

Review

Scaling up solid-state fermentation for organic waste valorisation: Current challenges and emerging opportunities

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ABSTRACT

Solid-state fermentation (SSF) is becoming an attractive approach to transform organic waste into valuable bioproducts. By using microorganisms on solid substrates with low water requirements water, SSF supports the shift towards more circular and sustainable systems. Although SSF offers potential environmental and operational advantages, its industrial adoption is still limited. Nevertheless, SSF has strong potential to complement conventional submerged fermentation and other bioprocessing technologies within future sustainable biorefinery strategies. Scaling up SSF processes faces challenges mainly related to heterogeneous mass transfer distribution and temperature gradients during fermentation. This work summarises the key limitations observed when moving from laboratory to large scale and explores promising strategies to overcome them. Potential solutions include the use of biotrickling reactors to achieve more uniform moisture distribution and improve mass transfer, the integration of advanced modelling tools such as computational fluid dynamics and AI for process control, and the application of thermotolerant strains capable of maintaining activity across a wide temperature range, among others. These advances could help SSF become a more reliable and scalable technology for waste valorisation.

1. Introduction

1.1. Basic of SSF

Solid-state fermentation (SSF) is traditionally defined as “the fermentation involving solids in absence (or near absence) of free water” (Pandey, 2003). Although this definition remains accurate, the concept has evolved. Historically, SSF has played a central role in traditional Asian food fermentations, such as the Koji process with *Aspergillus oryzae* for soy and rice fermentation, or tempeh production with *Rhizopus oligosporus*. During the twentieth century, SSF expanded beyond food applications to industrial bioprocesses, such as citric acid production by *Aspergillus niger* (Couto and Sanromán, 2006; Yafetto, 2022). Today, interest in SSF has renewed, especially due to its suitability to use organic residues as substrates in a circular economy context.

Accordingly, agricultural waste, food waste, and industrial by-products are increasingly emerging as renewable feedstocks, representing a shift in paradigm (Sánchez, 2024). Depending on the microbial strain and substrate, SSF processes produce marketable compounds like enzymes, edible biomass and organic acids (Chilakamarthy et al., 2022;

Khaswal et al., 2024; Silva et al., 2024). Several practical and environmental advantages further boost the growing interest in SSF as a sustainable biotechnology, especially for valorising agro-industrial residues. Its low water requirement, relatively low energy consumption, and ability to produce bioproducts of industrial interest make it a promising option within a future range of complementary technologies.

SSF processes are typically aerobic and rely on efficient oxygen transfer through a porous solid matrix, operating under low water activity conditions that distinguish them from submerged fermentation (SmF). SSF systems contain solid, liquid, and gaseous phases, which interact within the moist solid substrate and support microbial growth and metabolic activity, as schematized in Fig. 1.

Unlike submerged systems, SSF often uses minimally processed solids, avoiding complex and energy-intensive pretreatments such as chemical treatments, steam explosion, or other methods usually needed to solubilise components like fermentable sugars. These features lead to simpler setups and relatively low energy demands. Considering all these points, SSF is now broadly defined as an aerobic, solid-phase microbial transformation of biodegradable organic matter under low-moisture conditions, offering a sustainable biotechnological approach that

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reduces resource use.

1.2. Aligning SSF with sustainable value-added production

SSF closely aligns with several United Nations Sustainable Development Goals (SDGs), most notably SDG 12 (Responsible Consumption and Production), because it enables the conversion of organic residues into value-added products while promoting more efficient use of materials and reducing waste generation. In this sense, SSF is particularly consistent with Target 12.2, which aims to achieve sustainable management and efficient use of natural resources, and with Target 12.5, which calls for a substantial reduction in waste generation through prevention, reduction, recycling, and reuse. Agro-industrial residues such as crop husks, straw, lignocellulosic by-products, and other food-chain wastes can be transformed into valuable resources, thereby reducing disposal volumes and mitigating potential impacts on soil, water, and air quality (Banat et al., 2021; Šelo et al., 2021). More broadly, SSF fits within the logic of sustainable consumption and production patterns promoted under Target 12.1, as it supports circular approaches based on residue valorisation and process intensification. Its flexibility makes it an attractive option for industries seeking to align production systems with sustainability goals, although the actual environmental benefits remain strongly dependent on the nature of the substrate, the target bioproduct, and the downstream processing requirements.

A further advantage of SSF is its potential for water conservation, linking it to SDG 6 (Clean Water and Sanitation), since it generally requires lower water inputs during fermentation than submerged processes. This may reduce wastewater generation and alleviate pressure on treatment infrastructure. Nevertheless, the overall water footprint of SSF should be assessed carefully, since product recovery from the solid matrix can demand significant volumes of water, buffer solutions, or organic solvents, depending on the extraction strategy employed. SSF may also offer energy savings relative to conventional liquid-phase systems, thereby contributing to SDG 13 (Climate Action) through lower greenhouse gas emissions. However, these commonly cited advantages should not be generalized uncritically, as downstream purification can involve energy-intensive separation steps that partially offset the environmental gains achieved during fermentation. Finally, SSF can be integrated into biorefinery schemes, where it complements processes such as anaerobic digestion to maximize resource recovery and renewable energy generation from waste, thus contributing to SDG 7

(Affordable and Clean Energy) (Bueno-Mancebo et al., 2025; Oiza et al., 2026).

1.3. SSF bioreactors

From an operational perspective, SSF may appear relatively simple, as it relies on moist solid substrates and typically operates with low water input and aeration requirements compared with submerged fermentation. Nevertheless, this does not imply easy control, especially at larger scales. In aerated systems, gas exchange and heat removal depend on the passage of air through the interparticle spaces of the bed, making bed structure and porosity key factors for process performance. Its potential for large-scale application is illustrated by industrial composting, which is a specific type of SSF based on complex microbial consortia that can stabilise large volumes of organic residues under controlled conditions (Barrios-Nolasco et al., 2024). Even so, scaling up other SSF processes remains challenging, particularly for monoculture systems. Maintaining uniform aeration, moisture, and temperature throughout the bed becomes increasingly difficult as reactor size increases, which can compromise process performance and stability (Kumar et al., 2021).

Bioreactors offer controlled conditions that support high biological reaction rates, enabling efficient microbial growth, substrate utilisation and product synthesis. A variety of SSF bioreactor designs are used in both research and industrial applications. These systems mainly differ in how the solid substrate is arranged and in the aeration method employed. The choice of configuration depends on the type of fermentation and the working volume, meaning that some designs are better suited to specific processes, which makes direct comparisons difficult. In all cases, maintaining adequate porosity is essential to preserve aerobic conditions throughout the packed bed and to sustain microbial activity. The different bioreactor configurations for SSF have been extensively addressed elsewhere (Mitchell et al., 2023). Representative examples of these bioreactors are shown in Fig. 2.

