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Two-phase and two-dimensional model describing heat and water transfer during solid-state fermentation within a packed-bed bioreactor

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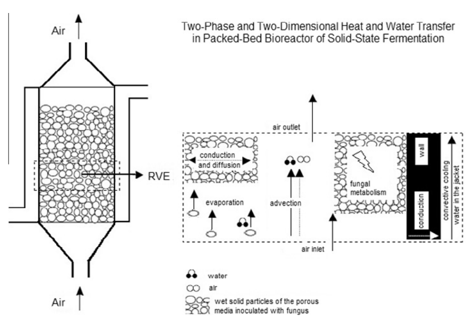
HIGHLIGHTS

- We proposed novel two-phase and two-dimensional model for solid-state fermentation.
- Heat and water transfers are modeled and simulated in packed-bed bioreactor.
- Most transport mechanisms are included and realistic parameters are applied.
- Model predictions agreed with experimental data concerning overheating and drying.
- The novel model can guide the scale-up of bioreactors for solid-state fermentation.

GRAPHICAL ABSTRACT



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ABSTRACT

In the current paper, a two-phase and two-dimensional model describing heat and water transfer in a packed-bed bioreactor (PBB) for solid-state fermentation (SSF) is proposed. The model considers most of the transport mechanisms taking place in solid and gas phases and for axial and radial directions. For simulation, realistic physical properties of the particles and of the bed were employed, as well as interface coefficients were calculated based on classical correlations. The case-study was the solid-state cultivation of the newly isolated thermophilic fungus *Myceliophthora thermophila* I-1D3b in a mixture of sugarcane bagasse (SCB) and wheat bran (WB) within a narrow cylindrical and jacketed PBB. For non-saturated aeration, results showed that substrate drying near the inlet of the bioreactor harms fungal growth. For narrow PBB, jacket plays important rule on heat removal; for large-diameter PBB, radial heat removal becomes negligible. Simulated results agreed with experimental ones. The novel model here proposed is a powerful tool for guiding the scale-up of PBB for SSF.

1. Introduction

Packed-beds are extensively used in important unity operation in chemical, food and process industries. Some application examples include their use as separators, absorbers, dryers, filters, heat exchangers and chemical and biochemical reactors [1–3]. Solid state fermentation (SSF) bioreactor is a particular case of packed beds, which is under the spotlight in literature.

SSF is a biotechnological process that offers numerous economic and industrial advantages to reduce production costs of fermented products. It concerns the culture of microorganisms on moist solid

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substrates, without dripping water, and a continuous gas-phase in the inter-particle spaces. SSF technology provides new processes opportunities as it allows the use of agro-industrial by-products as substrates without needing an extensive pretreatment, leading to the production of high concentrations of high-added value products, such as enzymes. Moreover, because SSF products are not highly diluted, they can be easier to recover than products produced in traditional submerged fermentation (SbF) [4,5].

A special group of enzymes that has received attention from scientific and technological communities is the group of cellulolytic enzymes. These enzymes are able to depolymerize the biomass of agricultural residues into fermentable sugars through an ecologically friendly route. The final target is producing biofuels from biomass, a sustainable alternative to increase fuel production without decreasing croplands for food production. SSF has been used to produce cellulases, hemicellulases and ligninases from a variety of biomasses, such as green or dried grasses, sugarcane bagasse, wheat bran, rice straw, soybean hulls, sawdust, orange pulp and peel, corncob and corn straw [6–14].

Due to the low water activities, filamentous fungi are the most suitable microorganisms for SSF. Moreover, for the majority of filamentous fungal species, solid-state media reproduce their natural habitat [15]. One extra-advantage in using filamentous fungi in SSF is that such microorganisms have an extraordinary capacity to secrete large amounts of proteins and other metabolic products to the growth medium, so it is feasible to be exploited by the biotechnological industry for the production of industrial enzymes [16]. Moreover, thermophilic fungi are gaining attention from researches in SSF due to the intrinsic thermal stability of the enzymes [17] and because some thermophilic fungi have been recently reported as good producers of cellulolytic enzymes complexes in experiments carried out in glass flasks or in plastic bags [9,18,19].

