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REVIEW

Sessile Fermentation Using Functional Biofilms as Engineered Microbial Systems for Safe, Stable and Intensified Food Processing

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Abstract

Fermentation research has traditionally concentrated on free-floating microorganisms. In contrast, biofilms are commonly seen as a contamination danger. However, many food fermentations, like kombucha, cheese rinds and koji, rely on surface-attached populations. This review defines sessile fermentation as the purposeful utilization of controlled biofilms as functional aids in food systems. We combine biofilm biology and process engineering to describe how natural biofilm fermentations maintain stability and safety. Key processes include diffusion reaction gradients, microenvironments and quorum sensing. Surface design, cell immobilization and reactor types are all parts of engineering techniques. We then focus on three practical contributions, namely continuous processing, bio-preservation and functional food production. We also handle real-world issues including scale-up, fouling, cleaning-in-place and process control. Overall, altering our perspective on biofilms from issue to platform provides a realistic pathway to more efficient and scalable food fermentation.

Keywords Sessile fermentation · Biofilm-based bioreactors · Functional biofilms · Controlled fermentation · Microbial consortia · Food processing engineering · Continuous fermentation

Highlights

- Biofilms are redefined as functional biocatalysts rather than fermentation contaminants
- Traditional fermented foods demonstrate naturally optimized sessile microbial ecosystems
- Sessile fermentation enables spatial metabolism, resilience and process stability
- Engineered biofilms allow rational control of surfaces, matrices and microbial consortia
- Sessile systems support continuous fermentation, bio-preservation and sustainability

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Introduction

Modern food fermentation science has been shaped by a long-standing planktonic paradigm, in which microorganisms are primarily conceptualized as free-floating, homogeneous populations whose behavior can be controlled through bulk environmental parameters such as temperature, pH and substrate availability (Voidarou et al., 2020). This framework has underpinned the design of industrial fermentation, starter culture development and microbial risk assessment for decades. However, mounting evidence from both traditional food systems and contemporary microbiological research challenges the assumption that planktonic growth represents the optimal or even the dominant functional state of microorganisms during fermentation (Heo et al., 2022). In many of the world's most stable, complex and culturally significant fermented foods, microbial activity is governed not by dispersed cells, but by structured, surface-associated communities of biofilms that function as self-organized, resilient biocatalytic ecosystems (Ghosh et al., 2022).

In food science, biofilms have historically been framed almost exclusively as a problem. They are commonly associated with persistent contamination, antimicrobial resistance

and sanitation failures in food processing environments. This risk-centric perspective, while essential for ensuring food safety, has inadvertently obscured a parallel and equally important reality: biofilms are also fundamental to some of the most successful fermentation processes known (Sun et al., 2025). From the cellulose-rich symbiotic culture of bacteria and yeasts (SCOBY) in kombucha, to vinegar "mothers," kefir grains, koji molds and cheese rind consortia, biofilm-based microbial architectures have been empirically selected over centuries for their robustness, productivity, and ability to generate complex sensory and functional attributes (Gong et al., 2021). These naturally occurring systems demonstrate stable and reproducible fermentation performance. These systems operate not despite their sessile nature, but because of it.

From an engineering perspective, biofilm-based food processing systems introduce unique transport and kinetic characteristics that distinguish them fundamentally from planktonic fermentation and also from conventional immobilized-cell systems and engineered biofilm reactors (Sharma et al., 2023). Substrate diffusion through the extracellular polymeric matrix, formation of concentration gradients and spatial metabolic stratification directly influence reaction rates, yield, and process stability. These transport-related phenomena necessitate the integration of reaction engineering, mass transfer analysis and hydrodynamic design principles, including diffusion coefficients, shear stress, and Reynolds number, to optimize nutrient delivery, metabolite removal, and biofilm performance in sessile fermentation systems (Siney et al., 2025). Such characteristics may provide opportunities for process intensification and improved substrate utilization in engineered food bioprocesses. Despite these advantages, such engineering considerations remain underexplored in food fermentation contexts, limiting the translation of biofilm-based food processing systems into scalable industrial processes (Pawar et al., 2026).

Recent advances in biofilm biology, systems microbiology and bioprocess engineering now provide the conceptual and technical foundation to re-evaluate biofilms not merely as contaminants to be controlled, but as functional units to be deliberately harnessed. Biofilms exhibit emergent properties that are absent in planktonic cultures, including spatial organization, metabolic specialization, enhanced stress tolerance, and stabilized microbial interactions (Muhammad et al., 2020). The extracellular polymeric matrix, often viewed as a barrier in sanitation contexts, acts instead as a dynamic architectural framework that enables nutrient channeling, metabolite retention and localized microenvironments. These features may support functional stability under fluctuating or resource-limited conditions, although excessive biofilm development can also introduce diffusional limitations and operational challenges during large-scale processing (Xu et al., 2023). This improved resilience supports consistent product quality and operational stability under industrial processing conditions.

Within this emerging context, the concept of sessile fermentation is proposed as a distinct and underexplored paradigm in food and bioprocess design. Sessile fermentation refers to processes in which structured, surface-associated microbial communities rather than suspended cells constitute the primary biocatalytic entity driving product formation (Demirci et al., 2025). Importantly, this concept extends beyond traditional immobilized-cell technologies, which often rely on artificial carriers and lack ecological complexity. In contrast, sessile fermentation represents a self-organized, ecology-driven biocatalytic system in which endogenous extracellular matrix production, spatial microbial organization and functional metabolic zoning are intrinsic process features rather than externally engineered constraints (Fessler et al., 2022). Sessile fermentation emphasizes self-organizing microbial consortia, endogenous matrix production and spatially resolved metabolic activity, features that align closely with both traditional food fermentations and next-generation sustainable bioprocessing goals. However, despite growing interest in biofilm-enabled bioprocessing, important challenges remain regarding process reproducibility, scale-up consistency, biofilm heterogeneity, and regulatory acceptance in industrial food systems. Despite its relevance, sessile fermentation remains conceptually fragmented across disciplines, with insights scattered among studies on traditional foods, environmental biofilms and industrial biocatalysis (Wang et al., 2022). A cohesive framework linking biofilm structure, microbial interactions, and functional outcomes in food systems is still lacking. Moreover, critical questions remain regarding rational engineering, monitoring, scale-up, and regulatory acceptance of biofilm-based food processes. Addressing these challenges requires an integrated perspective that bridges microbiology, food chemistry, materials science, and process engineering (Satish Sharma et al., 2023).

This review aims to synthesize current knowledge on functional biofilms in food fermentation through the unifying lens of sessile fermentation. By re-examining traditional fermented foods as natural biofilm reactors, elucidating the mechanistic basis of biofilm-driven functionality and evaluating emerging engineering strategies and applications, this article seeks to reposition biofilm reactor systems as a central design element in future food and bioprocess systems. In addition to highlighting potential functional and engineering advantages, this review also critically discusses current limitations associated with industrial translation, process control, biosafety, and regulatory standardization of sessile fermentation systems. In doing so, it provides a critical roadmap for transforming an historically perceived liability into a strategic asset for resilient, efficient, and sustainable food production. As illustrated in Fig. 1, the conceptual

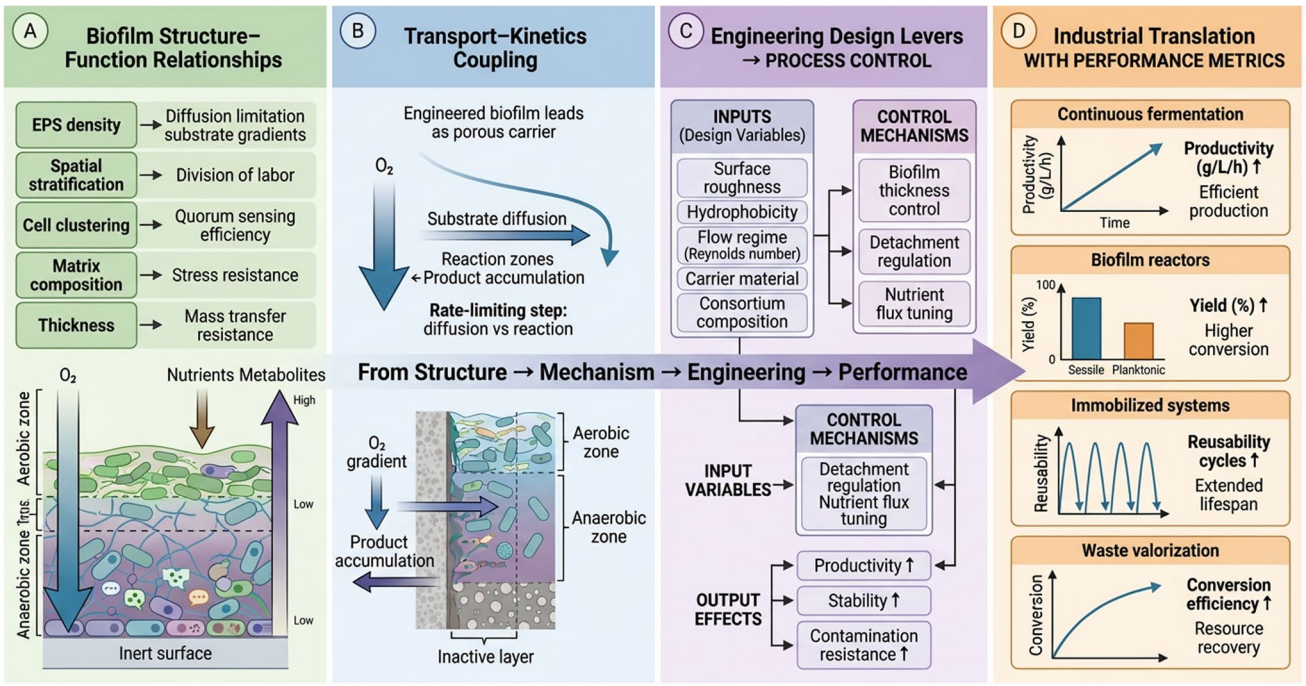


Fig. 1 Conceptual framework of sessile fermentation for food and bioprocess design. The figure illustrates the mechanistic and engineering basis of sessile fermentation, linking biofilm architecture to process performance. **A** Biofilm structural features, including extracellular polymeric substance (EPS) density, spatial stratification and matrix composition, are mapped to their functional roles in mass transfer, metabolic cooperation and stress tolerance. **B** Coupled transport–reaction phenomena within biofilms are depicted, highlighting substrate diffusion, physicochemical gradients and spatial metabolic differentiation that govern reaction kinetics and productivity. **C** Engineering design levers, including surface properties, hydrodynamic conditions and microbial consortium design, are presented as controllable parameters influencing biofilm formation, stability and activity. **D** Translation into industrial applications is illustrated through performance-oriented outcomes, including enhanced volumetric productivity, process stability, resource efficiency and operational scalability compared to conventional planktonic systems. This framework provides a basis for rational design and optimization of biofilm-based fermentation processes

framework of biofilm-based fermentation highlights the progression from naturally evolved sessile microbial ecosystems to engineered biofilm reactor processes and their subsequent translation into industrial food and bioprocessing applications.