Flasks and polypropylene bags represent the most economical and straightforward SSF systems. They are commonly chosen in research settings because they are easy to operate and well-suited for relatively small working volumes. The bag units are often applied at industrial level to produce edible mushrooms, such as *Pleurotus* species (Chutimanukul et al., 2025). In this context, the target product is not usually a soluble metabolite requiring intensive recovery, but rather the fungal body or colonised solid material itself, which makes bag-based

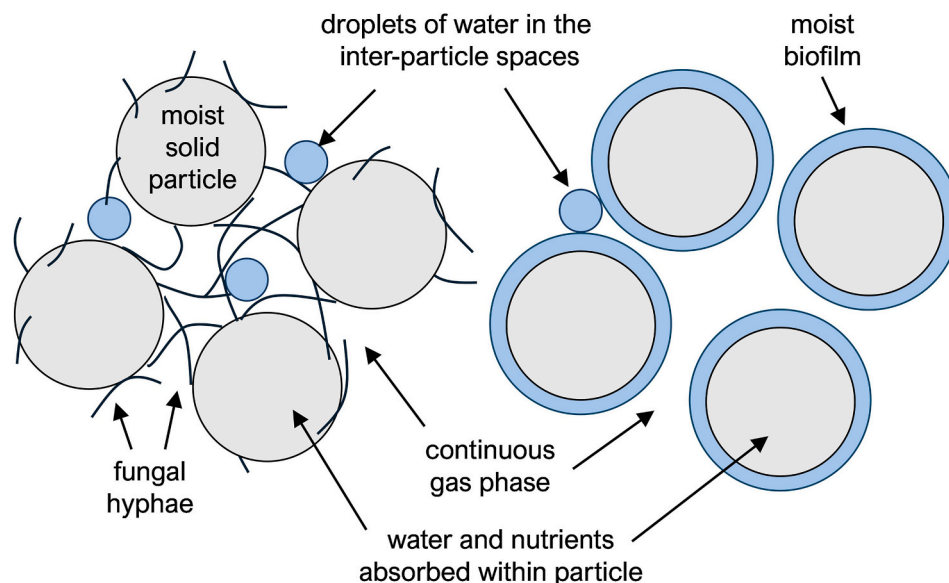


Fig. 1. Schematic outline of phases found in SSF (Adapted from Mitchell et al., 2023).

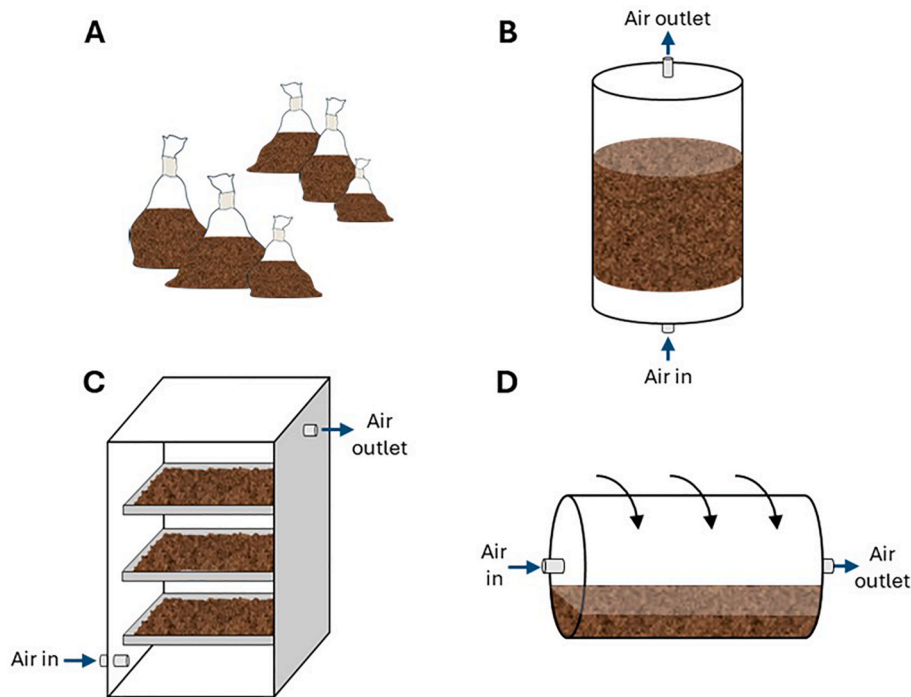


Fig. 2. Schematic SSF bioreactor design. (A) bags, (B) packed-bed reactor, (C) tray reactor, (D) rotating drum reactor.

systems attractive because the product can be harvested directly from the substrate with relatively simple downstream processing. Similar low-cost bag or flask systems are also suitable for inoculum development, fungal biomass production, and small-scale screening of enzyme or metabolite producing strains, prioritizing contamination control over volumetric productivity (Hultberg et al., 2023). However, they lack forced aeration, which limits gas exchange and heat removal, making them appropriate only when natural diffusion is sufficient to sustain microbial activity.

Tray-type reactors are better for processes with higher aeration needs and are often used in industrial applications (Manan and Webb, 2020). They are among the most widely adopted SSF configurations at industrial scale due to their simplicity and ease of operation. Tray-based systems are suitable for target products that benefit from shallow bed operation, good surface aeration, and limited mechanical stress, including traditional fermented foods and koji-type processes, extracellular enzymes such as amylases, cellulases, pectinases and proteases, organic acids, pigments, fungal spores, biocontrol agents, and protein-enriched feed or food ingredients (Mahmoodi et al., 2019; López-Gómez and Venus, 2021). In many of these applications, trays remain attractive because they provide modular operation, relatively simple loading and unloading, visual inspection of the substrate, and easier control of contamination at batch level. Their use is therefore often driven not only by engineering limitations, but also by the nature of the target product and by industrial familiarity with this configuration. In these systems, the thickness of the substrate layer in each tray is a critical parameter. Several studies have reported an optimal bed depth for fungal development between 5 and 15 cm, which constrains the quantity of material processed and requires substantial floor space, particularly when accounting for the spacing between trays needed for correct aeration (Dallastra et al., 2023).

Another reactor design used in SSF is the packed-bed reactor. Here, the substrate forms a fixed bed that fills much of the reactor's volume, and the air stream is forced to pass through it from the bottom. In contrast to tray reactors, this configuration allows larger quantities of material to be processed per unit of reactor volume, as a greater portion of the reactor volume can be dedicated to the working bed (Gómez-Ramos et al., 2024). Packed-bed systems are therefore

especially promising for target products whose production requires higher volumetric capacity and more intensified operation, such as bulk enzymes, biosurfactants, organic acids, aroma compounds, fermented feed ingredients, or other metabolites obtained from agro-industrial residues. However, these advantages are only realised when the target product and microorganism tolerate the stronger internal gradients that may develop in deeper beds, or when reactor design and control strategies are able to mitigate them (Sala et al., 2024; Ribeiro de Oliveira et al., 2026). A variation of this design is the rotary drum reactor, in which the bed is continuously or intermittently agitated by rotating the drum along its horizontal axis or through internal baffles. Effective mixing, however, is achieved only when the drum is partially filled, typically using about 40% of its total volume as working capacity, which also increases the specific energy consumption compared to simpler tray or packed-bed systems (Dallastra et al., 2023).

