Solid-state fermentation: a review of its opportunities and challenges in the framework of circular bioeconomy

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Fermentación en estado sólido: revisión de las oportunidades y retos de la tecnología en el marco de la bioeconomía circular

Fermentació en estat sòlid: revisió de les oportunitats i reptes de la tecnologia en el marc de la bioeconomia circular

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ABSTRACT

Solid-state fermentation (SSF) is on the way to become an attractive alternative for the valorisation of a wide range of organic waste. In biological terms, SSF can be defined as the cultivation process in which microorganisms grow on solid materials without the presence of free water. When these solid materials are organic waste and the objective is to produce one or several bioproducts of added value, SSF is a clear opportunity for circular bioeconomy, with a new paradigm "from waste to resource". The development of SSF started a couple of decades ago, with biomolecules that only could be produced through biological systems, such as enzymes or antibiotics. However, a new generation of SSF bioproducts, which have a "twin" produced by chemical pathways, has emerged in the last years, with the advantages of having lower environmental impacts (for instance, no need of water and less energy requirements) and using waste as substrate. Some of these compounds are highly relevant in the field of chemical engineering: biosurfactants, biopesticides, aromas, bioplastics, pigments and bioflocculants, among others. This review explores the new advances in SSF: from the organic waste used as substrate to the main challenges SSF is facing, that is, mass and heat transfer limitations, bioproducts downstream and scale-up.

Keywords: bioproducts; biorefinery; circular bioeconomy; organic waste; solid-state fermentation.

RESUMEN

La fermentación en estado sólido (FES) está en camino de convertirse en una alternativa atractiva para la valorización de una amplia gama de residuos orgánicos. En términos biológicos, la FES se puede definir como un proceso biotecnológico en el que los microorganismos crecen sobre materiales sólidos sin la presencia de agua libre. Cuando estos materiales sólidos son residuos orgánicos y el objetivo es producir uno o varios bioproductos de valor añadido, la FES es una clara oportunidad para la bioeconomía circular, con un nuevo paradigma "de residuo a recurso". El desarrollo de la FES comenzó hace un par de décadas, con biomoléculas que solo podían producirse a través de sistemas biológicos, como enzimas o antibióticos. Sin embargo, en los últimos años ha surgido una nueva generación de bioproductos, que tienen un "gemelo" producido por vías químicas, con la ventaja de tener menores impactos ambientales (por ejemplo, no necesitan agua y requieren menos energía) y utilizar residuos como materia prima. Algunos de estos compuestos son de gran relevancia en el campo de la ingeniería química: biosurfactantes, biopesticidas, aromas, bioplásticos, pigmentos y biofloculantes, entre otros. Esta revisión explora los nuevos avances en FES, desde los residuos orgánicos utilizados como sustrato hasta los principales desafíos a los que se enfrenta la FES: limitaciones de transferencia de materia y energía, necesidad de purificación de los bioproductos y escalado de los procesos.

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Palabras clave: bioeconomía circular; bioproductos; biorrefinería; fermentación en estado sólido; residuo orgánico.

RESUM

La fermentació en estat sòlid (FES) s'està convertint en una alternativa atractiva per a la valorització d'una àmplia gamma de residus orgànics. En termes biològics, la FES es pot definir com un procés biotecnològic en què els microorganismes creixen sobre materials sòlids sense presència d'aigua lliure. Quan aquests materials sòlids són residus orgànics i l'objectiu és produir un o diversos bioproductes de valor afegit, la FES és una oportunitat clara per a la bioeconomia circular, amb un nou paradigma "de residu a recurs". El desenvolupament de la FES va començar fa un parell de dècades, amb biomolècules que només es podien produir a través de sistemes biològics, com ara enzims o antibiòtics. Tot i això, en els últims anys ha sorgit una nova generació de bioproductes, que tenen un "bessó" produït per vies químiques, amb l'avantatge de tenir menors impactes ambientals (per exemple, no necessiten aigua i requereixen menys energia) i utilitzar residus com matèria primera. Alguns d'aquests compostos són de gran rellevància al camp de l'enginyeria química: biosurfactants, biopesticides, aromes, bioplàstics, pigments i biofloculants, entre d'altres. Aquesta revisió explora els nous avenços a FES, des dels residus orgànics utilitzats com a substrat fins als principals desafiaments a què s'enfronta la FES: limitacions de transferència de matèria i energia, necessitat de purificació dels bioproductes i escalat dels processos.

Paraules clau: bioeconomia circular; bioproductes; biorefineria; fermentació en estat sòlid; residu orgànic.