The Natural Blueprint: Sessile Ecosystems in Traditional Food Fermentation

Before the advent of stainless-steel bioreactors and defined starter cultures, traditional food fermentations had already perfected the art of cultivating functional sessile communities. These ancient practices provide a vital, time-tested blueprint, demonstrating that biofilms are not incidental contaminants but are often the central, deliberate engines of transformation (Shen et al., 2025). The most iconic examples are macroscopic, free-floating biofilm structures that function as self-propagating bioreactors, with representative traditional systems summarized in Table 1 (Muhammed et al., 2025). The kombucha symbiotic culture of bacteria and yeast (SCOBY) is a robust cellulose mat woven by *Komagataeibacter* species, which provides a stable, aerobic habitat for embedded acetic acid bacteria and yeasts, orchestrating a sequential metabolism of sugars into a complex profile of organic acids, ethanol and bioactive compounds. Similarly, water kefir grains and tibicos are gelatinous, polysaccharide-rich matrices (often composed of dextran or levan) that harbor a protected consortium of lactic acid bacteria and yeasts, enabling a reproducible fermentation across batches and generations (Michielsen et al., 2024). The vinegar "mother," a veil-like cellulose biofilm of *Acetobacter*, is both the catalyst for acetification and a living reservoir of the microbial culture, traditionally used to inoculate new batches. In parallel, surface-associated biofilms define the ecology and biochemistry of many solid-state fermentations. The ripening rinds of washed-rind cheeses, such as Limburger or Époisses, are landscapes of color and flavor engineered by successive waves of salt-tolerant yeast and bacterial (especially *Brevibacterium*) biofilms (Tran et al., 2020). These surface communities, encouraged by specific humidity and brushing regimes, create the characteristic pungent aromas

Table 1 Functional and comparative analysis of representative biofilm-driven food fermentations

Food product	Dominant biofilm type	Key microorganisms	Primary substrate	Sessile function	Process advantage	Comparative critical insight	References
Kombucha	Cellulose membrane (SCOBY)	*Komagataeibacter* spp., yeasts	Sweetened tea (sucrose)	Spatial organization of oxidation and metabolite exchange	Stable consortium and reusable inoculum	Strong coupling of aerobic–anaerobic metabolism; performance depends on pellicle thickness and oxygen diffusion	(Lynch et al., 2021)
Water kefir (tibicos)	EPS-rich granules	LAB,yeasts	Sugars, dried fruits	Protection of multispecies consortia	High resilience and rapid restart	Granular structure enhances microbial stability but composition varies between batches	(Lynch et al., 2021)
Milk kefir	Protein–polysaccharide grains	LAB, acetic acid bacteria, yeasts	Milk lactose	Lactose conversion and acidification	Stable symbiotic metabolism	Complex microbial interactions improve robustness but limit process standardization	(Farag et al., 2020; Wang et al., 2026)
Vinegar ("mother")	Cellulose surface biofilm	*Acetobacter*, *Komagataeibacter* spp.	Ethanol-containing liquids	Aerobic acetic acid production	Efficient oxygen utilization	Highly effective in continuous systems, but biofilm overgrowth may limit mass transfer	(Catarino et al., 2025)
Washed-rind cheeses	Surface-associated EPS biofilms	*Brevibacterium*, yeasts	Cheese matrix	Proteolysis and lipolysis	Controlled flavor development	Surface biofilms enable spatially controlled ripening, sensitive to environmental conditions (humidity, salinity)	(Ritschard & Schuppler, 2024)
Koji fermentation	Aerial mycelial biofilm	*Aspergillus oryzae*	Steamed grains	Enzyme secretion (amylases, proteases)	Efficient substrate hydrolysis	Represents highly optimized solid-state biofilm system with industrial scalability	(Ito & Matsuyama, 2021; Straka et al., 2025)
Sourdough starter	EPS-associated biofilms	LAB, yeasts	Cereal carbohydrates	Acidification and CO_2 productionstabilization	Long-term culture stability	Dynamic microbial equilibrium supports resilience but varies with flour type and process conditions	(Clark et al., 2024)

and textural development through extracellular proteolytic and lipolytic activity. In East Asian traditions, the cultivation of *Aspergillus oryzae* on steamed grains to produce *koji* involves the management of a vital aerial mycelial biofilm. The growth conditions temperature, moisture and aeration are meticulously controlled to optimize the fungal biofilm's production of amylases, proteases, and lipases, which then drive the subsequent fermentation into soy sauce, miso, or sake (de Melo et al., 2023). Collectively, these diverse traditions reveal a profound empirical understanding of biofilm function. Through trial and error over centuries, practitioners learned to manipulate substrate composition, temperature, acidity, oxygen exposure and physical handling to select for and maintain specific biofilm architectures and consortia (Sarker & Kaparaju, 2025). They intuitively harnessed the core advantages of the sessile state: creating spatially organized niches for sequential reactions, ensuring culture stability and resilience against invaders and developing reusable, self-immobilized catalysts. Thus, these traditional foods are not mere culinary artifacts; they are sophisticated pre-industrial prototypes of managed microbial ecosystems, offering invaluable insights for the rational design of modern sessile fermentation processes (Y. Zhang et al., 2025).

Mechanistic Basis of Sessile Fermentation

The functional superiority of sessile fermentation systems arises from a convergence of physical structure, biochemical regulation and microbial ecology that fundamentally distinguishes biofilms from planktonic cultures. In contrast to free-floating cells that experience relatively uniform environmental conditions, biofilms represent spatially organized, metabolically differentiated communities embedded within a self-produced extracellular matrix (Geng et al., 2019). This architecture transforms the fermentation environment from a homogeneous reaction vessel into a structured biocatalytic landscape, enabling emergent behaviors that directly influence fermentation kinetics, product composition, and system stability. These interlinked mechanisms underlying enhanced function in sessile fermentation are illustrated in Fig. 2 which depicts the coupled transport–reaction processes,

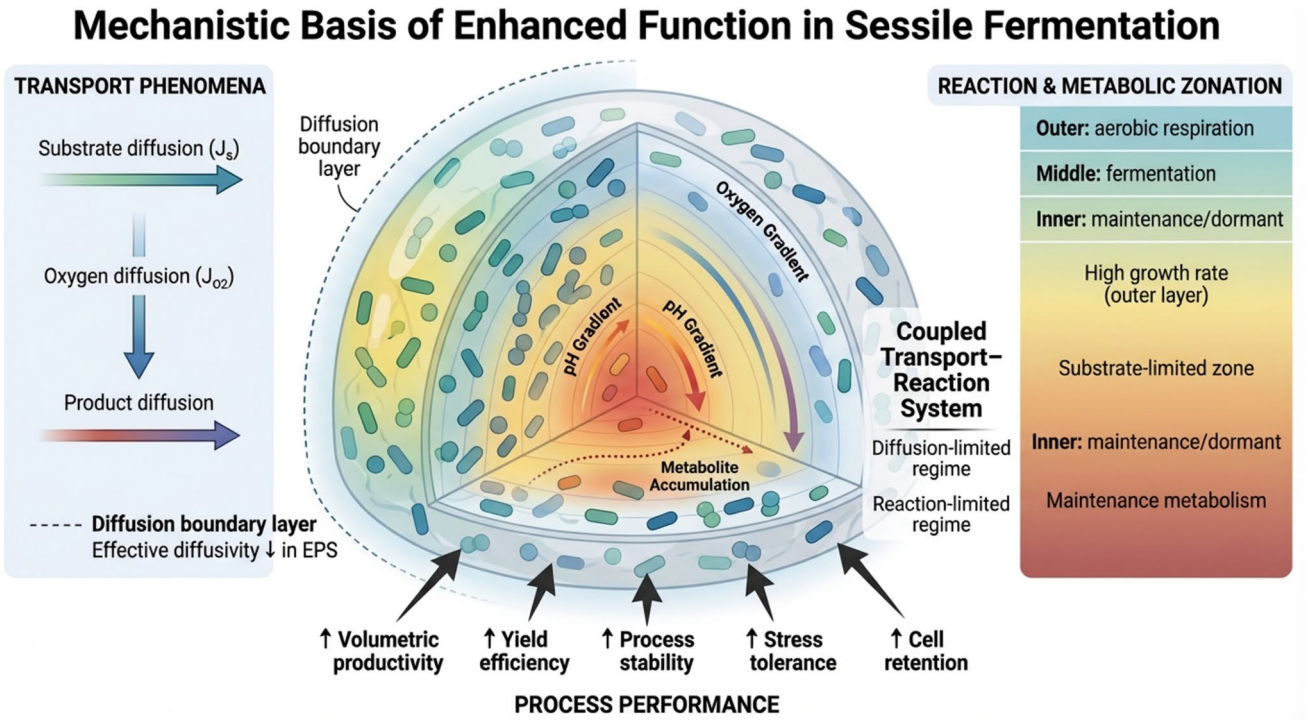


Fig. 2 Transport–reaction coupling and spatial metabolic organization governing enhanced performance in sessile fermentation systems. A mechanistic representation of a biofilm-based microbial consortium illustrating how coupled mass transfer and microbial kinetics determine fermentation performance. Substrate and oxygen diffusion into the biofilm generate physicochemical gradients that establish distinct metabolic zones, including an aerobic outer layer, a fermentative intermediate region and an anaerobic or inactive inner core. The extracellular polymeric substance (EPS) matrix imposes diffusion limitations, resulting in a coupled transport–reaction system where process rates are governed by both substrate flux and cellular activity. These gradients promote metabolic differentiation, cross-feeding and efficient substrate utilization within spatially organized microbial communities. The integrated system enhances volumetric productivity, yield, stress tolerance and operational stability compared to planktonic fermentation, providing a mechanistic foundation for rational design and optimization of sessile bioprocesses

spatial metabolic stratification and microbial interactions governing biofilm-based fermentation performance. Furthermore, Table 2 summarizes the key mechanisms responsible for the enhanced performance of sessile fermentation relative to planktonic fermentation systems. However, despite these mechanistic insights, current experimental studies remain fragmented across microbial ecology, systems biology and process engineering disciplines and there is still limited quantitative integration of biofilm-associated mechanisms into predictive fermentation models applicable to industrial food systems (Song et al., 2026). Furthermore, many existing studies rely on simplified laboratory-scale or single-species models, which may not fully capture the spatial, ecological and metabolic complexity of naturally occurring or industrial sessile fermentation environments (Cisneros et al., 2025).