Stirred SSF systems should also be distinguished from packed beds and simple rotating drums, since their suitability strongly depends on the morphology of the producing microorganism. For unicellular microorganisms, such as yeasts and some bacteria or bacterial-yeast consortia, dynamic operation can help maintain contact between cells and substrate, improve moisture distribution and reduce local accumulation of metabolites, particularly in ethanol- or enzyme-oriented processes using lignocellulosic residues (Lin et al., 2013; Ho et al., 2012). However, these systems are not equivalent to submerged stirred tanks, because the solid matrix still limits mixing, oxygen diffusion and heat removal. In the case of moulds, or filamentous fungi, agitation must be applied more cautiously. Their hyphal growth allows efficient colonisation of solid particles, but excessive stirring can damage the mycelial network or modify enzyme secretion. For this reason, studies with *Trichoderma*, *Aspergillus* and other moulds often favour low-speed or intermittent agitation, which can improve bed homogeneity and temperature control while limiting mechanical stress (Mahmoodi et al., 2019; Lopez-Ramirez et al., 2018). Thus, stirred configurations may be useful in SSF, but their design should be adapted to the microorganism: generally, more permissive for unicellular cultures, and gentler or intermittent for filamentous fungi.

Despite packed-bed configuration potential, most companies still rely on bag- or tray-based systems. Packed-bed designs could enable the

processing of larger volumes per batch, reduce space requirements and lower labour costs. However, their adoption remains limited due to key bottlenecks in scaling up SSF, particularly challenges related to mass and heat transfer. Consequently, the selection between bag, tray and packed-bed systems should not be based solely on reactor capacity, but also on the target product, the required downstream processing, the tolerance of the producing microorganism to gradients or shear, and the acceptable level of process control. For products such as mushrooms, fermented foods, fungal spores or crude enzyme preparations, bag- and tray-based systems may remain commercially practical despite their lower space-time productivity. In these configurations, industrial expansion is typically achieved through scale-out (numbering-up), by increasing the number of bags or trays operated in parallel rather than enlarging the size of individual units. In contrast, packed-bed reactors are generally designed for scale-up, where larger reactor volumes are used to process greater quantities of substrate within a single unit. This approach could become particularly attractive when large amounts of homogeneous solid substrate must be handled and when process intensification can compensate for the additional complexity associated with aeration, moisture and temperature control (Dallastra et al., 2023; Sala et al., 2024). Although difficulties in direct process monitoring and control are common to SSF in general, they become especially critical in packed-bed reactors as scale increases and internal gradients become more pronounced (Jin et al., 2020). Addressing these limitations would significantly advance the technological development and industrial scalability. Overcoming barriers to scaling up could advance SSF in packed-bed reactors from technology readiness level (TRL) 4-6, where systems are developed and tested at laboratory or pilot scale, to TRL 8-9, representing fully operational commercial technologies. Similar progress has already been achieved by other waste valorisation processes, such as anaerobic digestion and composting, which are now widely established at industrial scale (Salomão et al., 2019).

Overall, each SSF bioreactor configuration fulfils a specific role depending on the intended scale, target product, microorganism and required level of process control. Bag and flask systems are mainly useful for low-cost, small-scale or product-specific applications where diffusion is sufficient, while tray reactors provide modular operation and shallow-bed aeration for products requiring limited mechanical stress. Packed-bed reactors are more suitable for process intensification and higher substrate loading, whereas rotating drum systems improve mixing and homogeneity when the microorganism and substrate can tolerate mechanical agitation.

From a technological perspective, patent activity has primarily focused on improving process monitoring, automation, and operational robustness in SSF reactors rather than introducing radically new reactor configurations. Several inventions describe automated bag- and tray-based systems aimed at reducing manual handling and increasing process control. Examples include automated bag reactors incorporating filling, sterilization, and inoculation steps (Chang, 2022), parallelized arrays of small-scale bioreactors (Granucci and Granato Villas Boas, 2024), and self-discharging or compartmentalized tray reactors (Shih and Chiu, 2024; Xing, 2016). While these approaches may facilitate process standardization, their economic viability at larger industrial scales remains uncertain.

For packed-bed systems, patented developments have mainly focused on process integration and reactor performance. Recent designs include end-to-end SSF platforms integrating upstream inoculum production with downstream product processing and packaging (Mou et al., 2024). Temperature management has received comparatively limited attention, with only a few patents proposing solutions such as internal heating and cooling pipe networks (Pan et al., 2022). In contrast, mass-transfer optimization is a recurring theme, encompassing novel stirring mechanisms to reduce substrate layering and dead zones (Zhou et al., 2023), screw-based mixing systems for vertical packed-bed and rotating drum reactors (Zhang et al., 2021; Li and Shao, 2016), and advanced aeration strategies, including multi-point oxygen distribution

systems with integrated monitoring and alarm functions (He, 2016) and micro-perforated gas panels designed to improve gas homogeneity (Li, 2022).

Overall, current patent trends indicate that technological innovation in SSF is largely directed toward improving process control, scalability, and operational efficiency rather than developing fundamentally new reactor concepts.

In light of these considerations, the present work aims to provide a brief overview of the main technical barriers to scaling up SSF processes in a packed-bed reactor, proposing potential strategies to overcome these challenges, including bioreactor design improvements, advanced AI tools and the use of thermotolerant and thermophilic strains.

2. Main limitations in scaling up SSF and potential solutions

2.1. Heat transfer

The management of heat transfer is one of the most critical bottlenecks in the scale-up of SSF systems. Inadequate thermal conductivity, heterogeneous airflow distribution, and suboptimal aeration rates often lead to pronounced axial and radial temperature gradients that directly affect microbial growth and productivity (Mitchell et al., 2023). This challenge is intensified by the fact that filamentous fungi, which are commonly used in SSF, tend to be sensitive to mechanical agitation. Their sensitivity limits the use of mixing strategies that could otherwise improve heat dissipation. As a result, temperatures can rise beyond the thermal tolerance of the microorganism, causing reductions in growth and product formation. This effect is closely linked to the solid content and bed loading used during SSF. Although high solid contents are one of the defining features of SSF, the optimal value should be understood as a balance between water availability, substrate accessibility and gas-filled porosity rather than as the maximum possible dry-matter loading (Raimbault, 1998). Increasing the amount of dry matter per reactor volume also increases the amount of metabolically active material and, therefore, the heat released within the bed. At the same time, excessive solids loading can reduce the free air space required for convective heat removal, especially when particle size distribution, moisture and compaction are not properly controlled (Casciadori et al., 2016). Therefore, the preferred solid content should be selected together with bed height, particle size, bulking agent addition and superficial airflow, since these parameters jointly determine aeration efficiency and the development of temperature gradients during scale-up (Mitchell et al., 2023).

