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REVIEW

Enzyme Production by Solid State Fermentation: General Aspects and an Analysis of the Physicochemical Characteristics of Substrates for Agro-industrial Wastes Valorization

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Abstract Solid state fermentation (SSF) is being used as a powerful technology for producing various microbial metabolites such as enzymes. The characteristics of this process, such as low risk of contamination, increased yield, utilization of low-cost substrates, processing simplicity, lower energy requirement and decreased waste water production, have made it more attractive than submerged fermentation (SmF). Thus, this mini review aimed to present the general aspects of SSF processes, drawing parallels with SmF processes. The application potential of SSF was determined from data on the production of several metabolites in a comparative analysis with SmF, with a specific focus on enzyme production. The important parameters related to the physicochemical characteristics of agro-industrial wastes used for SSF and their effects on the production of several enzymes are also discussed.

Keywords Solid state fermentation · Agro-industrial wastes · Enzyme production · Physicochemical parameters

Introduction

Solid state fermentation (SSF) has gained significant credibility in the biotechnology industry in recent years because of its potential for application in the production of biologically active metabolites and its wide range of applications in the food, fuel, chemical and pharmaceutical industries. The search for sustainable and ecologically friendly processes to replace traditional chemical processes for making products has transformed the industrial sector. Thus SSF is very relevant, since it has several characteristics that make it eco-friendly such as lower energy consumption, less wastewater generation and the employment of agricultural and agroindustrial wastes as substrates, avoiding environmental problems caused by their disposal [1, 2].

SSF involves the growth of microorganisms on moist solid material where the spaces between the particles of the material are filled with a continuous gas phase. It is important to note that the majority of SSF processes involve aerobic organisms such as the filamentous fungi. Thus the word "fermentation" within the concept of "solid state fermentation" is generally used in the more broad sense of "controlled microbial processes" and does not imply that the microorganism is necessarily using fermentation metabolic pathways during cultivation [3].

In recent years, innovative biotechnological processes have explored the use of SSF as a potential technology for producing valuable secondary metabolites such as antibiotics, enzymes, organic acids, bio-pesticides, bio-herbicides, bio-surfactants, biofuels and aromatic compounds [4, 5]. Due to high industrial demand, enzymes produced by microorganisms are well known. Microorganisms are of interest in several research fields because they are excellent sources, are biochemically diverse and can be genetically manipulated [6]. Filamentous fungi, yeasts and bacteria are widely used to produce enzymes by SSF. SSF is an attractive process for filamentous fungus cultivation because the solid substrates have characteristics similar to the natural habitat of the fungi, resulting in improved growth and secretion of a wide range of enzymes. Other characteristics

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of SSF, such as low risk of contamination, high yield, utilization of low-cost substrates, simplicity of processing, lower energy requirements and decreased waste-water production make this process more attractive when compared to submerged fermentation (SmF) [7, 8]. A comparative summary between the major characteristics of SmF and SSF is shown in Table 1. Data relevant to some production processes of several metabolites by SmF and SSF are shown in Table 2.

SSF has generated more economic interest in regions with abundant biomass and low-cost agro-industrial wastes [16]. Data on continental and worldwide production of some agro-industrial products are presented in Table 3 [17]. Processing these raw materials produces byproducts, such as meal and bran, which have low aggregate value but high nutritional value, resulting in a large portion being used as animal feed. Using these waste products as substrates for biotechnological processes, such as producing enzymes by SSF, is a promising example of its potential for generating biomolecules with high aggregate value from low-cost substrates (Table 4).

This mini review aimed to show the aspects that are important for the optimization of SSF enzyme production processes, with a particular focus on physicochemical parameters of the substrates for wastes valorization and several strategies that have been used in scientific research.