Importantly, to clarify the conceptual positioning of sessile fermentation and avoid overlap with existing frameworks, it is essential to distinguish it from related but fundamentally different systems (Dar et al., 2021). Immobilized-cell systems rely on artificial carriers or entrapment matrices and primarily function through passive cell retention without intrinsic ecological organization. Engineered biofilm reactors are process systems designed to retain biomass under controlled hydrodynamic conditions, where biofilms are treated mainly as a functional growth state within engineered equipment (Wahalathanthrige et al., 2026). In contrast, sessile fermentation represents a self-organized, ecology-driven biocatalytic paradigm in which endogenous extracellular matrix formation, spatial microbial organization and functional metabolic zoning emerge naturally as intrinsic properties of the microbial community and directly determine process performance (Grasso, 2026). This distinction highlights sessile fermentation as an integrated framework combining microbial ecology, biofilm functionality and fermentation engineering, rather than simply a variation of immobilized-cell or biofilm reactor technologies.

The Biofilm Matrix as a Functional Architecture

At the core of sessile fermentation lies the extracellular polymeric substance (EPS) matrix, a composite network of polysaccharides, proteins, lipids and extracellular DNA. Far from being a passive scaffold, the matrix functions as an active biochemical interface between microorganisms and their environment (Sakalauskienė & Radzevičienė, 2025). By immobilizing cells in close proximity, the matrix facilitates high local cell densities while preventing washout, a feature particularly advantageous for continuous or low-nutrient fermentations. This immobilization enhanced reaction efficiency and volumetric productivity by increasing effective enzyme concentrations and reducing diffusion distances between metabolite producers and consumers (Gao et al., 2021). The EPS matrix also introduces diffusional resistance, which can be described using Fick's law, influencing substrate penetration and metabolite removal. According to Fick's first law, substrate flux within the biofilm can be expressed as:

$$J = -D\frac{dC}{dx}$$

where J represents diffusion flux, D is the effective diffusion coefficient within the biofilm matrix and $\frac{dC}{dx}$ is the concentration gradient across the biofilm thickness (Saifullah et al., 2019; van den Berg et al., 2020). In microbial biofilms, effective diffusion coefficients are commonly reported within the range of 10^{-9} to 10^{-10} m^2/s, depending on matrix density, hydration level and biofilm composition. Typical biofilm thickness in fermentation systems ranges from approximately 50 to 1000 µm, significantly influencing substrate penetration depth and metabolite transport efficiency (Aljuhani et al., 2025). This creates reaction diffusion coupling within the biofilm, a key parameter governing overall biocatalytic efficiency (Pinto et al., 2020).

The matrix also plays a critical role in nutrient capture and metabolite retention. Charged and hydrophobic components within the EPS can selectively bind substrates, metal ions and flavor precursors, effectively creating localized reservoirs that buffer against external fluctuations. Similarly, fermentation intermediates and secondary metabolites may be temporarily sequestered within the matrix, prolonging their availability for downstream metabolic conversions (Shen et al., 2023). These retention effects contribute to localized metabolite accumulation and enhanced biochemical conversion efficiency within biofilm-based reactor systems.

Beyond its biological function, the EPS matrix also represents an important engineering target in sessile fermentation systems. Matrix composition governs mechanical stability, permeability and interactions with substrates and metabolites, thereby directly influencing biofilm performance and process stability (Pinto et al., 2020). Rather than being treated as an uncontrolled byproduct, EPS production can be indirectly regulated through strain selection, nutrient composition and environmental conditions (Amaro et al., 2023). Controlled nutrient limitation, shear stress and hydration levels can be strategically manipulated to regulate biofilm density, thickness and diffusional properties, enabling dynamic tuning of metabolic efficiency while maintaining compatibility with food safety and clean-label requirements (Nair et al., 2025). This integrated perspective highlights the EPS matrix not only as a mechanistic foundation of sessile fermentation, but also as a practical design lever for industrial food bioprocessing systems (Djandja et al., 2026). Nevertheless, current understanding of EPS functionality remains largely derived from simplified laboratory-scale

Table 2 Key mechanisms underlying enhanced performance of sessile versus planktonic fermentation

Mechanism	Biofilm-specific feature	Functional outcome	Impact on fermentation performance	Comparison with planktonic systems	References
Spatial organization of cells	Structured microcolonies within matrix	Formation of metabolic niches	Supports coordinated and sequential metabolic reactions	Planktonic systems lack spatial stratification, limiting metabolic specialization	(Dal Co et al., 2023)
EPS formation	Polymer matrix embedding cells	Cell immobilization and protection	Enhances stability and retention of metabolites	Cells remain freely suspended and more prone to environmental fluctuations	(Chen et al., 2024)
Metabolite channeling	Reduced diffusion distances	Efficient cross-feeding interactions	Improves metabolic efficiency in mixed cultures	Higher loss of intermediates in bulk liquid phase	(Pareek et al., 2021)
Stress protection	Matrix buffering capacity	Resistance to environmental stress	Sustains activity under adverse conditions	Greater sensitivity to pH, ethanol and oxidative stress	(Lin et al., 2021; Liu et al., 2025)
Cell immobilization	Surface attachment or aggregation	High local biomass density	Supports repeated-batch and continuous processes	Lower biomass retention due to washout	(Zhang et al., 2024a, b)
Quorum sensing and local signaling	Signal accumulation at high cell density	Coordinated gene expression	Promotes synchronized metabolic responses	Signal dilution reduces coordination efficiency	(Naoun et al., 2022)
Controlled mass transfer gradients	Oxygen and nutrient gradients	Coexistence of diverse metabolic states	Enables simultaneous aerobic and anaerobic pathways	Homogeneous environment limits metabolic diversity	(Zheng et al., 2022)
Community stabilization	Spatial niche partitioning	Reduced competitive exclusion	Maintains multispecies stability	Competitive dominance more common in planktonic cultures	(Einum et al., 2026)

studies using single-species or highly controlled model systems (Zahra et al., 2024). Quantitative relationships between matrix heterogeneity, diffusional behavior and large-scale fermentation performance across diverse food matrices remain insufficiently characterized, limiting the development of predictive and standardized engineering frameworks for industrial sessile fermentation systems (Dębowski et al., 2026).

Microenvironment Formation and Metabolic Differentiation

One of the defining mechanistic features of biofilm-based fermentation is the establishment of microscale physicochemical gradients. Gradients in oxygen, pH, redox potential, and nutrient availability arise naturally within the biofilm due to limited diffusion and localized metabolic activity. Such gradients can be quantitatively described using diffusion–reaction models, where substrate consumption rates exceed diffusion rates, leading to stratified metabolic zones within the biofilm. A simplified diffusion–reaction relationship within biofilms can be expressed as:

$$D\frac{d^2C}{dx^2} - r(C) = 0$$

where D represents the diffusion coefficient and $r(C)$ denotes substrate consumption within the biofilm matrix (Usha et al., 2012). When microbial reaction rates exceed substrate diffusion rates, localized nutrient depletion and metabolic stratification occur, resulting in distinct functional zones within the sessile community. Oxygen penetration depth in dense microbial biofilms is often limited to approximately 100–300 µm, depending on biofilm density and metabolic activity (Jones et al., 2025). Rather than representing a limitation, these gradients enable metabolic stratification, where distinct microbial subpopulations specialize in complementary biochemical functions (Jo et al., 2022).

In mixed-species fermentations, such stratification stabilizes cross-feeding interactions, allowing, for example, primary fermenters to generate substrates that are immediately consumed by secondary metabolizers within adjacent biofilm layers. This spatial organization minimizes competitive exclusion and promotes cooperative metabolism, resulting in higher overall conversion efficiency and reduced accumulation of inhibitory byproducts (Culp & Goodman, 2023). In fungal–bacterial biofilm reactor systems, fungal hydrolytic activity may additionally supply intermediate metabolites that support adjacent bacterial populations, reinforcing cooperative nutrient exchange within the biofilm matrix (López-García et al., 2025). Fungal hyphae and extracellular enzymes facilitate the localized release of sugars, amino acids and other intermediate metabolites, which are subsequently utilized by bacteria occupying adjacent microenvironments within the biofilm matrix (Joshi et al., 2026). Such spatially coordinated metabolic interactions create synergistic nutrient exchange networks that are difficult to reproduce in homogeneous planktonic systems, where rapid dilution and limited cellular proximity often disrupt stable cross-kingdom interactions (Joshi et al., 2026).

Importantly, the spatial arrangement of sessile communities also contributes to the reduction of metabolic inhibition during fermentation. Localized substrate channeling and sequential metabolite consumption within adjacent biofilm layers prevent the excessive accumulation of inhibitory intermediates, organic acids and reactive metabolites that may otherwise impair microbial growth and fermentation efficiency (Yao et al., 2022). This self-organized metabolic compartmentalization enhances community stability, supports sustained cooperative metabolism and improves overall process resilience under dynamic fermentation conditions (Gopalakrishnappa et al., 2022). From a process design perspective, these features suggest that biofilms inherently perform functions analogous to multi-stage reactors within a single, self-assembled structure. However, a key limitation in current research is the difficulty of experimentally validating spatial metabolic models in complex, multi-species food fermentations, leading to uncertainties in translating microscale gradient theories into industrial-scale process predictions.