As reactor size increases, efficient heat removal becomes even more difficult, and temperature gradients develop naturally within the bed. In industrial systems, cooling jackets or internal coils can be added to promote heat dissipation, although these solutions involve high operational and energy costs and remain constrained by the inherently low heat conduction of static solids. In exothermic fermentations, heat generated by microbial activity accumulates within the bed, and the air flowing through the reactor is progressively heated as it passes through the warmer solid matrix, contributing to marked inlet-to-outlet temperature gradients. While small reactors may exceed the optimal temperature by only a few degrees, larger units usually experience much greater deviations unless operating conditions are carefully adjusted during scale-up (Casciadori et al., 2016).

2.1.1. Advanced modelling for gradient control in SSF

One potential strategy to mitigate these gradients involves increasing the airflow rate; however, this approach may excessively dry the substrate, compromising microbial metabolism. In this context, evaporative cooling could be considered as a scale-up strategy. By promoting controlled water evaporation from the solid matrix, part of the metabolic heat can be removed as latent heat, which is especially relevant in large packed-bed reactors where heat removal through the reactor wall becomes less effective. However, its usefulness depends on maintaining

a careful balance between heat dissipation and moisture preservation. If the inlet air is too dry or the airflow is too high, evaporative cooling may shift the problem from overheating to local drying, reduced water activity and loss of microbial performance. Therefore, evaporative cooling should be coupled with humidified inlet air, intermittent water addition or liquid recirculation, and supported by heat–water transfer models able to predict temperature and moisture profiles during scale-up (Casciadori et al., 2016; Finkler et al., 2021). Thus, there is a growing interest in applying advanced modelling tools and artificial intelligence (AI) to dynamically adjust airflow parameters, such as flow rate, saturation level and airflow timing to optimise both temperature control and moisture retention. For instance, Computational Fluid Dynamics (CFD) has demonstrated effectiveness in simulating mass and heat transfer within bioreactors by accounting for local variations in porosity, airflow, and moisture distribution (Barrios-Nolasco et al., 2024). Beyond describing internal gradients, advanced models are useful because they allow scale-up decisions to be tested before building larger reactors. Recent studies have used heat–water transfer models and CFD simulations to estimate temperature and moisture profiles, identify non-uniform airflow, evaluate bed height limitations and define operating windows for packed-bed SSF systems (Pessoa et al., 2019; Jin et al., 2020). This is particularly relevant for scale-up because variables such as air flow rate, bed porosity, substrate moisture and reactor geometry cannot be changed independently at large scale. Therefore, modelling should be considered a practical design tool to narrow the range of experimental conditions, anticipate overheating or drying zones, and support the selection of aeration and cooling strategies before pilot-scale validation (Vauris et al., 2022). This detailed modelling could facilitate the creation of digital twins, virtual replicas capable of simulating different process scenarios, optimising design parameters, and supporting scale-up strategies (Perez et al., 2019).

In parallel, AI has emerged as a powerful complement to these types of mechanistic modelling. Techniques such as artificial neural networks (ANN) and hybrid models integrating metaheuristic optimization algorithms have shown remarkable predictive accuracy in capturing complex, nonlinear interactions among physical, chemical and biological variables. These AI-driven approaches not only reduce the number of

experimental runs required but also improve reproducibility and operational efficiency (Bezerra et al., 2021). Moreover, predictive modelling with AI enhances the understanding of how process variables influence internal gradients within the solid matrix, thereby supporting the development of more robust and controlled fermentation systems. AI also enables the evaluation of reactor designs and operational strategies without extensive pilot-scale experimentation (Chandukishore et al., 2023). Nevertheless, this should be interpreted mainly in the context of process modelling, prediction and optimization, rather than as direct evidence of fully autonomous industrial control in SSF. Most reported AI applications are still focused on supporting process development by identifying relevant variables, reducing experimental workload and improving the selection of operating conditions.

The application of digital twin technology in SSF is still in its early stages, and existing research including CFD studies and models such as those by Perez et al. (2019), provides a foundational basis for its further development. Particularly in packed-bed reactor configurations, it highlights a promising direction for future research. Despite these advancements, the widespread adoption of mechanistic and AI-based models is still limited by the need for specialised programming skills, emphasising the importance of developing more accessible modelling tools to fully exploit their potential. Recent examples of modelling and AI-based applications in SSF are summarised in Table 1.

Recent studies have also explored pressurised bioreactor systems as an effective approach to reduce heat and mass transfer gradients, enhancing microbial performance and allowing greater bed loading without compromising temperature control or product yield such as lipase production and spore viability (Chen and He, 2013; Oliveira et al., 2017). Together, these strategies represent promising avenues to improve process control and overcome scale-up limitations in SSF, although further validation under industrially relevant conditions is still needed.

2.1.2. Thermophilic microorganisms' prospects

The use of thermophilic and thermotolerant microbial strains offers a practical strategy to mitigate heat transfer limitations in SSF. These microorganisms, naturally adapted to high-temperature environments

Table 1

Recent examples of modelling and artificial intelligence tools applied to SSF using waste as substrate.

Microorganism	Waste Substrate	Target Product	Parameters Analysed with AI	AI Tools	Brief description	Ref.
<i>Myceliophthora thermophila</i> I-1D3b	Sugarcane bagasse	Cellulolytic enzymes	Temperature of the bed	2-D model and Damköhler number	Maximum bed height	Perez et al. (2019)
<i>Aspergillus niger</i>	Wheat bran and sugarcane bagasse	Pectinase	Heat/mass transfer Moisture Temperature	CFD	Used for detailed simulation of SSF bed dynamics	Pessoa et al. (2019)
<i>Trichoderma stromaticum</i> AM7	Peach-palm waste	Cellulase	Nitrogen source Temperature	ANN + GA	Identified optimal fermentation conditions	Bezerra et al. (2021)
<i>Aspergillus terreus</i>	Mixed food waste	Glucoamylase	Temperature Biomass	ANN + GA	Outperformed the traditional Box-Behnken design	Chandukishore et al. (2023)
<i>Aspergillus cristatus</i>	Mulberry leaves	Flavonoids	Optimal fungal strain combination	BP-ANN	Reduced experiments and optimized fungal combinations	Zhao et al. (2023)
<i>Aureobasidium pullulans</i> AKW	Broad bean biomass	Polysaccharide	Temperature Moisture Substrate ratio	ANN	Predicted pullulan yield with high accuracy, better than OVAT	Eldadamy et al. (2024)
<i>Bacillus cereus</i>	Agro-industrial waste	Peptidase	Substrate ratio	ANN	Basic ANN for process optimization	Ekpenyong M et al. (2024)
<i>Aspergillus niger</i> ATCC 9142	Avocado seed, Coconut pulp, pome	Lipase	Substrate ratio	SVR and other models	Provided the highest prediction accuracy	Amenaghawon et al. (2024)
<i>Streptomyces violaceoruber</i>	Wheat bran and soybean	L-glutaminase	Substrate ratio Nutrients	ANN + CCD	ANN improved prediction and optimization over CCD	El-Naggar et al. (2024)
<i>Yarrowia lipolytica</i> 2.2 ab	Agri-food by-products	Proteases	Heat/mass transfer Growth rate	CFD	Modelled oxygen flow and heat distribution in packed-tray bioreactor	Barrios-Nolasco et al. (2024)
<i>Pleurotus pulmonarius</i>	Cocoa shell, Peach-palm waste	Amylase	Temperature	ANN	Modelled amylase activity under varied conditions	Silva et al. (2025)

ANN Artificial Neural Networks, GA Genetic Algorithms, CCD Central Composite Design, BP-ANN Backpropagation Artificial Neural Networks, SVM Support Vector Machines, CFD Computational Fluid Dynamics.