INTRODUCTION

With the continuous increase in the worldwide generation of organic waste, the need to find cleaner and sustainable alternatives to the traditional ways of treatment and management, such as incineration and disposal in landfills, is being intensively explored. This need, together with the current situation of scarcity of materials and energy, favours an approach in which organic waste plays an important role as a part of circular economy, considering waste as resource. The main technologies already available to lead this transition are anaerobic digestion [1] and composting [2]. Notwithstanding this, in recent years, a new alternative has been gaining acceptance: solid-state fermentation (SSF). According to Pandey [3], SSF is defined as "the fermentation involving solids in absence (or near absence) of free water; however, substrate must possess enough moisture to support growth and metabolism of microorganisms". When using organic waste as substrate, the main objective of SSF is to produce biological compounds of high value as an alternative to traditional chemical compounds, with the benefit of being biodegradable [4]. In addition to this, the exhaust solid resulting from the SSF after the recovery of the bioproducts can be valorised using anaerobic digestion or composting [5].

In practical terms, SSF takes place in a bioreactor, typically aerobic, which is filled with the solid substrate and inoculated with the strain of interest to produce the desired bioproduct [6]. Once produced, this bioproduct must be recovered, although in some cases the final fermented solid can be used as end product, without a defined downstream process [7]. Several types of reactors have been used in SSF: packed-bed reactors, mechanically stirred reactors, tray reactors and some approaches to continuous or semicontinuous flow configurations [8]. Figure 1 shows a schematic representation of the different elements involved in solid-state fermentation, with examples of different microorganisms, support materials, carbon sources, other specific sources, reactor types and bioproducts produced. All these configurations have a common objective in the scaling process: to overcome the limitations of mass and heat transfer in an organic porous matrix, which hampers the scale-up of SSF, one of the main obstacles to its full use and commercialization [9,10].

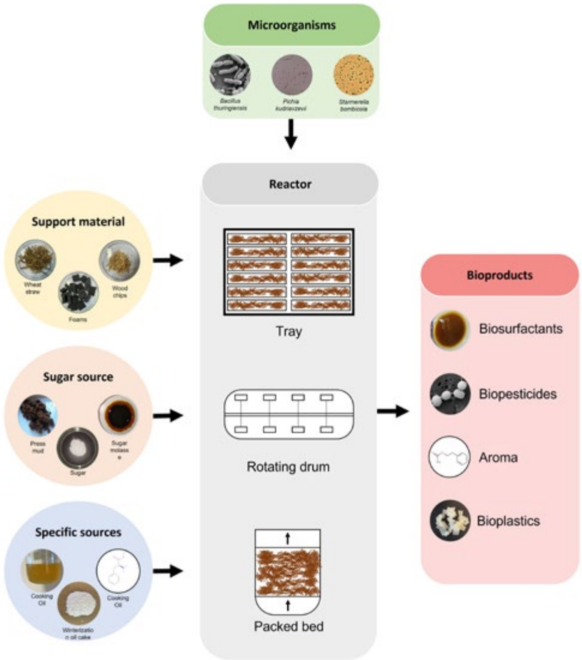

Figure 1: *Schematic representation of the different elements involved in solid-state fermentation. Examples of different microorganisms, support materials, carbon sources, other specific sources, reactor types and bioproducts produced.*

SSF is not a totally new idea as it has been used in the food industry. Composting can be also considered a type of SSF. However, in the last two decades, this technology has become a promising biotechnological tool to produce new bioproducts, beyond the hydrolytic enzymes, which were the first ones produced by SSF [11]. Currently, SSF is being investigated to produce materials that replace high-volume chemical products such as biopesticides, biosurfactants, aromas or bioplastics, among others. This work is focused on these new generation of bioproducts, the organic waste used as substrate and some of the main limitations of SSF.

ORGANIC WASTE AS SUBSTRATE FOR SOLID-STATE FERMENTATION

Lignocellulosic agricultural waste is the most commonly used substrate in SSF [12]. However, other typologies of organic waste have been recently used as substrates to obtain a defined bioproduct to take profit of their specific biochemical composition. This is the typical case of biosurfactants, for instance, where lipids are essential [13], whereas other complex organic materials such as the organic fraction of municipal solid waste or digestate have been also tested [14].

Table 1 summarizes a compilation of some substrates used in SSF to produce specific metabolites. Table 1 does not intend to be exhaustive but to show recent and representative organic waste used in SSF.

Table 1 shows the wide variety of combinations used in SSF to produce selected bioproducts. It is important to note that most studies are performed at lab scale under well-controlled conditions, which is somewhat unrealistic. It can also be observed that fungi have a predominant role in SSF. Nonetheless, it is expected an increase of the number of strains used in SSF, as new microorganisms are being isolated [19].

