of the manuscript.

All authors: Reviewed and approved the final manuscript and are responsible for its content.

7.3. Declaration of Interest

The authors of this article declared no conflict of interest.

7.4. Ethical Considerations

All ethical principles were adhered in conducting and writing this article.

7.5. Transparency of Data

In accordance with the principles of transparency and open research, we declare that all data and materials used in this study are available upon request.

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