(typically above 45 °C), remain metabolically active under conditions that would inhibit or inactivate mesophilic species. Their application can complement other technical approaches, such as operational modifications or the use of advanced mathematical models, for improving process stability under thermal stress (Perez et al., 2019).

Although interest in this approach is growing, its application at industrial scale remains limited. Yet, incorporating thermophilic strains into SSF processes could significantly reduce the impact of heat accumulation, especially in large-scale systems where temperature control is both more difficult and more critical to process success. Beyond improving thermal stability, operating SSF systems at elevated temperatures (between 40 °C and 60 °C) may also help minimise the risk of contamination by opportunistic microorganisms (Hou et al., 2019).

Thermophilic strains for SSF can be obtained either by isolating wild-type microorganisms from naturally hot environments, such as compost, hot springs, or geothermal soils, or by developing strains with enhanced thermal tolerance. Their suitability, however, depends on the intended application of the process, since safety, regulatory, and product-quality requirements may restrict the use of environmental isolates or improved strains in certain sectors, particularly in food and feed production. Composting environments are especially relevant in this context, as they harbour diverse thermotolerant microbial communities with strong hydrolytic and metabolic capabilities (Moreno et al., 2021). Although many thermophilic and thermotolerant microorganisms have been reported in the literature, Table 2 summarises selected examples published from 2021 onwards in which these microorganisms were applied to SSF processes using waste substrates as nutrient sources.

Operating with thermophilic strains at elevated temperatures may also offer an additional advantage by limiting the growth of unwanted microorganisms, thereby reducing contamination risks and easing sterility requirements. Nevertheless, the practical implementation of this strategy still depends on identifying strains that not only remain highly productive under these conditions, but are also suitable and acceptable for the target bioproduct and its intended end use.

2.2. Mass transfer

Oxygen plays a crucial role in sustaining microbial activity during SSF, but achieving uniform aeration at large scales becomes increasingly complex. Insufficient porosity or substrate compaction led to preferential air pathways, which limit microbial growth. Continuous adjustments of aeration systems are often required to maintain optimal conditions. These structural limitations also affect the initial distribution of the inoculum within the solid matrix, since homogeneous mixing between the microbial culture and the substrate is difficult to achieve in the absence of a free-flowing liquid phase. Spatial gradients arise due to substrate heterogeneity, such as in biowaste, and are also affected by microbial metabolism, which alters the matrix properties. While mechanical mixing systems have been proposed for packed-bed reactors, their efficiency depends on the matrix properties and microorganism. Many industrial strategies address substrate homogenisation by modifying reactor design, for example, by adding paddles or rotating elements. These systems can help improve mixing and heat and mass transfer, but their feasibility strongly depends on reactor size. While they may work at pilot scale, using them at much larger scales can lead to local overheating and compaction of the solid bed. It is also important to consider the extra energy required to operate these systems and the mechanical load they must withstand.

The solid nature of the medium also makes real-time monitoring and accurate biomass measurement difficult, often relying on indirect indicators like outlet gas composition or labour-intensive extraction from heterogeneous samples (Kumar et al., 2021). Nutrient availability is strongly influenced by the physical structure of the substrate, including its porosity, particle size, and moisture content. Particles that are too small tend to compact, restricting air flow, while very large particles reduce surface area for microbial colonisation and enzymatic activity. Moisture management is another critical factor. Bacterial cultures typically require moisture contents above 70%, while filamentous fungi can tolerate broader ranges (40 - 70%). Reported moisture levels in SSF systems vary widely (30 - 85%), highlighting the importance of controlling within optimal ranges to ensure process efficiency and reproducibility (Carboue et al., 2020). Evaporation during fermentation can

Table 2
Examples of thermophiles applied to SSF using waste as substrate since 2021.

Microorganism	Isolated from	Waste substrate	Target product	Reactor temperature (°C)	Scale	Reference
<i>Bacillus subtilis</i> CBI-7S1	Compost	Winterization oil cake Sugarcane molasses	Biosurfactants	30-50	50 L	Bueno-Mancebo et al. (2026)
<i>Geotrichum candidum</i> PO27	Olive pomace	Olive pomace	Amylases	60	250 mL flask	Chaib et al. (2025)
<i>Trametes villosa</i>	Decomposing wood	Wheat bran	Lignocelluloses	65	250 mL flask	Corrêa et al. (2024)
<i>Trichoderma asperellum</i>		Grape pomace				
<i>Bacillus licheniformis</i>	Cigarette	Soybean meal	Protease	55	150 mL flask	Dai et al. (2022)
<i>Phoma herbarum</i> KU4	Soil	Rice straw	Laccase and protease	50	250 mL flask	Debnath et al. (2021)
<i>Bacillus</i> sp.	Compost	Food waste and Winterization oil cake	Biosurfactants	50	0.5 L packed bed reactor	Farooq et al. (2024)
<i>Aspergillus</i> sp.						
<i>Streptomyces</i> sp						
<i>Rasamsonia composticola</i>	Lab collection	Wheat bran and sugarcane bagasse	Endoxylanase	80	250 mL flask	Franco et al., 2023
Protease-producing strain	Soybean meal	Brewer's spent grain Soybean meal	Value-added peptides	55	250 mL flask	Liu et al. (2023)
<i>Bacillus subtilis</i> L5	Lake mud	Soybean meal	Fermented feed	50	0.5 L flask	Qi et al. (2024)
<i>Aspergillus niger</i>	Decayed tomato fruits	Bagasse from sugarcane	Polygalacturonase	55	250 mL flask	Sinshaw et al. (2024)
<i>B. licheniformis</i> and <i>Streptomyces</i> sp.	Paper manufacturer water	Rice straw	Cellulase, xylanase	60	250 mL flask	Suwannaphan et al. (2024)
<i>Mycothermus thermophilus</i>	Hydrothermal spring	Agro wastes	Proteases	45–50	250 mL flask	Talhi et al. (2022)
<i>Thermoascus aurantiacus</i> SL16W	Soil	Rice bran, wheat bran	Phytase, endoglucanase, and xylanase	45	250 mL flask	Tanruean et al. (2021)
Thermophilic microbial consortium TMC1–3	Compost	Pretreated corn straw	Feed protein	55	0.5 L flask	Wang et al. (2025)
<i>Sporotrichum thermophile</i>	Mutant strain	Corn stover Wheat bran	Cellulases	40–50	250 mL flask	Zhang et al. (2024)

cause localised drying, negatively impacting microbial growth and product yield (Bueno-Mancebo et al., 2026). Insufficient water limits nutrient solubility, while excessive water encourages particle adhesion and reduces gas exchange. Adding bulking agents can improve porosity and aeration, especially in large-scale operations where compaction is more likely.