Analysis of Physicochemical Parameters for SSF

Several important aspects should be considered when developing and optimizing SSF processes. These mainly include the appropriate selection of variables to be used in the process such as microbial strain, substrate, initial moisture of the medium, incubation temperature and inoculum. In this mini review, special attention was given to the physicochemical parameters of the substrates, which can be understood as the characteristics relating to their physical and structural properties and their chemical composition, including particle size, water absorption capacity, different carbon and nitrogen sources and how these parameters can be used as an interesting tool in the production of enzymes by SSF.

Selecting the appropriate substrate is an extremely important aspect of SSF, as the solid material will act as a physical support and nutrient source. Several materials can be used as SSF supports, including inert supports such as vermiculite, perlite and polyethylene, which can be embedded with a nutrient solution appropriate for microbial growth; and natural supports such as agro-industrial wastes, which already have all of the characteristics needed to promote microorganism growth. Natural supports will be given special attention in this study. The physical and chemical characteristics of these substrates are important parameters for enzyme production using SSF. The effects of particle size, water absorption capacity and chemical composition the substrate on enzyme production by SSF will be discussed below.

Particle Size

The size of the substrate's particles is an important factor for producing enzymes by SSF, as it is directly related to the porosity of the solid substrate. This parameter can be analyzed by granulometric distribution using sieves with known mesh diameters or by determining apparent density.

A more careful analysis of this parameter includes the classification of particle properties based on the porous structure of the substrate, which will directly affect microbial growth and substrate bioconversion. These properties can be classified into intra-particle (thermal, moisture content, grain size, porosity and biological process kinetic properties) and extra-particle (heat transfer, permeability and mass transfer condition properties). The characteristics

Table 1 Comparison between the major characteristics of solid state fermentation (SSF) and submerged fermentation (SmF)

Characteristic	SmF	SSF	References
Culture medium (cost)	High	Low	[1]
Energy requirement	High demand	Low demand	
Yield	Smaller	Greater	
Wastewater generation	High	Low	[2]
Space required	Large	Small	
Temperature control	Easy	Difficult	[3]
pH regulation	Easy	Difficult	
Agitation control	Easy	Difficult	
Nutrient and product regulation	Easy	Difficult	
O_2 solubility and diffusion	Low	High	
Bacterial contamination	High risk	Low risk	[4]
Product recovery and purification	Easy	Less easy	[10]

Table 2 Comparison between the culture medium required in solid state fermentation (SSF) and submerged fermentation (SmF) for the production of various metabolites by microorganisms