Enhanced Stress Tolerance and Functional Resilience

Sessile fermentation systems consistently exhibit superior tolerance to environmental stresses compared to their planktonic counterparts. The EPS matrix provides a physical barrier that moderates exposure to heat, acidity, osmotic stress and antimicrobial compounds. Additionally, the biofilm lifestyle induces physiological adaptations, including altered membrane composition, stress-responsive gene expression and slowed growth rates, all of which contribute to enhanced survival and persistence (Bircher et al., 2020). From a process engineering standpoint, this enhanced resistance reduces process variability and improves operational robustness under fluctuating environmental conditions (Tinajero et al., 2025).

This resilience has direct implications for food fermentation, particularly in minimally processed or low-input systems where environmental control is limited. Biofilm-based fermentations are less prone to collapse under suboptimal conditions and demonstrate functional stability across repeated production cycles (Nahum et al., 2025). The ability to reuse biofilm biomass without the need for frequent reinoculation further enhances process efficiency and reduces production costs, aligning sessile fermentation with principles of sustainable bioprocessing. Comparative analyses further indicate that

biofilm reactor systems generally exhibit improved biomass retention, operational stability and stress resistance relative to planktonic fermentation systems, as illustrated in Fig. 3 which compares the functional and operational characteristics of biofilm-based and planktonic fermentation processes.

Quorum Sensing and Coordinated Metabolic Control

Beyond physical structure, biofilms are defined by sophisticated regulatory networks that coordinate collective behavior. Quorum sensing (QS) systems enable microorganisms to synchronize gene expression in response to population density and environmental cues, regulating processes such as enzyme production, matrix synthesis and secondary metabolite formation. In sessile fermentation, QS-mediated coordination contributes to temporal control over fermentation stages, allowing microbial communities to dynamically adjust metabolic outputs in response to substrate depletion or stress (Sadr et al., 2025).

This coordinated regulation contrasts sharply with planktonic systems, where population-level synchronization is weaker and more susceptible to stochastic variation. By stabilizing metabolic trajectories, QS enhances reproducibility and predictability qualities that are essential for industrial food production yet often challenging to achieve in complex fermentations (Gregory & Boyd, 2021).

Implications for Rational Process Design

Collectively, these mechanistic features position biofilms not merely as dense microbial aggregates, but as integrated biocatalytic systems whose performance emerges from structure–function relationships. Understanding sessile fermentation through this mechanistic lens enables a shift from empirical optimization toward rational design. By manipulating surface properties, matrix composition and microbial community structure, it becomes possible to stable and reproducible fermentation performance with a level of precision that remains elusive in planktonic systems (Xiong et al., 2024).

Importantly, these mechanisms provide the biological justification for reimagining fermentation infrastructure,

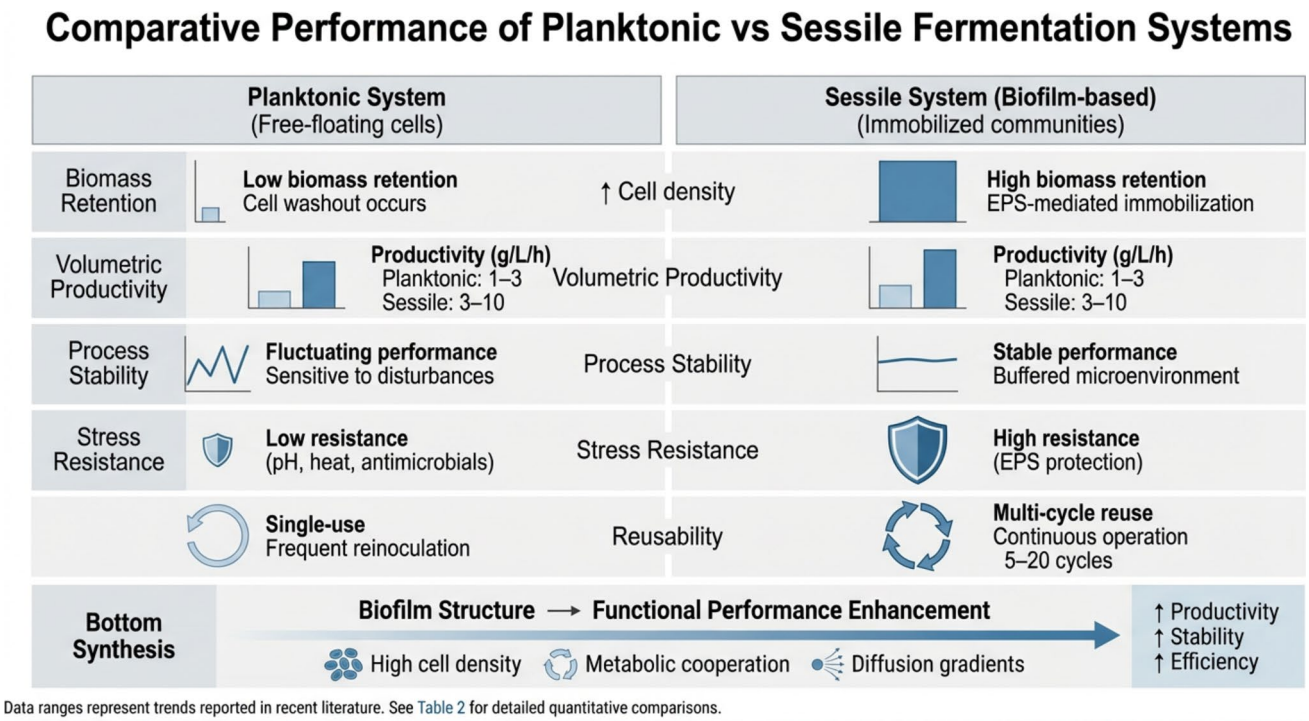


Fig. 3 Comparative performance analysis of planktonic and sessile fermentation systems across key bioprocess metrics. The figure presents a semi-quantitative comparison of planktonic and sessile (biofilm-based) fermentation systems across critical performance indicators, including biomass retention, volumetric productivity, process stability, stress resistance and reusability. Sessile systems demonstrate enhanced performance due to cell immobilization within the extracellular polymeric substance (EPS) matrix, enabling higher cell density, reduced washout and improved metabolic cooperation. The schematic further highlights the role of diffusion–reaction coupling, spatial metabolic stratification, and reactor-scale transport interactions in governing biofilm functionality and process efficiency. In addition, hydrodynamic regulation and controlled mass transfer are illustrated as key engineering factors influencing substrate diffusion, metabolite exchange, and long-term operational stability within sessile fermentation systems. These features result in increased productivity, operational stability and resilience under environmental stress. Approximate performance ranges are included based on representative literature trends, with detailed data provided in Table 2

starter culture formulation and control strategies. Sessile fermentation thus represents a broader conceptual expansion of microbial process engineering in food and bioprocessing systems (Siddiqui et al., 2023).

Engineering Principles of Sessile Fermentation Systems

Sessile fermentation systems can be understood through classical chemical and biochemical engineering frameworks. Unlike planktonic systems, biofilm reactors are governed by coupled mass transfer and reaction kinetics (Chen et al., 2024). Substrate flux into the biofilm can be expressed as a function of diffusion coefficients and concentration gradients, while microbial growth follows modified Monod kinetics constrained by diffusion limitations (Pérez & Picioreanu, 2025). Microbial growth within biofilm reactor systems can be represented using modified Monod kinetics:

$$\mu = \mu_{\max} \frac{S}{K_s + S}$$

where μ is the specific growth rate, $\mu_{\max}$ is the maximum growth rate, S is substrate concentration and K_s is the half-saturation constant (Ribes et al., 2004). Under dense biofilm conditions, effective substrate utilization is strongly influenced by diffusional resistance within biofilm layers typically ranging from 100 to 1000 µm in thickness (Lakshminarasimman et al., 2025). Hydrodynamic conditions play a critical role, as shear stress influences biofilm thickness, detachment rates, and structural stability. Low shear promotes thick biofilms with diffusion limitations, whereas high shear enhances mass transfer but may reduce biomass retention (Krsmanovic et al., 2021). Typical shear stress values reported in biofilm reactors range from approximately 0.01 to 10 Pa, depending on reactor configuration and flow conditions (Garcia et al., 2022).

Dimensionless numbers such as the Reynolds number and Sherwood number can be used to characterize flow regimes and mass transfer efficiency in biofilm reactors. The Reynolds number is commonly used to characterize hydrodynamic flow conditions:

$$Re = \frac{\rho u L}{\mu}$$

where ρ is fluid density, u is flow velocity, L is characteristic length and μ is fluid viscosity (Qi et al., 2022). Laminar flow conditions commonly observed in food biofilm systems generally occur at $Re < 2000$. Mass transfer efficiency can additionally be evaluated using the Sherwood number:

$$Sh = \frac{kL}{D}$$

where k is the mass transfer coefficient and D is the diffusion coefficient (Wang et al., 2020). Higher Sherwood numbers indicate enhanced substrate transport and improved metabolite exchange across the biofilm interface (Southwell et al., 2023). These parameters are essential for scaling up sessile fermentation processes from laboratory to industrial systems (Cappello, 2020). Despite these established engineering frameworks, a major gap remains in integrating classical transport models with dynamic, evolving biofilm architectures, which limits accurate scale-up prediction and real-time process control in sessile fermentation systems.

Engineering Functional Sessile Systems

While traditional food fermentations demonstrate the inherent functional advantages of biofilms, translating sessile fermentation into a controllable and scalable process requires deliberate engineering. Engineering functional biofilm reactor systems extends beyond promoting microbial attachment; it involves the coordinated design of surfaces, microbial consortia, extracellular matrix properties and process conditions to achieve predictable, reproducible, and safe fermentation outcomes (Carrascosa et al., 2021). Unlike conventional immobilized-cell technologies that primarily focus on passive cell retention, sessile fermentation emphasizes self-organized biofilm development, endogenous matrix production and dynamic microbial interactions that collectively determine system functionality and metabolic performance (Liang et al., 2020). This section outlines the key engineering principles that transform biofilms from spontaneous biological structures into reliable food and bioprocessing platforms. An integrated framework summarizing these engineering dimensions is presented in Fig. 4 which illustrates the coordinated roles of surface engineering, microbial consortium design, matrix tuning, reactor integration and real-time monitoring in the development of functional biofilm-based fermentation systems.