To address these challenges, biotrickling reactors (Fig. 3) offer a promising alternative to conventional SSF. Traditionally applied in gaseous emissions control, wastewater treatment, and bioremediation strategies (Dupnock and Deshusses, 2021; López et al., 2021), these systems can be adapted to enhance metabolite production in SSF. Introducing a controlled trickling liquid phase shifts conventional SSF toward a solid-substrate fermentation (SSuF) framework, mitigating heterogeneous moisture distribution, facilitating oxygen diffusion, and reducing the accumulation of inhibitory metabolites within the solid matrix. In addition, the presence of a minimal circulating liquid phase enables real-time monitoring of key parameters such as microbial growth, pH, and nutrient consumption through liquid sampling, overcoming the limitations of indirect approaches such as gas analysis in SSF.

Recent research highlights the potential of different trickle-bed reactor configurations for sustainable bioproduct generation. Singh and Murthy (2025) designed an innovative horizontal trickle-bed reactor (HTBR) equipped with a newly developed impeller featuring angled blades capable of generating both linear and circular mixing motions (Singh and Murthy, 2025). This configuration was specifically engineered to mitigate substrate compaction, temperature gradients, and bed drying—typical limitations of SSF systems. The HTBR, with a total volume of 5 L and a solid loading capacity of 1.5 kg, operated at high solid fractions using wheat bran as an agro-industrial substrate for pectinase production. The integration of manual helical mixing and liquid recirculation improved thermal and moisture homogeneity, promoting fungal growth and enhanced mass transfer. As a result, the system achieved a 2.7-fold higher pectinase yield compared to tray-based reactors, demonstrating the performance benefits of intensified mixing

and trickling. Despite these advantages, the study also identified scale-up considerations related to manual agitation, mycelial sensitivity to shear, and indirect thermal control, which remain relevant for industrial implementation.

Bueno-Mancebo et al. (2025) evaluated the implementation of a trickle-bed reactor as an intensification strategy for SSuF aimed at sophorolipid production by *Starmerella bombicola*. Their 0.5 L reactor integrated liquid recirculation and a rotating distribution system that improved moisture and nutrient homogeneity within the solid bed, mitigating gradients commonly observed in conventional SSF. The substrate consisted of agricultural residues (primarily wheat straw and winterization oil cake) combined with structural bulking agents to preserve porosity and prevent compaction. The reactor operated with a solid loading of approximately 175 g of substrate per litre of reactor volume, providing a porous matrix that supported effective liquid distribution and aerobic microbial activity. Under optimized trickling and nutrient supplementation conditions, the system significantly increased microbial growth by 45.4% and sophorolipid production by 31.2% compared to non-trickled control. Importantly, the trickled liquid phase enabled continuous monitoring of glucose consumption, yeast growth, and pH, highlighting the potential of trickle-bed configurations to improve process observability and control through non-invasive real-time sampling.

Some research assesses the technological possibility of using trickling reactor configurations not only for solid residue valorisation, but also for integrating liquid waste streams as nutrient carriers. Digestates and nutrient-rich effluents can be used as trickling media, enabling simultaneous microbial conversion and resource recovery (Gabler et al., 2025). In this hybrid solid-liquid system, the liquid phase contributes to improved nutrient distribution and bed homogeneity while acting as a vehicle for circular reuse of nitrogen, phosphorus and micronutrient-rich streams. This expands the concept of solid-substrate fermentation into integrated bioprocessing platforms. However, this integration should not be interpreted as universally beneficial. The use

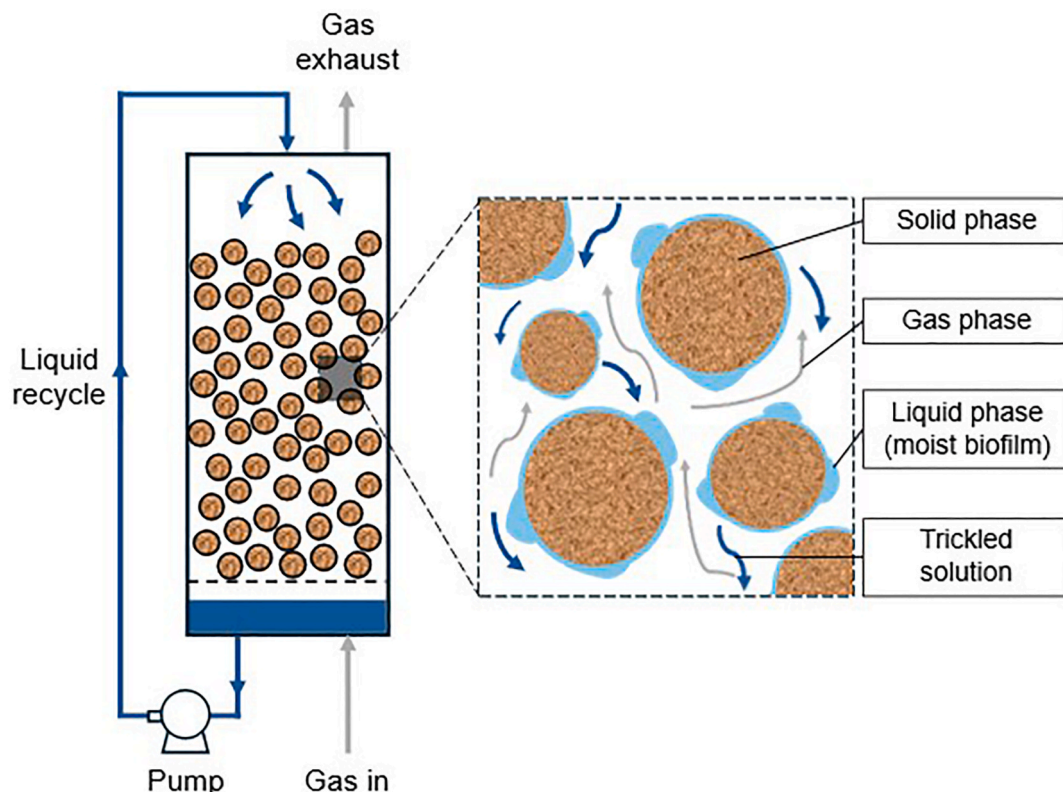


Fig. 3. Scheme of a biotrickling reactor for solid-substrate fermentation.

of trickling reactors for both solid waste and liquid nutrient carriers can improve microbial conversion and resource recovery only when the liquid stream is compatible with the microorganism, target product and bed structure. Under suitable conditions, nutrient-rich liquids may partially replace process water or synthetic supplementation, support staged feeding and moisture control, and enable monitoring or recovery of soluble metabolites through the recirculating phase. Thus, trickling systems may expand SSuF into an integrated platform for the combined valorisation of solid and liquid residues (Bueno-Mancebo et al., 2025).