Metabolite of interest	Micro-organism	Culture medium		Production		References
		SmF	SSF	SmF	SSF	
Feruloil esterase	*Aspergillus niger*	Concentration in g L^{-1}: ammonium tartrate (1.842), yeast extract (0.5), KH_2PO_4 (0.2), $CaCl_2$ (0.0132), $MgSO_4$ (0.5), beet pulp (15.0), maltose (2.5)	Concentration in g per 100 g dried beet pulp: ammonium tartrate (12.3), yeast extract (3.4), KH_2PO_4 (1.3), $CaCl_2$ (0.09), $MgSO_4$ (3.3) and maltose (2.5)	2.2 nkat g^{-1}	9.6 nkat g^{-1}	[9]
Proteases	*Aspergillus oryzae*	Concentration in g L^{-1}: potassium hydrogen phosphate (1.0), magnesium sulfate (5.0), sodium chloride (5.0) and iron sulfate (0.04); wheat bran (2.0 %)	Wheat meal supplemented with a salt solution similar to the one used for Smf	8.7 U g^{-1}	31.2 U g^{-1}	[10]
Lipases	*Aspergillus* spp.	Concentration in g L^{-1}: wheat meal (10.0), yeast extract (45.0), soybean oil (20.0), KH_2PO_4 (2.0) and $MgSO_4$ (1.0). Trace element solution (mg L^{-1}): $FeSO_4$ (0.63), $MnSO_4$ (0.01) and $ZnSO_4$ (0.62)	Mixture of soybean meal (85.7 %) and rice husk (14.3 %) supplemented with a salt solution containing (g L^{-1}): KH_2PO_4 (2.0), $MgSO_4$ (1.0). Trace element solution (mg L^{-1}): $FeSO_4$ (0.63), $MnSO_4$ (0.01) and $ZnSO_4$ (0.62). Olive oil (2.0 % w/w) and sodium nitrate (2.0 % w/w)	4.52 U	25.22 U	[11]
Tannin acylhydrolase	*Lactobacillus plantarum*	Concentration in g L^{-1}: tannic acid (13.16), glucose (1.5), NH_4Cl (1.0), $CaCl_2$ (1.0), K_2HPO_4 (0.5), KH_2PO_4 (0.5), $MgSO_4$ (0.5) and $MnSO_4$ (0.03)	Coffee husk supplemented with a mineral solution containing (g L^{-1}): tannic acid (10.0); NH_4NO_3 (5.0); KH_2PO_4 (1.0); NaCl (1.0), $MgSO_4$ (1.0) and $CaCl_2$ (0.5)	9.13 U mL^{-1}	5.32 U mL^{-1}	[12]
Proteases	*Aspergillus oryzae*	Tomato pulp (40 g L^{-1}) supplemented with wheat meal (7.92 g L^{-1}) and NaCl (1.18 g L^{-1})	10 g of tomato pulp supplemented with casein (19.79 g L^{-1}) and NaCl (0.92 g L^{-1})	2343.50 U g^{-1}	21,309 U g^{-1}	[13]
Keratinases	*Aspergillus niger*	Concentration in g L^{-1}: $(NH_4)_2SO_4$ (3.5), KH_2PO_4 (1.0), $MgSO_4$ (0.5), KCl (0.1), $ZnSO_4$ (5×10^{-3}) and chicken feathers (10 feathers L^{-1})	Mixture of chicken feathers (0.4 g) and wheat meal (40 g) moistened with a solution of $(NH_4)_2SO_4$ (0.9 %)	21.3 U mL^{-1}	172.7 U mL^{-1}	[14]
Monacolin K	*Monascus purpureus*	Concentration in g L^{-1}: glycerol (180.0), soybean meal (20.0), $NaNO_3$ (2.0), $MgSO_4$ (1.0), K_2HPO_4 (1.0), $ZnSO_4$ (2.0) and corn steep liquor (10 mL L^{-1})	Composition similar to the one used for SmF, with the addition of agar (4.0 %)	2047.03 mg L^{-1}	458.37 mg L^{-1}	[15]

of the substrate particles can directly impact various other parameters, as SSF is a system containing a combination of the three major phases: the substrate itself is the solid phase, the water retained in the matrix and the inter-particle spaces is the liquid phase and the gas present in the spaces or pores is the gas phase (Fig. 1) [4, 27].

In general, small substrate particles provide a larger surface area for microbial attachment, which is desirable.

Table 3 Data on continental and worldwide production (10^3 tons) of several agro-industrial products that create wastes used in solid state fermentation processes

Agro-industrial products	Production quantity (10^3 tons)					
	Africa	America	Asia	Europe	Oceania	World
Cottonseed	2602.50	6088.10	33,794.90	533.8	1522.10	44,541.40
Linseed	115.9	835.1	792.9	485.6	9.4	2238.90
Mustard seed	2.5	171.1	261.8	136.4	–	571.8
Olives	3187.60	492.2	3117.60	13,453.20	93.5	20,404.10
Oranges	7928.10	34,199.20	19,996.30	5699.20	400.9	68,223.70
Rice	29,318.40	36,488.60	6,74,835.70	3895.10	1171.70	7,45,669.50
Rye	93.4	463.2	1159.40	14,944.50	35.1	16,695.60
Soybeans	2246.30	2,40,830.80	27,293.80	5943.30	91.8	2,76,406.00
Sugar cane	97,168.70	10,05,988.90	7,44,857.50	5.4	29,084.60	18,77,105.10
Sunflower seed	2137.70	4602.70	6079.90	31,888.50	44.4	44,753.20
Wheat	28,072.50	1,17,504.40	3,18,834.40	2,25,468.20	23,303.40	7,13,182.90