EMERGING BIOPRODUCTS FROM SOLID-STATE FERMENTATION

The current list of bioproducts produced from SSF is very long and it changes in time, to be updated with new products and processes [6,20]. In this review, some of the main ones will be considered:

Biosurfactants: Biosurfactants refer to surfactants of microbial origin. Like synthetic surfactants, they are composed of a hydrophilic moiety made up of amino acids, peptides, (poly)saccharides or sugar alcohols and a hydrophobic moiety consisting of fatty acids. Correspondingly, the significant classes of biosurfactants include glycolipids, lipopeptides and lipoproteins, and polymeric surfactants [12,21].

Biopesticides: A large number of microorganisms are able to produce compounds that are lethal for some typical plagues that are a problem for the cultivation of certain crops. Biopesticides have gained importance in the last years in comparison to traditional chemical products, because of their selective action, its biodegradability and, in general, their innocuousness to the environment and food chain. Biopesticides is a denomination that include biological control agents for plagues of mainly insects and fungi, and they are produced from a wide number of species [18,22]. In the case of SSF using waste as substrate, their development is relatively recent. The reason for this is that not all the biopesticide producing strains are able to thrive in non-sterile solid-state media.

Aromas and flavours: This field is especially interesting as typically synthetic products or natural products (after a costly extraction) are being used in food and other industries. Some molecules such as 2-phenylethanol, widely used in industry due to its rose-like odour and antibacterial properties, have been produced via SSF using several agro-industrial wastes (mainly bagasse and molasses). Other similar processes have been focused on the production of fruit-like odour, using advanced reactor configurations [23,24].

Bioplastics: This field has been traditionally related to wastewater research, especially in the case of PHA (polyhydroxyalkanoate) and PHB (polyhydroxybutyrate). In the case of SSF, several recent works report how to produce these novel materials through SSF, using lignocellulosic-derived residues to produce lignocellulolytic enzymes from fungal strains [25].

Table 1: *Compilation of the nexus organic waste/strain/bioproduct recently used in solid-state fermentation.*

Solid-state fermentation objectives	Bioproduct	Strain	Reference
Increase the nutritional value and degrade the lignin of wine production waste	Animal feed	White rot fungi	[15]
Use of radiofrequency for drying the SSF solid using soybean and rice residues as substrates	Antioxidants	*Wolfiporia cocos*	[16]
Techno-economic analysis of the production of sophorolipids using molasses and sunflower oil winterization waste	Sophorolipids	*Starmerella bombicola*	[17]
Continuous distillation combined with vapour permeation for the extraction of ethanol produced by the fermentation of sorghum in a rotary drum	Bioethanol	*Saccharomyces cerevisiae*	[11]
Production of fungal conidia from rice husk and beer production waste as substrates	Biopesticides	*Trichoderma harzianum*	[18]

Antioxidants: this is a property of certain chemicals that is of high value for the food and cosmetics industry, among others. In the case of SSF, there are several works showing the suitability of certain waste to be used as a substrate for the production of antioxidant phenolic compounds, being waste from olive oil production the most used [26].

Recent literature is full of other specific bioproducts obtained from SSF of selected organic waste: bioflocculants, pigments or other more specific compounds. Although interesting, most of these studies are again performed at lab scale [27].

MAIN CHALLENGES OF SOLID-STATE FERMENTATION

Heat and mass transfer limitations. Scale-up

To reach the status of a consolidated and commercial technology, SSF still needs to overcome a big challenge regarding mass and heat transfer limitations in solid organic matrices. More specifically, several variables are critically affected by these limitations. This is the case of temperature, which plays an important role in SSF performance at pilot or representative demonstration scales. On one hand, microbial strains used in SSF often need very specific temperature conditions for their growth, hence it is very important to control this parameter. On the other hand, SSF produces a temperature increase that needs to be regulated in an organic matrix with low thermal conductivity and a significant percentage of free air space [28]. Temperature control in SSF is normally achieved by convection through forced-aeration to increase heat dissipation and to avoid undesired temperature gradients. However, forced aeration also provokes moisture losses and drying, therefore, it must be carefully controlled [29]. In this sense, the configuration of novel SSF bioreactors, with innovative aeration and cooling strategies (including irrigation, mixing, etc.) has been the topic of recent research [30,31]. Figure 2 shows a representation of how different aeration strategies can affect different parameters such as temperature or moisture. The first image (left) shows an inefficient aeration system, where the air takes the path of least resistance creating gradients of temperature and moisture shown in the image as darker substrate. The second image (right) shows a more optimized strategy that allows an even aeration of the substrate.