Surface and Substrate Engineering

Surface properties play a decisive role in biofilm initiation, architecture and long-term stability. Parameters such as roughness, porosity, hydrophobicity, and surface chemistry influence microbial adhesion and spatial organization. Historically, food fermentations have relied on natural substrates, cellulose matrices, cereal grains, plant tissues and protein-rich surfaces which provide both physical support and metabolic compatibility (Muhammed et al., 2025). Modern materials science enables rational surface design using food-grade polymers, biopolymers and functionalized carriers. Porous and structured materials increase effective surface area and facilitate microenvironment formation,

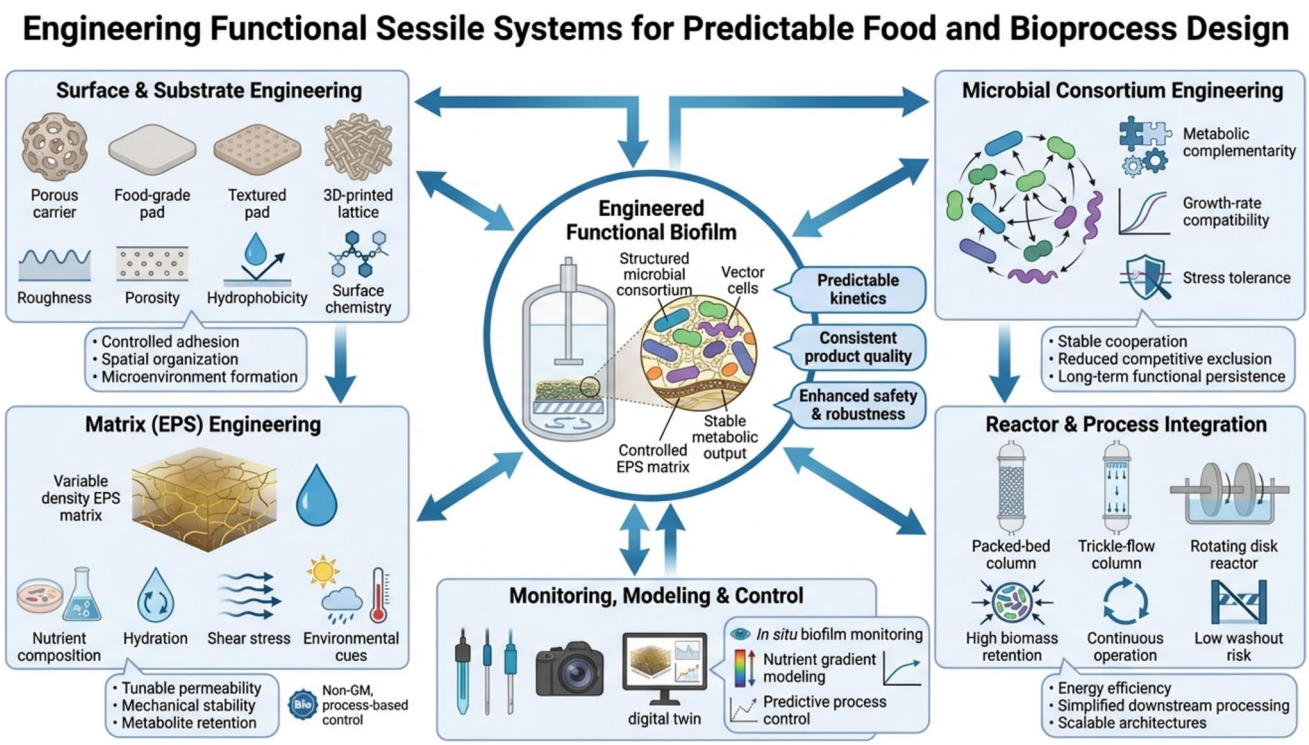


Fig. 4 An integrated framework for engineering functional biofilm-based fermentation. This systems-engineering schematic presents a modular approach to designing predictable sessile bioprocesses. The central engineered functional biofilm represented as a spatially organized microbial consortium embedded within a controlled extracellular matrix, is optimized through five interacting modules: (1) Surface engineering for directed adhesion, (2) Microbial consortium design for stable cooperation, (3) Matrix tuning for tailored permeability and stability, (4) Reactor integration for continuous operation and (5) Real-Time monitoring and modeling for control and reproducibility. The framework further illustrates the integration of diffusion–reaction interactions, hydrodynamic regulation, feedback control systems and reactor-scale transport phenomena as critical engineering parameters governing biofilm stability, metabolic performance, and long-term operational efficiency. Together, this framework shifts biofilm management from a persistent challenge to a foundation for robust, scalable and consistent fermentation processes

while chemical modification can selectively promote attachment of desirable microorganisms. Emerging tools such as 3D-printed scaffolds and biodegradable supports allow precise control over biofilm geometry and mass transfer, offering modular and scalable solutions for sessile fermentation systems (Ma et al., 2024). In sessile fermentation, however, these materials function not merely as passive immobilization supports but as engineered microenvironments that facilitate self-organized biofilm maturation, endogenous EPS development and spatially coordinated microbial interactions (Júnior et al., 2026). Importantly, sessile fermentation systems may also emerge through self-supporting biological structures without reliance on artificial carriers. Naturally formed cellulose pellicles, fungal mycelial networks and grain-associated biofilm matrices can function as self-organized structural frameworks that simultaneously provide mechanical stability, nutrient accessibility, and ecological organization within the fermentation environment (Venturelli et al., 2025; Wang et al., 2024). Such systems better reflect the fundamental sessile fermentation concept, where endogenous matrix production and microbial self-assembly collectively drive spatial organization and process functionality (Guzmán-Soto et al., 2021). These advances are particularly relevant for industrial application in food manufacturing systems requiring consistent and scalable biofilm formation. However, despite these advantages, engineered surfaces may also introduce operational trade-offs. Excessively dense biofilm formation on highly porous or rough substrates can increase diffusional resistance, reduce oxygen penetration and promote heterogeneous metabolite distribution within the sessile matrix (Saba et al., 2024). In addition, prolonged operation may lead to surface fouling, uneven colonization and difficulties in cleaning and sanitation, particularly in food-grade continuous processing systems. Such challenges may ultimately compromise process reproducibility and increase batch-to-batch variability under industrial operating conditions (Ashok et al., 2023).

In the context of solid-state fermentation (SSF), the design of sessile fermentation systems requires additional consideration of substrate structure, moisture distribution and oxygen diffusion within low-water-activity environments (Nussbaum et al., 2025). Unlike liquid-phase systems,

SSF relies on solid matrices that simultaneously function as nutrient sources and physical scaffolds for microbial colonization. Porous agricultural substrates, cereal-based materials and fibrous plant matrices facilitate fungal hyphal attachment and spatially organized bacterial colonization, thereby promoting stable sessile community formation (Browner & Adamatzky, 2025; Gerber et al., 2026). Substrate particle size, porosity and water-holding capacity critically influence local microenvironment formation, heat transfer, and metabolite diffusion within SSF systems (He et al., 2019). Beyond surface adhesion, the internal microporous architecture of solid substrates also plays a critical role in governing oxygen transfer, heat dissipation and spatial heterogeneity within SSF-based biofilms (Wang et al., 2018). Interconnected pore networks create localized diffusion pathways and microscale ecological niches that support uneven distributions of moisture, nutrients and metabolic activity throughout the sessile matrix (Borer et al., 2018). Such heterogeneous microenvironments influence fungal hyphal penetration, bacterial localization and metabolite exchange, thereby shaping the structural and functional organization of biofilm communities within solid substrates (Guo et al., 2024).

Furthermore, rational engineering of SSF-based biofilm reactor systems should consider spatial heterogeneity and controlled aeration to maintain metabolic activity across the solid matrix. Structured substrates and layered biofilm architectures can improve oxygen penetration while reducing localized metabolite accumulation and diffusional limitations (Ghosh et al., 2021). Such design strategies are particularly important in fungal–bacterial fermentations, where spatial organization enhances cooperative metabolism, substrate accessibility and process stability (Tong et al., 2026). These characteristics highlight the importance of integrating material engineering and microenvironment control when designing sessile fermentation platforms for solid-state food bioprocessing applications (Shen et al., 2025). However, comparative studies between natural self-assembled biofilms and engineered carrier-based systems remain limited, making it difficult to conclusively determine whether material design or microbial self-organization plays the dominant role in process stability across different fermentation contexts.

Engineering Microbial Consortia

Functional sessile fermentation is inherently a community-level phenomenon. Biofilm-based fermentations typically involve multispecies consortia in which microorganisms occupy distinct spatial and metabolic niches. Engineering such systems require an ecological rather than strain-centric approach, emphasizing metabolic complementarity, growth-rate compatibility and stress resilience (Joshi et al., 2021).

Synthetic microbial ecology provides tools to assemble stable consortia through rational strain selection and controlled co-cultivation. Within biofilms, spatial segregation and matrix-mediated immobilization reduce competitive exclusion and stabilize cooperative interactions such as cross-feeding (Liang et al., 2022). As a result, engineered sessile consortia can maintain functionality over extended fermentation cycles and, in some systems, may outperform planktonic co-cultures in stability and consistency. However, these benefits remain highly dependent on community composition, nutrient availability and reactor conditions. Complex multispecies biofilms may also exhibit unstable population dynamics, local nutrient competition, and heterogeneous metabolite production, particularly during long-term industrial operation. Furthermore, maintaining reproducible microbial balance across repeated fermentation cycles remains a major challenge for large-scale sessile fermentation systems.

Matrix Engineering as a Design Lever

As discussed in "The Biofilm Matrix as a Functional Architecture" section, the extracellular polymeric substance (EPS) matrix serves not only as a structural component of sessile fermentation systems but also as an engineerable parameter influencing biofilm stability, permeability and metabolic performance (Blanco-Romero et al., 2024).