However, very small particles can have the opposite effect, resulting in clustering, reduced oxygen diffusion and consequently limiting microorganism growth. By contrast larger particles provide larger spaces between the particles, providing better conditions for heat and mass transfer, but they can provide limited surface area for microbial attachment [26–29]. Thus, solid substrates with heterogeneous particle size distributions or with particles of intermediate size are more appropriate for enzyme production by SSF, as they have the necessary characteristics for satisfactory oxygen diffusion together with a larger surface area for microbial growth. Although there is some indication of the most appropriate substrate particle size, this parameter must be assessed for each process. As demonstrated below, the most suitable particle size for solid substrates is extremely variable, it being a function of other process parameters, such as the microorganism and the product of interest.

Melikoglu et al. [30] studied the effects of various culture parameters on protease and glycoamylase production by the microorganism *Aspergillus awamori* using SSF with bread waste. The particles of the bread waste were separated into sizes ranging from 5 to 50 mm and were used as solid substrate. Size directly affected microbial growth and enzyme production during fermentation. The largest values for simultaneous protease and glycoamylase production were 56.4 and 73.6 U g^{-1}, respectively, measured in fermentations performed with 20 mm diameter particles. Enzyme production by the microorganism reacted differently with particles with extreme sizes. The lowest glycoamylase production was observed in fermentations with solid substrate containing 5 and 10 mm particle sizes, whereas the lowest protease production was observed with solid substrate containing 50 mm particles.

Buenrostro-Figueroa et al. [18] evaluated the use of lignocellulosic waste, including sugarcane bagasse, corncobs, coconut husks and candelilla stems (*Euphorbia antisyphilitica*) for ellagitannase production by *A. niger* using SSF. One of the parameters analyzed involved measuring the apparent density of the waste and its effect on enzyme production. The authors were able to detect a direct effect of apparent density on ellagitannase production, where the lowest values of enzymatic activity were detected in solid substrate containing candelilla stems with an apparent density of 0.86 g cm^{-3}, and the highest values were obtained in solid substrate fermented with coconut husks with an apparent density of 0.82 g cm^{-3}, an intermediate value for the wastes analyzed. According to Chávez-González et al. [31], apparent density provides information on the degree of compaction of the material, and it is directly related to the available space for mass and energy transfer. Higher apparent density values imply a lower area:volume ratio, which can result in oxygen diffusion problems by reducing the amount of empty space between particles.

Table 5 summarizes some studies in which the effect of the particle size of different agroindustrial wastes on the production of various enzymes under SSF was demonstrated.

Water Absorption Capacity

One of the most important characteristics for a substrate to be considered adequate for SSF is water retention capacity. This measurement indicates the capacity of the substrate particles to absorb water and is directly related to the availability of hydrophilic groups for binding water molecules [37]. The water absorption capacity of a substrate is crucial for microbial growth and fermentation because it directly impacts physical characteristics of the solid substrate such as pore size, which can be changed by the swelling of the solid particles after water absorption,

Table 4 Enzyme production with industrial applications using various agro-industrial wastes and solid state fermentation (SSF)