Regarding mass transfer, this specific limitation cannot be considered as independent from those related to heat transfer. In SSF, the access to oxygen is essential for the microbiological process and, in consequence, to have a proper aeration system becomes critical [32]. Mixing is also a useful strategy to address mass (and heat) transfer issues, maintaining more uniform conditions of temperature and enhancing gas or liquid interface transport. The presence of a heterogeneous medium can hamper the access of microorganisms to substrates, with zones with different nutrient content [33]. However, mixing must be carefully designed, as it can have a negative impact on porosity, on the microorganisms' attachment to the substrate, etc.

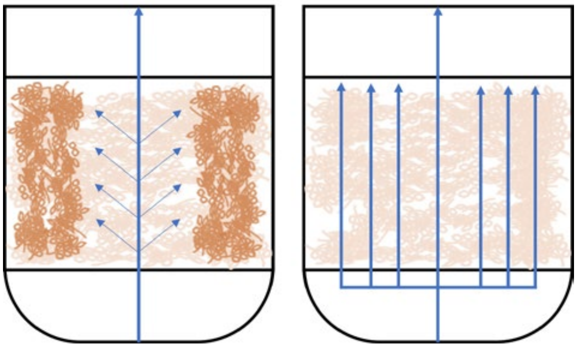

Figure 2: *Representation of how different aeration strategies can affect different parameters such as temperature or moisture. Left: an inefficient aeration system, where the air takes the path of least resistance creating gradients of temperature and moisture shown in the image as darker substrate. Right: a more optimized strategy that allows an even aeration of the substrate.*

All the above mentioned issues imply important problems in the modelling or scale-up of SSF processes [34]. In the case of SSF bioreactors, several attempts to find a suitable model for scaling them up have been recently published [28,35]. In summary, tray and packed bed reactors are the most used and known configurations [9,15,36].

Purification and down-stream

The other main challenge of SSF is the downstream or purification of the end bioproducts to get a commercial material. This challenge is mainly due to the heterogeneity and solid-state of the materials, which usually results in a complex multiple-step downstream processes. In fact, SSF downstream cost can reach up to 70% of the total cost if a high recovery yield and purity is to be achieved [37]. Moreover, SSF has another typical problem related to the extraction of some bioproducts: the use of environmentally unfriendly solvents [38]. Contrarily to the problems derived from heat and mass transfer limitations and the proposal of new SSF bioreactors, scientific literature on downstream processes of SSF bioproducts is very limited.

Nevertheless, it is worthwhile to mention that, in some applications, the fermented solid can be directly used as the final product, thus avoiding an expensive process with a high environmental impact [7]. If this strategy is not possible, after the extraction of the bioproducts, the exhausted solid becomes a new waste to manage. Animal feed, substrate for anaerobic digestion or composting and SSF are the most attractive options to valorise this material [39].

Product recovery can be more difficult if the metabolites of interest diffuse into the solid matrix, as the extraction often involves the use of organic solvents, which has several disadvantages: high cost, high environmental impact, time constraints and toxic solvents that affect the recovery of the spent solid [40]. This strategy also presents some incompatibilities with health regulations, preventing the marketing of some bioproducts. For this reason, new techniques have

Table 2: *Summary of some processes used in the purification of bioproducts obtained from solid-state fermentation.*

Category	Bioproducts	Extraction methods	Details	References
Biosurfactant	Sophorolipids	Solvent extraction	Ethyl acetate	[34]
Biopesticides	Bt-crystal protein	Enriched compost		[7]
Bioplastics	PHA	Solvent extraction		[41]
Aromas	2-phenyl-ethanol	Methanol	Filtration	[42]
Antioxidants	Phenolic compounds	Microwave	Water or ethanol	[34]
Other bioproducts	6-Pentyl-a-pyrone	Soxhlet extraction	Hexane	[44]
	Bioflocculant	Water		[27]
	Animal feed	Improvement of solid properties		[14]

emerged to overcome this problem, such as ultrasonic-assisted extraction, microwave-assisted extraction, supercritical fluid extraction, solid-liquid extraction, with pressurized liquids, subcritical water extraction, solid-solid extraction or enzyme-assisted extraction [6]. Anyway, the selection of an extraction method depends on the characteristics of the product to be extracted and there are no universal recipes (Table 2). Nowadays, downstream seems the more important handicap for a full development and implementation of SSF.

CONCLUSIONS

This review highlights the most novel and recent applications of SSF to obtain bioproducts using practically all typologies of organic waste as substrate. Bioproducts from SSF are of a wide variety and some of them are called to play a key role in the full development of the Circular Bioeconomy. However, given that SSF research is still in an emerging stage with an important lack of studies that, at least, present bench-scale SSF experiments, the main challenges of SSF to overcome in the next years are scale-up and downstream.

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