Therefore, process-level regulation of matrix properties through strain selection, nutrient composition and environmental control remains an important strategy for optimizing sessile fermentation efficiency while maintaining compatibility with food safety and clean-label requirements (Shen et al., 2025). For example, controlled nutrient limitation and carbon-to-nitrogen ratio adjustment can alter EPS density and permeability, while moderate shear stress may promote the formation of mechanically stable biofilms with improved mass transfer characteristics (Singh et al., 2026). In addition, controlled modulation of EPS density and composition can improve mass transfer characteristics, regulate biofilm thickness and enhance resistance to environmental fluctuations, thereby supporting stable long-term operation in industrial sessile fermentation systemsecs (Fitsum et al., 2025). Despite these advantages, excessive EPS accumulation may negatively affect mass transfer by limiting substrate diffusion and oxygen penetration into deeper biofilm layers. Dense matrix formation can additionally complicate process monitoring, cleaning efficiency and reactor control, particularly in continuous fermentation systems where biofilm overgrowth and partial detachment may occur simultaneously. These trade-offs highlight the importance of balancing biofilm stability with transport efficiency during sessile process optimization.

Reactor and Process Integration

The practical implementation of sessile fermentation depends on its integration into suitable process architectures. Biofilm-based reactors, including packed-bed, trickle-flow, rotating surface and membrane-associated systems, enable high biomass retention and continuous operation. Biofilm-based reactors such as packed-bed reactors, fluidized-bed systems and rotating biological contactors provide distinct advantages in biomass retention and continuous operation. Compared to suspended-cell systems, these reactors enable higher cell densities, improved volumetric productivity and reduced washout risks (Espinosa-Ortiz et al., 2023). Compared with stirred-tank fermenters, biofilm reactor systems can provide lower energy input, reduced washout risk and improved biomass retention under optimized conditions (Gunes, 2021). However, these advantages are not universal and often depend strongly on reactor configuration, flow regime and biofilm architecture. Trade-offs associated with biofilm reactor systems include biofilm overgrowth, diffusional limitations, uneven metabolite distribution, and increased reactor fouling during prolonged operation.

Engineering challenges center on managing mass transfer and biofilm overgrowth. Excessive thickening can lead to diffusion limitations, while detachment events may compromise process stability. Process design must consider residence time distribution, mass transfer coefficients, flow regime (laminar vs turbulent) and biofilm thickness control (Al-Sharify et al., 2025). Excessive biofilm thickening may create inactive or nutrient-depleted zones that reduce metabolic efficiency and contribute to heterogeneous product formation. Likewise, uncontrolled detachment events can destabilize reactor performance, increase downstream contamination risk and generate batch variability (Samrot et al., 2021). Sessile fermentation systems may also require longer startup periods for stable biofilm establishment compared with conventional suspended-cell fermentations, potentially limiting short-cycle industrial applications (Sha et al., 2022). Advanced reactor designs increasingly incorporate flow control, surface renewal and modular components to maintain optimal biofilm performance (Gao et al., 2025). Importantly, sessile bioreactors should not be viewed solely as biomass-retention systems analogous to classical immobilized-cell reactors. Instead, they are designed to support spatially organized microbial ecosystems characterized by adaptive biofilm maturation, matrix-mediated interactions and localized metabolic differentiation (Han et al., 2022). Accordingly, future reactor configurations should increasingly support autonomous biofilm structuring and self-maintained ecological organization rather than relying exclusively on artificial attachment carriers (González-Juárez et al., 2026). These developments support the industrial applicability of sessile fermentation systems, particularly for complex or high-value food products. Nevertheless, large-scale implementation remains challenging due to difficulties in maintaining uniform shear conditions, oxygen transfer and spatial microbial organization across industrial reactors. Scale-up inconsistencies, cleaning and sanitation constraints and the potential persistence of undesirable or pathogenic microorganisms within mature biofilms continue to represent important barriers to widespread industrial adoption (Imran et al., 2025). Such reactor configurations are highly relevant for industrial application in continuous food manufacturing systems. For solid-state fermentation systems, sessile reactor design requires additional emphasis on aeration, moisture regulation and spatial heat management within densely colonized solid matrices (Jin et al., 2026). Unlike submerged biofilm reactors, SSF-based biofilm reactor systems often depend on tray, packed-bed, or rotating drum configurations that facilitate oxygen transfer while minimizing excessive moisture accumulation and thermal gradients. Controlled airflow distribution and substrate layering are essential to maintain stable microbial activity and prevent localized overheating or anaerobic zone formation within the sessile matrix (Al-Sharify et al., 2025; Shanmugam et al., 2022).

In fungal-dominated SSF systems, reactor architecture must also accommodate hyphal penetration, substrate accessibility and gradual nutrient diffusion across the solid support. Modular packed-bed and rotating solid-support reactors can enhance surface colonization while preserving spatially organized microbial interactions characteristic of sessile fermentation (da Silva et al., 2018; Sugai-Guérios et al., 2016). These reactor strategies improve metabolic stability, reduce inhibitory metabolite accumulation and support long-term operational performance, thereby providing a more suitable engineering framework for translating sessile fermentation concepts into industrial solid-state food bioprocessing systems (Gómez-Ramos et al., 2024). Nevertheless, current reactor designs are still largely adapted from wastewater and bioprocess engineering, and their direct applicability to food-grade sessile fermentation systems remains insufficiently validated under long-term industrial operating conditions.

Monitoring, Modeling and Control

Reliable engineering of sessile fermentation requires tools to observe and predict biofilm behavior in situ. Advances in noninvasive imaging, microsensors and omics technologies have improved understanding of spatially resolved metabolism within biofilms. Mathematical modeling of biofilm reactor systems is essential for predictive control. Diffusion–reaction models, computational fluid dynamics (CFD), and biofilm growth kinetics can be integrated to simulate reactor performance (Dzianach et al., 2019). When

combined with computational modeling, these data enable simulation of nutrient gradients, metabolic fluxes and community dynamics (Sanches et al., 2024).

Such integrative approaches support the transition from empirical optimization to predictive control, a key requirement for industrial adoption, including predictive modeling and simulation of biofilm-based fermentation systems. Advanced sensing technologies, including biosensors and real-time imaging, can enable dynamic monitoring of biofilm activity and structural evolution. As digitalization and process analytics become increasingly embedded in food manufacturing, sessile fermentation systems are well positioned to benefit from data-driven optimization and real-time control strategies (Coppola et al., 2025). These tools are essential for process control and optimization in large-scale industrial fermentation systems. Real-time detection and spatial tracking of pathogenic or antimicrobial-resistant populations within dense multispecies biofilms remain technically challenging, particularly under industrial operating conditions (Maroju et al., 2026). However, despite rapid progress in biosensing and computational modeling, real-time validation of spatial biofilm models in industrial food fermentation remains limited and significant uncertainty persists in linking model predictions with actual product quality and microbial stability at scale.

Safety and Regulatory Considerations by Design

Unlike environmental or clinical biofilm systems, food-related biofilm reactor systems must meet stringent safety and regulatory standards. Engineering strategies must therefore prioritize pathogen exclusion, genetic stability and reproducibility. Selective surfaces, defined starter consortia, competitive exclusion principles and controlled process boundaries are essential to minimizing risk (Zheng et al., 2025).

Importantly, deliberately engineered biofilms offer greater safety control than unmanaged spontaneous biofilm formation. Framing sessile fermentation as a designed and monitored process aligns innovation with regulatory expectations and consumer trust, facilitating translation from laboratory concepts to commercial food production (Mukherjee & Cao, 2020). This alignment is critical for regulatory approval and adoption in industrial food processing environments. Despite these advances, sessile fermentation systems also raise important biosafety concerns. Persistent biofilm formation on food-contact surfaces may increase resistance to cleaning and disinfection procedures, while unintended colonization by spoilage organisms or opportunistic pathogens may compromise product safety and process reliability. The EPS matrix may further protect embedded microorganisms from environmental stresses and sanitizer exposure, thereby increasing the persistence of undesirable microbial populations within mature biofilms (Wang et al., 2021). In addition, the close spatial proximity of microorganisms within sessile communities may facilitate horizontal gene transfer, including the dissemination of antimicrobial resistance and stress-adaptation genes (Ban-Cucerzan et al., 2025). Consequently, long-term industrial implementation requires rigorous monitoring, sanitation validation and standardized regulatory frameworks to ensure safe and reproducible operation. Future sessile fermentation systems should therefore incorporate risk assessment frameworks integrating HACCP-based monitoring, molecular surveillance and real-time microbial tracking to improve early detection of contamination events and enhance biosafety management during industrial-scale operation.

Applications in Food and Bioprocessing

Sessile fermentation provides a unifying framework that links traditional food fermentations with emerging bioprocess technologies. By exploiting the structural organization and metabolic advantages of biofilm-associated microbial communities, biofilm reactor systems enable production strategies that exceed the functional limits of planktonic cultures (Fonseca et al., 2022). Their applications extend across food fermentation, ingredient production, bio-preservation and sustainable bioprocessing. These systems also contribute to improved product quality and extended shelf-life through enhanced microbial stability and controlled metabolite production (Table 3). Comparative applications and technological relevance of sessile fermentation systems in food and bioprocessing illustrates these diverse applications and their industrial significance.

Traditional Fermented Foods as Naturally Optimized Sessile Systems

Many established fermented foods function as inherently stable sessile fermentation platforms. Biofilm consortia such as kombucha SCOBYs, vinegar mothers, kefir grains and surface-ripened cheeses operate as self-immobilized microbial reactors, supporting sustained metabolic activity and consistent product quality. The matrix-mediated organization of these systems enhances microbial persistence, buffers environmental stress and stabilizes fermentation performance (Aung & Kim, 2024).

Reframing these traditional products through a sessile fermentation lens enables scientific rationalization of their robustness and sensory complexity. This perspective supports improved process control and standardization while preserving the microbial diversity and functional traits that define artisanal fermented foods (Alhosry et al., 2026).