Enzyme	Microorganism	Substrate	Culture conditions	References
Protease	Native microbial population	Soy fiber	Solid:liquid ratio: 1:1 Incubation temperature: 37 °C Fermentation time: 96 h	[5]
Elagitanase	*Aspergillus niger*	Sugar cane bagasse, corn cobs and coconut husk	Fermentation time: 32 h Incubation temperature: 35–40 °C Inoculum: 2×10^7 spores g^{-1}	[18]
Protease	*Aspergillus niger*	Wheat, soy and cottonseed meal	Initial moisture content of the medium: 50 % Fermentation time: 24–96 h Incubation temperature: 30 °C Inoculum: 10^7 spores g^{-1}	[19]
Polygalacturonase	*Aspergillus sojae*	Wheat meal	Initial moisture content of the medium: 62 % Incubation temperature: 37 °C Fermentation time: 96 h Inoculation: 10^7 spores g^{-1}	[20]
Xylanase	*Trichoderma viride*	Wheat, soy and sunflower meal, rice husk, sugarcane bagasse and corn cobs	Solid:liquid ratio: 11:10 Fermentation time: 7 days Incubation temperature: 30 °C Inoculation: 10 %	[21]
Peroxidase	*Phanerochaete chrysosporium*	Cassava waste	Solid:liquid ratio: 2:1 Fermentation time: 10 days Incubation temperature: 30 °C	[22]
Chitinase	*Penicillium ochrochloron* MTCC 517	Wheat and rice meal	Initial moisture content of the medium: 70–74 % Fermentation time: 72–96 h Incubation temperature: 30 °C	[23]
Xylanase	*Sporotrichum thermophile*	*Jatropha* seed cake	Solid:liquid ratio: 1:1.5 Incubation temperature: 35 °C Fermentation time: 96 h Inoculum: 6 %	[24]
Protease and lipase	*Aspergillus versicolor*	*Jatropha* seed cake	Initial moisture content of the medium: 20–70 % Fermentation time: 24–240 h Incubation temperature: 20–35 °C Inoculum: 10^3–10^8 spores mL^{-1}	[25]

making them favorable or unfavorable for biodegradation and biomass bioconversion [26]. Having the appropriate amount of water in the solid substrate also plays an important function associated with the availability and diffusion of nutrients and carbon dioxide:oxygen exchange mechanisms during fermentation [38].

The critical humidity point of a substrate is a measure that can be used in parallel with the estimated water absorption capacity of the substrate. This parameter can be calculated from the dehydration kinetics of the material, in which the drying velocities were related to the amount of water removed as a function of time. It represents the amount of water strongly bound to the support and therefore not available for utilization by the microorganisms. Thus, it is recommended that substrates with low critical humidity point values be used [37, 38].

The water absorption capacity and critical humidity point of malt bagasse (waste from the beer-making industry), wheat straw, corncobs, coffee husks, oak cork and vegetable sponge were used as parameters to select the best

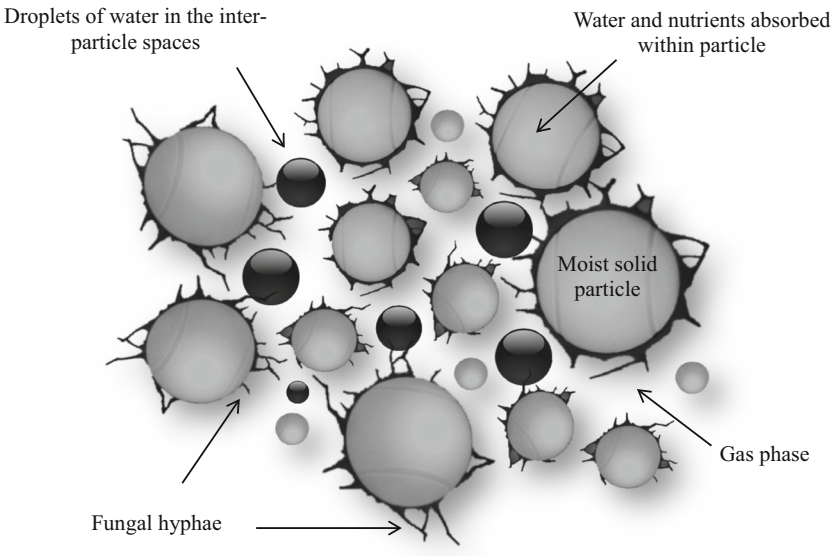

Fig. 1 Diagram of the arrangement of the solid particles and major components of the SSF system during filamentous fungal growth (figure adapted from Mitchel et al. [2])

Table 5 Effect of different particle sizes of various agroindustrial wastes for enzymes production under solid state fermentation