Nevertheless, the same strategy also introduces additional operational complexity. Liquid recirculation requires pumping, distribution devices, flow control, and often pretreatment or sterilization of the liquid stream, depending on the microbial system and product requirements. Moreover, poorly controlled trickling may intensify hydrodynamic problems such as channeling, bed compaction, excessive pressure drops, nutrient leaching, dilution of the product, or the accumulation of inhibitory compounds in the recirculating liquid. Therefore, the implementation of liquid nutrient carriers should be justified by a clear improvement in process performance, resource recovery, or downstream integration, rather than being considered an inherent advantage of SSuF (Atta et al., 2007; Suneja and Roy, 2023).

Furthermore, these configurations could be used for the recovery of water-soluble metabolites, including organic acids, extracellular enzymes and polar secondary products (Rocha et al., 2024). The ability to collect and analyze the circulating liquid phase supports enhanced process control, downstream integration, and scalability while maintaining operational sterility.

Using trickling liquid to control temperature in SSF is a promising and unexplored research direction. Distributing small amounts of liquid through the solid matrix may help enhance heat removal and reduce temperature gradients, especially in packed-bed configurations. Although similar approaches have been considered in related solid-state processes such as composting, their application in SSF packed-bed systems has, to the authors' knowledge, not yet been experimentally investigated in detail. Exploring how controlled liquid trickling influences temperature regulation, moisture distribution, and microbial performance could therefore provide valuable insights and contribute to the development of improved scale-up strategies.

However, although liquid percolation helps overcome mass-transfer limitations, it can also introduce challenges at larger scales, such as channelling, bed compaction, and excessive pressure drop. In such cases, proper liquid distribution becomes essential to avoid dry zones and ensure homogeneous wetting (Atta et al., 2007). One way to improve distribution would be to replace a single top-feeding point with multiple drip points or sectional distribution zones. Good liquid distributors can help prevent maldistribution, which affects both wetting and the overall pressure profile. Likewise, solid support and loading procedures should aim for uniform porosity, and liquid flow rates should be adjusted to maintain this porosity and prevent excessive material carryover from the mix. In addition to improving moisture distribution and mass transfer, the introduction of a trickling liquid phase may offer an important operational advantage by enabling process monitoring without the need for invasive solid sampling. Traditionally, SSF progress is monitored through oxygen consumption in the exhaust gas, which provides an indirect estimate of overall microbial activity, but does not directly indicate the formation of the target product and may fail to detect contamination events. By contrast, analysis of the recirculating liquid can provide more direct and real-time information on variables such as pH, soluble nutrient consumption, or biomass-related changes in the system.

Several process parameters strongly influence SSF performance, including substrate composition, inoculum size, and pH. Biowaste can be used as substrates due to their high nutrient content, although their heterogeneity and native microbiome complicate process control. Inoculum size must be carefully balanced, as low levels delay colonisation whereas excessive inoculation can limit airflow and mass transfer.

pH is also a critical factor, given the distinct preferences of bacteria, fungi, and yeasts; however, its control in SSF is challenging due to the lack of real-time measurement technologies in solid matrices. In this context, trickling bioreactor configurations provide a promising strategy to enhance SSF by enabling a fed-batch-like operation through the controlled trickling of liquid streams. This approach allows staged nutrient supplementation, inoculum addition, and indirect pH adjustment via acidic or basic solutions. Moreover, the percolating phase facilitates the recovery of soluble compounds, such as extracellular enzymes, thereby improving process integration and overall techno-economic feasibility. Beyond these general effects, variations in material composition are particularly relevant when biowaste is used, because differences in C/N ratio, nutrients fractions, buffering capacity and indigenous microbiota can modify substrate accessibility, oxygen demand, microbial competition and the evolution of pH during fermentation (Soccol et al., 2017). Therefore, process performance depends not only on the initial mix, but also on batch-to-batch variability and on how the substrate structure changes as degradation progresses. Inoculum size should also be interpreted in relation to substrate load and aeration capacity: insufficient inoculation may favour the growth of native microorganisms, whereas excessive inoculation can accelerate oxygen consumption, heat release and local nutrient depletion, especially in poorly aerated zones (Selo et al., 2021; Perwez and Al Asheh, 2025). In this context, trickling configurations can help mitigate the effects of biowaste heterogeneity by redistributing soluble nutrients and providing an accessible liquid phase for pH monitoring or correction. From an economic perspective, their implementation is justified only when these benefits translate into higher product yield, lower supplementation needs, improved process control or simpler downstream recovery, since additional pumps, liquid distribution systems and possible liquid pretreatment also increase operational complexity and cost.

3. Other key aspects: economic and environmental benefits

In parallel with technical limitations and reactor design considerations, the economic and environmental performance plays a decisive role in industrial adoption. Expanding the portfolio of bioproducts obtainable through SSF is essential to increase industrial attractiveness and provide flexibility under evolving market conditions. In recent years, SSF has been linked to an increasingly diverse range of products. Some applications are relatively well established in the agri-food sector, such as the cultivation of edible fungi from *Pleurotus* strains for functional food improvement (Li et al., 2026) and the production of high-nutrient protein sources (Zhang et al., 2026; Bueno-Mancebo et al., 2026; Mazzola et al., 2026). At the same time, emerging research is exploring higher-value metabolites, including biosurfactants such as mannosylerythritol lipids produced by *Ustilago maydis* and *Moesziomyces bullatus* (Bueno-Mancebo et al., 2025), as well as lipopeptides generated by *Staphylococcus* sp. DG-2 (Man et al., 2026). SSF is particularly attractive when the products generated can be directly reintegrated into the same sector that produces the residues used as substrates, strengthening circular economy strategies. Biosurfactants are a clear example, as they can be applied in the agri-food industry, for example as antimicrobial agent, without requiring extensive downstream purification (Bueno-Mancebo et al., 2024).

Downstream processing remains a key factor affecting SSF viability, since product recovery from solids often relies on solvent extraction. Extraction efficiency depends on the solvent system, solid-to-liquid ratio, extraction time, and purity requirements. While the use of heterogeneous waste substrates can complicate downstream operations, alternative techniques such as microwave-assisted extraction, ultrasound-assisted extraction, and supercritical fluids are being explored to improve recovery efficiency (Taha et al., 2023). Nevertheless, sustainable SSF schemes must also consider the management of residual streams and exhausted solids to avoid shifting environmental burdens downstream. In some applications, such as environmental

remediation or bioenergy production, crude extracts or partially processed products may be sufficient, allowing costly purification steps to be avoided. An alternative strategy involves targeting bioproducts that can be efficiently recovered using water-based extraction, thereby avoiding organic solvents altogether. This approach is well established in SSF for enzyme production, where extracellular enzymes can be readily extracted with aqueous solutions, significantly simplifying downstream processing and improving overall process sustainability (Leite et al., 2021).