Table 3 Comparative applications and technological relevance of sessile fermentation systems

Application area	Biofilm format	Target product	Key advantage	Technology readiness level (TRL)	Process and industrial relevance	References
Traditional fermented beverages	Free-floating cellulose or EPS biofilms	Organic acids, ethanol, bioactives	Culture stability and reuse	8–9 (commercial)	Highly robust systems with established scalability, though microbial composition may vary between batches	(Khatun & Ray, 2024; Vermelho et al., 2025)
Vinegar production	Surface-associated cellulose biofilm	Acetic acid	Efficient oxygen utilization	9 (industrial standard)	Widely implemented in continuous reactors; performance influenced by oxygen transfer and biofilm thickness	(Catarino et al., 2025; Sriphochanart et al., 2024)
Cheese ripening and surface fermentation	Surface biofilms on solid substrates	Flavor and texture compounds	Controlled enzymatic modification	8–9 (commercial)	Process strongly dependent on environmental parameters (humidity, temperature), requiring tight control	(Coelho et al., 2022; Ritschard & Schuppler, 2024)
Koji-based fermentations	Mycelial biofilm on grains	Hydrolytic enzymes	High enzyme secretion efficiency	8–9 (commercial)	Represents optimized solid-state fermentation with high industrial reproducibility	(Somadder et al., 2025)
Starter culture immobilization	Self-organized sessile biofilms on engineered supports	Lactic acid fermentation	Reduced cell loss and improved stability	6–7 (pilot scale)	Promising for industrial scale-up, but carrier material and reactor design remain critical factors	(Sadeghi et al., 2024)
Functional ingredient production	Engineered multispecies biofilms	EPS, vitamins, organic acids	Enhanced metabolic cooperation	5–6 (pilot scale)	Emerging approach with potential for yield improvement, though system control remains challenging	(Schmeckebier et al., 2022; Son et al., 2025)
Continuous food bioprocessing	Self-organized sessile bioreactors	Fermented intermediates	Sustained productivity	4–6 (emerging)	Offers potential for process intensification, but biofilm control and fouling remain key challenges	(Gunes, 2021; Tiso et al., 2024)
Precision fermentation platforms	Structured sessile ecosystem platforms	High-value food ingredients	Spatial metabolic control	3–4 (early-stage)	Represents future direction with high design flexibility but currently limited scalability	(Lu et al., 2024; Malos et al., 2025)

Unlike conventional immobilized-cell technologies focused primarily on passive biomass retention, sessile fermentation systems emphasize self-organized biofilm development, endogenous matrix formation and dynamic ecological interactions that collectively influence metabolic functionality and process stability

Biofilm-Based Immobilized Cell Reactors and Continuous Fermentation

Sessile fermentation offers a biologically self-assembled alternative to conventional immobilized cell technologies. Biofilm-based reactors maintain high cell densities and prolonged biomass retention without synthetic carriers, enabling continuous or semi-continuous operation. These systems are particularly advantageous for the production of organic acids, enzymes, fermented beverages and functional ingredients requiring stable productivity over extended timeframes (Lago et al., 2024).

Compared to planktonic batch processes, sessile reactors often demonstrate enhanced volumetric productivity, reduced startup times and improved tolerance to operational perturbations. These attributes align with current industrial priorities, including process intensification, reduced downtime and lower resource inputs (Kifor et al., 2023).

Sensory and Functional Quality Enhancement

The spatial and metabolic heterogeneity characteristic of biofilms directly shapes the chemical complexity of fermented products. Sessile fermentation promotes localized enzyme accumulation and sequential metabolic transformations, enabling flavor and aroma development that is difficult to replicate in homogeneous liquid cultures. This is particularly relevant for fermented foods where depth of sensory profile is a key quality attribute (Zhao et al., 2023).

In addition, biofilm-associated exopolysaccharides contribute to texture modification, enhancing viscosity, mouthfeel and structural stability. As a result, biofilm reactor systems provide integrated control over both biochemical conversion and physical properties of the final product, offering a multifunctional approach to quality design (Lahiri et al., 2023). The integration of artificial intelligence (AI), digital twins, and in-situ sensing technologies may further enhance process precision in sessile fermentation systems characterized by spatial heterogeneity (Yee et al., 2025). AI-assisted analysis of real-time sensor data, including localized pH, oxygen and moisture gradients, can support predictive modeling and adaptive feedback control under non-uniform biofilm conditions (Cai et al., 2025). Such approaches enable dynamic adjustment of operational parameters, including aeration, hydration and flow conditions, thereby improving process stability, product consistency and overall fermentation performance in complex sessile systems.

Bio-Preservation and Ecological Pathogen Control

Sessile fermentation systems inherently support bio-preservation by establishing stable microbial niches that suppress undesirable microorganisms. Biofilm consortia can exclude pathogens and spoilage organisms through nutrient competition, acidification, and the localized production of antimicrobial compounds. Unlike post-processing interventions, these protective effects are embedded within the fermentation ecosystem (Zanzan et al., 2024).

Such in situ bio-preservation strategies are especially relevant for minimally processed and clean-label foods, where chemical preservatives and intensive thermal treatments are increasingly avoided. Sessile fermentation thus enables safety-by-design approaches that integrate product quality and microbial control (Fliss et al., 2025).

Probiotic and Postbiotic Production and Delivery

Biofilm-based fermentation systems offer emerging opportunities for functional food development. Biofilm-associated probiotic cells often exhibit enhanced stress tolerance, improving survival during processing, storage and gastrointestinal transit. The biofilm matrix itself can function as a natural encapsulation system, supporting controlled release and improved functional efficacy (Rezaei et al., 2023).

Sessile fermentation also facilitates efficient postbiotic production, enabling the accumulation of bioactive metabolites such as organic acids, peptides and polysaccharides. These compounds can be incorporated into food matrices without the regulatory and safety challenges associated with live microorganisms, expanding the functional ingredient toolbox (Hsiao et al., 2022).

Sustainable Processing and Waste Valorization

The resilience and metabolic versatility of sessile fermentation systems make them well suited for the conversion of low-value or heterogeneous substrates. Biofilm consortia can tolerate variable feedstock composition and inhibitory compounds, enabling the valorization of food processing side streams into value-added ingredients and biochemicals (Kumar & Eswari J, 2023).

This capacity positions sessile fermentation as a key enabling technology for circular food systems. By integrating biofilm-based processes into existing production chains, manufacturers can enhance sustainability while maintaining economic viability (Nguyen et al., 2025).

Scale-Up and Commercial Translation: Navigating the Valley of Death

The translation of sessile fermentation from laboratory-scale demonstrations to industrial food and bioprocessing remains limited by technical, operational and regulatory challenges. Unlike planktonic systems, biofilm-based processes require deliberate management of spatial organization, microbial

ecology and mass transfer, necessitating a fundamental shift in process design philosophy (Kim et al., 2022). A translational pathway outlining the key technical, regulatory and economic milestones for industrial adoption of engineered sessile fermentation is presented in Fig. 5 which illustrates the progression from laboratory-scale development to commercial deployment alongside the major scale-up challenges, mitigation strategies and regulatory requirements associated with biofilm-based fermentation systems. A primary constraint in scaling sessile fermentation is the control of mass transfer within structured biofilms. While biofilm architecture enhances nutrient retention and metabolic efficiency, excessive thickness can generate diffusion limitations, leading to metabolic heterogeneity and reduced process predictability (Saini et al., 2023). Industrial-scale systems must therefore balance biofilm stability with controlled renewal through strategies such as regulated shear forces, modular surface designs, or staged biofilm growth zones.

(Fathima et al., 2024). Scale-up of sessile fermentation systems presents unique engineering challenges. Biofilm heterogeneity across industrial reactors may generate localized gradients in oxygen, nutrients and metabolite accumulation, resulting in uneven microbial activity and variable product formation (Oguntomi et al., 2026). In addition, biofilm detachment dynamics are strongly influenced by hydrodynamic shear stress and matrix mechanical stability, where uncontrolled sloughing events may reduce biomass retention and destabilize continuous processing performance (Pechaud et al., 2022). These challenges are particularly critical in food-grade systems requiring strict hygienic design (Tan et al., 2025). Biofilm overgrowth, channeling and mass transfer limitations can reduce reactor efficiency. Fouling and cleaning remain critical concerns, particularly in food-grade systems requiring strict hygienic design (Soomro et al., 2025).

Process reproducibility is another critical barrier to commercialization. Biofilm reactor systems exhibit inherent spatial and temporal variability driven by biofilm development, matrix production and detachment dynamics (Papadopoulos, 2023). Without appropriate control, this variability can compromise product consistency, a non-negotiable requirement for food manufacturing. The integration of real-time monitoring technologies, combined with predictive modeling and feedback control, will be essential for