Enzyme	Microorganism	Substrate	Reactor system	Particle size range	Production	References
Glucoamylase	*Aspergillus niger*	A mixed substrate composed by wheat bran and whole corn flour	500 mL Erlenmeyer flasks containing 50 g of solid substrate	180–300 μm	788.12 U g^{-1}	[32]
				300–425 μm	785.98 U g^{-1}	
				425–500 μm	911.03 U g^{-1}	
				500–600 μm	852.94 U g^{-1}	
				850 μm–1 mm	685.82 U g^{-1}	
				1.0–1.4 mm	598.98 U g^{-1}	
				>1.4 mm	508.87 U g^{-1}	
Fibrinolytic enzyme	*Fusarium oxysporum*	Rice chaff	300 mL Erlenmeyer flasks containing 20 g of solid substrate	76 μm	38 IU mL^{-1}	[33]
				104 μm	38 IU mL^{-1}	
				180 μm	59 IU mL^{-1}	
				400 μm	86 IU mL^{-1}	
				900 μm	36 IU mL^{-1}	
				>900 μm	32 IU mL^{-1}	
Protease	*Engyodontium album*	Wheat bran	250 mL Erlenmeyer flasks containing 10 g of solid substrate	<425 μm	12,089 U g^{-1}	[34]
				425–1400 μm	10,267 U g^{-1}	
Xylanase	*Aspergillus fumigatus*	Oil palm trunk	Flasks (flask volume and quantity of solid substrate—not specified)	125 μm	418 U g^{-1}	[35]
				250 μm	310 U g^{-1}	
				500 μm	290 U g^{-1}	
				600 μm	290 U g^{-1}	
				710 μm	275 U g^{-1}	
				800 μm	200 U g^{-1}	
Laccase	*Pleurotus ostreatus* IE-8	Sugar cane bagasse	250 mL Erlenmeyer flasks containing 5 g of solid substrate	0.92 mm	0.006 U g^{-1}	[36]
				1.68 mm	0.005 U g^{-1}	
				2.90 mm	0.021 U g^{-1}	

substrate for producing β-fructofuranosidase by *A. japonicus* ATCC 20236 [37]. The highest water absorption capacities were observed for wheat straw, malt bagasse and coffee husks with estimated values of 9.95, 9.03 and 8.30 g of water per g of material, respectively. For critical humidity point, malt bagasse, oak cork and wheat straw had values of 60, 58 and 57 %, respectively, which were the highest values. According to the authors, an analysis based on these isolated parameters cannot precisely indicate which substrate would generate the highest production of β-fructofuranosidase by *A. japonicus* ATCC 20236. However, these parameters can be used to estimate in which substrates cellular adhesion and microbial growth are favored. The highest enzyme production was detected when the microorganism was cultured in corncobs, which had the lowest critical humidity point (50 %) and the second lowest water absorption capacity (3.77 g water/g material) [37].

Orzua et al. [38] analyzed the feasibility of using ten agro-industrial wastes as supports for growing a strain of *A. niger* in SSF. The authors included the parameters water absorption capacity and critical humidity point as determinants for better selection. The study concluded that coconut husks, apple pulp, lime peels and orange peels were the most promising materials for SSF utilization, as they have a high water absorption capacity and adequate critical humidity point in addition to allowing a good growth rate for the *A. niger* strain.

Although there is some indication that substrates with higher water absorption capacity are better for culturing filamentous fungi in SSF, it can be inferred that when this value rises above a certain limit, the mechanisms involved in microorganism growth and (consequently) enzyme secretion are compromised. Two important considerations should be remembered: the first is the selection of substrates with high water absorption indices and the second is the selection of substrates with low capacity. Materials with high water absorption capacity have the desirable effect of maintaining their moisture level throughout the fermentation process. However, if the amount of water added to the solid substrate is sufficiently high to be completely absorbed by the material, this results in very high initial moisture content values, decreased porosity, loss of particle structure and reduced gas exchange. These phenomena negatively impact microorganism growth and enzyme production. In contrast, the amount of water that can be added to the solid substrate when using a substrate with low water absorption capacity is limited, can result in low initial moisture levels and, consequently, reduced nutrient solubility, less substrate swelling and higher surface tension of water particles, hindering microbial growth.