From a techno-economic perspective, SSF offers cost-saving opportunities by enabling the direct use of organic residues with minimal pretreatment, thereby reducing expenses associated with raw materials and waste management. The process generally requires low water input, although solvent demand during downstream processing must be carefully balanced. Environmentally, SSF has been reported to exhibit low emissions, contributing to a reduced environmental footprint (Catalán et al., 2019). Recent techno-economic analyses reinforce this perspective by demonstrating that residue-based SSF platforms can achieve competitive profitability when process parameters and product markets are optimized. For example, Sosa-Martínez et al. (2024) reported favourable return-on-investment and payback periods for enzyme co-production from agro-industrial residues, highlighting the economic relevance of substrate valorisation and process integration. Complementary large-scale fermentation modelling by Cunniffe et al. (2025) further illustrates how downstream purification and substrate costs dominate overall economics, underscoring the importance of process intensification strategies that SSF can provide. Broader techno-economic and sustainability assessments of residue-based bioprocessing systems, such as those described by Ganguly et al. (2025), indicate that integrating biological conversion with waste streams can yield competitive production costs while reducing environmental burdens. However, life cycle assessment studies specific to SSF remain scarce and are mostly limited to laboratory-scale systems, highlighting the need for industrial-scale evaluations that capture real operational conditions and downstream impacts.

Within a biorefinery framework, SSF and SmF should be regarded as complementary rather than competing technologies. Residue characteristics, particularly moisture content, can guide the selection of SSF, SmF, or sequential combinations of both, as demonstrated in recent studies using integrated SSF–SmF schemes for enzyme production from organic waste (López-Gómez and Venus, 2021). Furthermore, the solid fraction remaining after SSF can be valorised through anaerobic digestion or composting, contributing to biogas production or fertiliser generation, provided that solvent residues and moisture levels are appropriately managed (Font-Pomarol et al., 2025). Altogether, this integration reinforces the role of SSF as a flexible and resource-efficient component of future biorefinery systems aimed at maximising residue valorisation and supporting zero-waste strategies.

4. Challenges, future perspectives, and concluding remarks

This review summarises the current role of solid-state fermentation as a promising platform for the valorisation of low-cost organic residues into marketable bioproducts, with particular attention to the challenges associated with scale-up in packed-bed reactors. SSF is increasingly regarded as an attractive option within sustainable waste management and circular bioeconomy frameworks because it can directly transform agro-industrial residues and other biodegradable solids into enzymes, biosurfactants, food and feed ingredients, and other value-added products, often with lower water requirements than other fermentation systems. At the same time, the review highlights that the industrial implementation of SSF remains far more limited than its laboratory development. Although composting demonstrates that biological treatment of solids can be successfully performed at large scale, the controlled production of target metabolites in monoculture SSF systems still faces important engineering and operational limitations that reduce

process robustness and industrial attractiveness.

Despite the recognised potential of SSF for residue valorisation, its large-scale implementation is still constrained by a set of technological barriers that are closely connected to the solid nature of the process. These barriers are particularly relevant when heterogeneous organic residues are used as substrates, since their composition, particle structure, moisture retention capacity and native microbiota directly influence microbial activity and product formation. Therefore, scaling up SSF should not be understood simply as increasing reactor volume, but as the need to maintain biological performance, process reproducibility and feasible product recovery under more demanding operational conditions. In this context, three critical challenges remain central:

- Mass transfer limitations, including uneven oxygen supply, moisture distribution, nutrient availability and inoculum dispersion within the solid matrix. These problems become more pronounced as bed height and reactor volume increase, especially when substrates are heterogeneous, easily compacted or structurally unstable.
- Heat transfer constraints, mainly associated with the accumulation of metabolic heat in poorly conductive solid beds. This can generate axial and radial temperature gradients, local overheating and reduced microbial growth or product formation, particularly in packed-bed systems.
- Downstream processing complexity, since recovering products from solid matrices often requires extraction, separation and purification steps involving water, buffers, solvents or additional energy input. These requirements can increase operational costs and may partially offset the environmental advantages achieved during fermentation.

Addressing these challenges requires an integrated scale-up strategy in which reactor design, aeration, moisture control, process monitoring, modelling tools and downstream processing are considered together from the early stages of development. In this sense, SSF should be evaluated not only as a low-water fermentation process, but as a complete bioprocess whose feasibility depends on the interaction between substrate properties, microbial behaviour, reactor configuration and product recovery.

Several future directions emerge as particularly relevant for overcoming these barriers. First, reactor design improvements should continue to focus on reducing internal gradients and improving process control. In this context, biotrickling and solid-substrate fermentation configurations appear especially promising because they introduce a controlled liquid phase that can enhance nutrient redistribution, facilitate staged feeding, and allow non-invasive monitoring through liquid sampling. These systems may also open new possibilities for recovering soluble metabolites and integrating additional nutrient-rich side streams into SSF schemes. Second, computational modelling should play a more central role in future scale-up research. CFD, digital twins, and AI-based tools offer strong potential to simulate airflow, moisture, and temperature behaviour, optimise operational strategies, and reduce the experimental burden associated with pilot-scale testing. Third, the use of thermotolerant and thermophilic microbial strains represents a practical complementary strategy to mitigate overheating in large-scale systems, improving process resilience under the thermal stress that commonly develops in packed beds. Although all these approaches are already showing encouraging results at laboratory scale, their validation under pilot and industrial conditions is still limited and requires further work.

Future studies should therefore move beyond isolated proof-of-concept experiments and address SSF scale-up through a more integrated perspective. More research is needed on optimal reactor operation, robust process design, sensor-based monitoring, accessible modelling platforms, and realistic product recovery strategies. In parallel, broader techno-economic and environmental assessments will be essential to determine under which conditions SSF can truly become competitive at industrial scale. In this regard, SSF should not be viewed as a universal replacement for submerged fermentation, but rather as a

complementary platform whose advantages depend on the right combination of residue type, microorganism, bioreactor design, target product, and downstream requirements. Within future biorefinery frameworks, SSF may be especially valuable when integrated with other technologies such as anaerobic digestion, composting, or sequential SSF–SmF schemes to maximize resource efficiency and minimise waste.

Overall, solid-state fermentation holds significant potential for converting low-cost solid residues into marketable bioproducts. However, its industrial-scale development using packed-bed reactors remains limited, mainly due to mass and heat transfer constraints, among others. Recent developments in bioreactor design, computational modelling, and the application of thermotolerant and thermophilic microbial strains offer promising solutions to overcome these barriers. Although these strategies are showing encouraging results at laboratory scale, their implementation under larger-scale conditions is still limited. Advancing SSF towards industrial applications will require targeted research focused on optimal operation, robust processes, and the adaptation of new technologies to practical industrial settings. Strengthening these areas will be crucial for transitioning SSF from a promising lab-scale technique to a robust industrial platform within sustainable waste management and circular bioeconomy frameworks.

CRedit authorship contribution statement

Jose Bueno-Mancebo: Conceptualization, Writing – original draft. **Adriana Artola:** Conceptualization, Supervision, Validation, Writing – review & editing. **Raquel Barrena:** Conceptualization, Resources, Supervision, Writing – review & editing. **Teresa Gea:** Conceptualization, Funding acquisition, Resources, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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