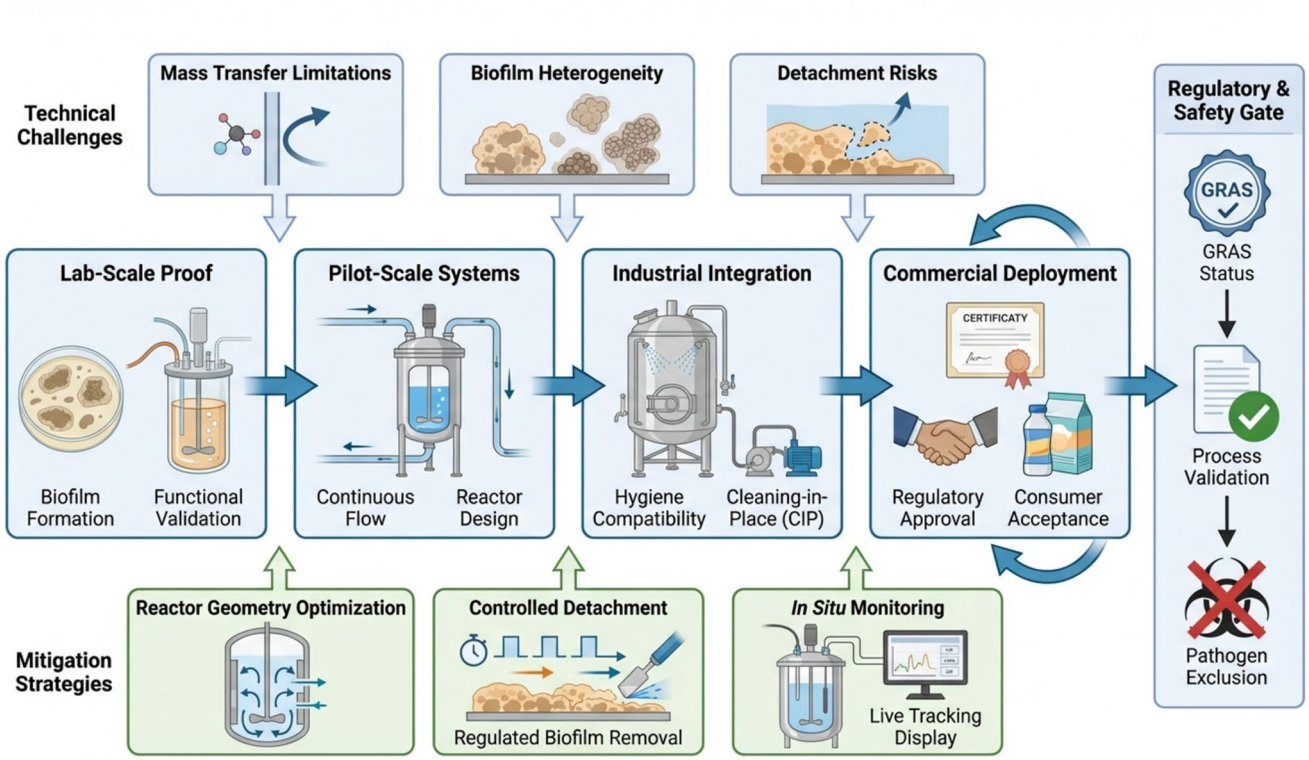


Fig. 5 Pathway to industrialization for engineered sessile fermentation. These schematic maps the critical development stages from Lab-Scale Proof to Commercial Deployment required to translate biofilm-based fermentation into robust industrial processes. Running parallel to the development pipeline are the predominant technical challenges (e.g., mass transfer limitations, biofilm heterogeneity) and corresponding mitigation strategies (e.g., reactor optimization, in-situ monitoring). A dedicated regulatory and safety gate highlights the essential requirements for GRAS (Generally Recognized As Safe) validation and pathogen control. The integrated view underscores that successful scale-up depends on concurrently advancing biological performance, engineering solutions and regulatory compliance

stabilizing performance and enabling reliable scale-up (Le et al., 2025). However, predictive control remains challenging because biofilm architecture continuously evolves under industrial flow conditions, making it difficult to accurately model detachment behavior, spatial heterogeneity and long-term fouling development (Galié et al., 2018). Sessile fermentation is intrinsically compatible with continuous processing due to sustained biomass retention and prolonged metabolic activity. However, transitioning from batch to continuous operation introduces challenges, including biofilm overgrowth, uneven flow distribution and hygienic design constraints (Zhang et al., 2024a, b). Reactor configurations that permit controlled biofilm regeneration and periodic harvesting are therefore critical for maintaining long-term operational stability while achieving economic advantages through reduced downtime and increased productivity (Zhan et al., 2025).

Safety and hygiene considerations represent a major conceptual and regulatory hurdle. Biofilms are traditionally regarded as contamination risks in food processing environments, creating resistance to their deliberate use. Commercial adoption will depend on demonstrating that engineered biofilms can be safe by design, incorporating defined microbial consortia, ecological dominance and intrinsic antimicrobial functionality (Ban-Cucerzan et al., 2025). Cleaning-in-place strategies must be adapted to selectively remove unwanted biofilms while preserving functional ones, representing a key design paradox in sessile fermentation systems (Singh & Anand, 2025). Such selective cleaning approaches may be supported through the integration of in-situ biosensors, imaging-based monitoring and targeted sanitation strategies capable of distinguishing functional biofilms from contaminant populations based on metabolic activity, species composition, or spatial localization (Bazsefidpar et al., 2024). In addition, localized enzymatic cleaning, controlled shear application, or phage-assisted sanitation may enable targeted disruption of undesirable biofilms while minimizing damage to stable functional sessile communities (Coppola et al., 2025). Effective cleaning-in-place strategies compatible with biofilm reactors must also be established to meet industrial hygiene standards. Regulatory uncertainty further limits translation. Existing frameworks are largely optimized for planktonic starter cultures and chemically defined ingredients, leaving biofilm-based food processing systems poorly classified (Maillard & Centeleghe, 2023). Advancing commercial acceptance will require standardized methods for biofilm characterization, clear safety assessment criteria and process-based regulatory evaluations that reflect system stability and historical food use. From an economic perspective, sessile fermentation offers potential advantages in process intensification, resource efficiency and waste reduction (Srinivasan et al., 2025).

However, these benefits must outweigh increased complexity in reactor design and process control. Near-term industrial adoption is most likely in high-value fermented foods and functional ingredients, where resilience, consistency and sustainability provide tangible market advantages.

Challenges and Future Work

Sessile fermentation represents a promising paradigm for next-generation food and bioprocessing; however, several critical challenges must be addressed to enable its reliable industrial implementation (Li et al., 2024).

Technical and Engineering Challenges

Sessile fermentation presents significant engineering challenges, particularly in controlling mass transfer within structured biofilms. Excessive biofilm thickness can introduce diffusion limitations, metabolic heterogeneity and reduced process predictability (Hindieh et al., 2025). Achieving a balance between biofilm stability and controlled detachment is therefore critical. Mechanistically, excessive biofilm accumulation may create nutrient-depleted or metabolically inactive zones, while sudden detachment events can disrupt reactor hydrodynamics and reduce process consistency (Tang et al., 2024). Strategies involving hydrodynamic regulation, modular reactor design and spatial control of biofilm growth are necessary to maintain consistent performance under industrial conditions (Waqas et al., 2023). In addition, inherent biofilm heterogeneity, arising from spatial and temporal variations in microbial activity and matrix composition, can result in fluctuations in product yield and quality, necessitating advanced reactor configurations and real-time monitoring approaches to ensure reproducibility (Chen et al., 2024).

Scale-Up and Process Control Limitations

The transition of sessile fermentation systems from laboratory to industrial scale remains a major bottleneck. Unlike planktonic systems, biofilm-based processes require precise management of surface interactions, microbial community dynamics and coupled transport–reaction phenomena (Bäcker et al., 2026). Operational challenges such as channeling, uneven flow distribution and uncontrolled biofilm overgrowth can compromise reactor efficiency and long-term stability. These phenomena are further complicated by dynamic fouling behavior and spatial biofilm heterogeneity, which may alter local shear conditions, substrate diffusion

and microbial activity throughout the reactor system during long-term operation.

(Wang et al., 2026a, b). Furthermore, the integration of biofilm reactor systems into continuous processing frameworks introduces additional complexity, as stable biofilm architecture must be maintained alongside consistent product output (Dzianach et al., 2019). Addressing these issues requires the development of predictive models that integrate diffusion–reaction kinetics with hydrodynamic parameters, enabling rational scale-up and improved process control (Wang et al., 2026a, b).

Safety, Hygiene and Regulatory Barriers

Despite their functional advantages, biofilms are traditionally associated with contamination risks in food processing environments, which presents a major conceptual and regulatory challenge. The intentional use of biofilms in food production demands rigorous demonstration of safety, stability and reproducibility (Olanbiwoninu & Popoola, 2023). This includes the development of defined microbial consortia capable of excluding pathogenic organisms while maintaining functional performance. In parallel, selective cleaning strategies must be established to remove undesirable biofilms without disrupting beneficial ones (Wang et al., 2025a, b). The absence of standardized methodologies for biofilm characterization and risk assessment further complicates regulatory acceptance. Existing regulatory frameworks, largely designed for planktonic systems, do not adequately address the unique characteristics of biofilm-based processes, highlighting the need for updated guidelines tailored to sessile fermentation (Highmore et al., 2022).

Future Research Directions

Future research should aim to transition sessile fermentation from an empirically driven approach toward a predictive and controllable bioprocessing platform. Advances in synthetic ecology will enable the rational design of microbial consortia with optimized metabolic interactions and enhanced stability (Angeles Flores et al., 2025). Matrix engineering approaches offer additional opportunities to tailor biofilm permeability, mechanical properties and metabolite retention. In addition, integration of multi-omics platforms, including metagenomics, transcriptomics, metabolomics, and proteomics, may enable spatial and temporal characterization of microbial interactions, metabolic fluxes, and functional differentiation within sessile communities (Dutta et al., 2024). Such datasets can support the development of predictive biofilm models linking microbial composition with fermentation performance and product quality. Artificial intelligence (AI) and machine learning approaches further provide opportunities for dynamic optimization of sessile fermentation systems through pattern recognition, predictive modeling and anomaly detection (Nkuna et al., 2026). For example, AI-assisted analysis of sensor-derived data, including pH, dissolved oxygen, metabolite profiles and imaging outputs, could enable early detection of biofilm instability, contamination events, or metabolic shifts during industrial fermentation processes (Debbarma et al., 2026).

The integration of digital technologies, including multi-omics, real-time sensing and machine learning, will further support the development of predictive models and dynamic control systems (Mustapha et al., 2026). Real-time monitoring workflows integrating biosensors, microsensors, computational fluid dynamics (CFD) models and automated feedback control systems may allow continuous adjustment of aeration, nutrient supply and shear conditions to maintain stable sessile biofilm functionality under industrial operating environments (Subramanian et al., 2020). In this context, digital twin frameworks represent a promising strategy for simulating and optimizing biofilm-based fermentation processes under variable operating conditions (Yee et al., 2025). Despite these advances, major challenges remain regarding data integration, model validation, computational complexity and real-time scalability, particularly for heterogeneous multispecies biofilms in food-grade industrial systems.

Outlook

Addressing these challenges will require coordinated efforts across microbiology, food engineering, materials science and regulatory science. With continued advances in these areas, sessile fermentation has the potential to evolve into a robust, scalable and sustainable platform capable of enhancing efficiency, consistency, and product quality in modern food and bioprocessing systems.

Concluding Remarks

Fermentation science usually looks at microbes floating around. But honestly, a lot of the best, most efficient food fermentations actually happen with microbes stuck together in biofilms. This idea of sessile fermentation, where biofilms are not a problem but something we can actually control and use, is kind of underexplored. Bringing together old brewing tricks with new stuff about biofilms, how microbes live together and how to engineer things, shows how these structured communities could make things work better, be more stable and turn out more consistently. It gives us a way to design these biofilm systems on purpose. Yeah, scaling them up, controlling them and getting them approved is still tricky, but with new materials, ways to build microbial

communities, and better digital monitoring, these stuck-together fermentations will likely become a lot more common in factories. Basically, thinking about biofilms opens up new ways to design bioprocesses and could lead to food production that's tougher, greener and just works better.

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Declarations

Competing interests The authors declare no competing interests.

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