As well as SbF, SSF requires exploratory studies in flasks scale in order to evaluate the adaptation of the microorganism to the culture media and also if the concentration of the interesting product is commercially feasible. The parameters usually controlled at exploratory assays are composition, moisture content and pH of the substrate, temperature of cultivation and duration of the process. Independent and interaction effects are evaluated at this scale. After the exploratory studies, it is needed to design and develop a bioreactor which fulfils the process needs. However, it is not recommended that the optimal experimental conditions found in glass flasks tests be immediately transposed to the bioreactors tests, since the dynamic conditions observed in the reactors are quite different [20].

There are two basic configurations for SSF bioreactors: the fixed beds and the moving beds. The latter category is best represented by the rotating drum bioreactor, which is operationally flexible and provides efficient automatic control alternatives. Nevertheless, due to its complex design, high cost, elevated maintenance requirement, and non-adequacy to shear stress sensitive filamentous fungi, this equipment is used only in special processes [20]. The fixed bed is the most commonly applied due to its simple design, reduced cost and low maintenance requirements; it can be subdivided into the tray and the packed-bed bioreactors (PBB). The tray configuration is widely used for fermented food production in Far East countries, while the PBB has been largely explored in bench scale experiments for enzyme production especially by shear sensitive filamentous fungi [21,22].

Even though SSF has been considered a promising technique to produce bioproducts, it has not been successfully established as an industrial alternative due to a variety of factors, resulting in lack of industrial equipment, which depends on engineering developments, including simulation and experimentation. Similarly to chemical reactors, heat and mass transfer play crucial role in determining the performance of SSF processes in PBB [3].

One of the main drawbacks while operating PBB is the deficient removal of the metabolically generated heat, due to the low effective thermal conductivity of the substrate and to the low air flow rates employed, leading to poor options for temperature control and few alternatives for scaling up. High temperatures can achieve levels up to 20 °C above the ideal fermentation temperature, inhibiting the microorganism growth and affecting the production of metabolites [23–25]. This steep temperature increase is more common for mesophilic fungal strains, and in this case one should expect large variations in microbial growth and productivity.

A second equally important drawback in PPB operation for SSF is the reduction of the moisture content of the solid-phase along the process due to microbiological, physical and chemical issues. Water has many functions in SSF [26], since microorganisms are quite sensitive to the water activity of the fermentation system. Therefore, many studies have been published in literature about the dependence of enzyme production on the water content of the porous media. When the moisture content is insufficient, gas and solute diffusions decrease, and cell metabolism is affected due to either the lack of nutrients or the accumulation of toxic compounds in the vicinity of the cell. Water also solubilizes enzymes, which are fundamental for the whole metabolic system of the cell [27]. However, temperature profiles, and consequently moisture content profiles, are difficult to be avoided in PBB due to end-to-end aeration and the use of convective cooling with unidirectional flow of air. Even if the inlet air is saturated, the axial temperature gradients will change its relative humidity, giving it driving force to remove water from the solid-phase [28].

Heat and mass transfer phenomena in PBB for SSF are simultaneous and both depend somehow on the following factors [29]: (a) microbial biomass development: temperature and water activity required, tolerance to temperature and moisture content changes on the system, specific growth rate, microbial physiology, metabolic heat generation rate; (b) porous media characteristics: presence or absence of inert, particles dimension and shape, medium heterogeneity, bed porosity, moisture content, hygroscopic behavior; (c) equipment dimensions: length, diameter, air distribution inside the bed; (d) operational conditions: air flow rate, temperature and relative humidity of the air and jacket temperature. Some of these factors may be considered constant along fermentative processes, particularly the operational conditions, while some others, such as temperature, moisture content and microbial growth, may undergo dramatic changes that will strongly affect the previews of mathematical models.

In this context, mathematical modeling is an essential tool for guiding the design and operation of bioreactors, providing insights into how the several phenomena within the fermentation system combine to result overall process performance [28]. The aim of SSF bioreactor models is to describe how the performance is affected by the several operating variables that can be manipulated attempting to keep the process under control. For instance, a mathematical model may predict how inlet air flow rate, relative humidity and temperature will affect substrate temperature and water content and also how these environmental variables will affect microbial growth and product formation. Therefore bioreactor models should include the microbial growth kinetic to describe the dependence of growing rate, as well as metabolic heat, on the environmental variables [28].

Some mathematical models have been proposed in literature for heat transfer in SSF packed bed bioreactors [30–34], although some basic information required by the models, concerning the physical properties of the porous matrix and the biological characteristics of the microorganism, are scarce in literature and often