It is evident that a minimum water absorption capacity of the substrates used for enzyme production by SSF is necessary, to ensure microbial growth and the carrying out of their biological activities during the initial hours of fermentation. However, it is important to note that some strategies can be used to solve the problems related to the low water absorption capacity of agro-industrial wastes. In the specific case in which the substrate does not have sufficient water absorption capacity to preserve the minimal conditions for microbial growth, additional water can be provided during the fermentation process to maintain a suitable moisture content of the solid substrate. In addition, the formulation of solid substrates containing mixtures of agro-industrial wastes with different water absorption capacities is a way to balance this property, making them appropriate for microbial growth and enzyme production under SSF. These strategies can be used in order to increase the possibilities of using different agro-industrial residues.

Chemical Composition

Enzyme production by SSF can be affected by several culture parameters, including certain chemical components that can be added or are naturally present in the substrate and can be used as inducers. The substrate should contain an adequate proportion of nutrients that will be used as carbon and nitrogen sources (C:N ratio) for satisfactory microbial growth during fermentation [19].

Ghanem et al. [39] analyzed the production of xylanase by *A. terreus* using wheat straw and meal, corncobs, rice husks and barley bagasse as SSF substrates. The study included an analysis comparing production with the cellulose level in the substrate, which can promote secretion of the enzyme. Of the substrates evaluated, the wheat straw had the most cellulose (50.7 %), and it resulted in the highest production of xylanase by *A. terreus* (16.16 U mL^{-1}).

Agro-industrial waste obtained while extracting oil from seeds has also been reported to be a potential substrate for producing lipases from microorganisms due to their residual lipid content, which can induce enzyme production [40, 41]. Ferraz et al. [42] studied lipase production by *Sporobolomyces ruberrimus* using soybean meal, rice meal and sugarcane bagasse as SSF substrates. Of the wastes analyzed, the rice meal had the highest lipid content (16.43 %) and allowed the highest microorganismal lipase production.

Thanapimmetha et al. [43] performed a comparative analysis with a study by Chutmanop et al. [6] on the production of proteases using the same strain of *A. oryzae,* and deoiled *Jatropha curcas* seed cake, wheat bran or rice bran. The analysis showed that protease production with rice meal and wheat meal was 22 and 30 % lower, respectively, than with *Jatropha* seed cake. The increased protease production using *Jatropha* seed cake was due to the high level of proteins present in the substrate. When protein levels were

compared between substrates, *Jatropha* seed cake had 60 % protein, whereas the estimated values for rice and wheat meal were 13–14 and 12–17 %, respectively. According to these authors, protease secretion by the microorganisms can be stimulated by the amino acids present in the proteins, which results in higher protease production in substrates with higher amounts of protein. Similar results were observed by Castro et al. [19], wherein protein content was strongly and significantly correlated with the production of proteases by *A. niger* using wheat bran, soybean meal and cottonseed meal during the first 48 h of solid state fermentation.

Conclusion

Solid state fermentation (SSF) is a promising process for producing various biomolecules, including enzymes. The optimization of processes for producing enzymes by SSF includes the study of various culture parameters, which are extremely variable depending on the enzyme to be produced, the substrate used and the microorganism. In this study, special attention was paid to the physicochemical parameters of agro-industrial wastes, including particle size, water absorption capacity and chemical composition. Although these parameters have been discussed individually, they must be analyzed together to better understand their impact on fermentation processes in addition to the contribution of each one to the definition of the best microbial culture conditions to achieve high levels of production for metabolites of interest such as enzymes. It was evident that studies on solid state fermentation processes will continue to be systematically explored for the production of high value-added molecules, making it an important tool for the valorization of agro-industrial wastes.

Conflict of interest The authors declare that they have no conflict of interest.

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