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Design of solid state bioreactor for industrial applications: An overview to conventional bioreactors

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ABSTRACT

Industrial fermentation is the process that has been used in the production of a variety of bio-products that have a broad area of applications. Among the processes, the Solid State Fermentation (SSF) is vital, and its utilization has been growing every day. It is used in many industries including fertilizers, pharma, and food, where it has gained its importance as a substitute for the Submerged Fermentation (SmF). One primary application of SSF is in the production of enzymes that can be used for therapeutic purposes, whose yield is low and cost is higher in case of conventional methods. The major advantage of using SSF is the fact that raw materials for this process are obtained from agricultural wastes and to an extent some industrially produced wastes can be utilized. The usage of SSF is limited because of its inability to be used in large-scale production and in the extraction of the required products. The primary requirement is to overcome any difficulties that are associated with the currently used industrial bioreactors. Important factors that have to be considered is that every reactor has its own significance, and they can give a much better result when compared to other bioreactors; an extensive study has to be done to determine which bioreactors have a better capability on any particular enzyme. The main aim of this review is to study the limitations (e.g. heat transfer) of the conventional bioreactors that are available and how to overcome these limitations shall be addressed in the review.

1. Introduction

Industrial fermentation is the process in which the solid or liquid substrates are converted into high-value products by treating it with microorganisms resulting in the production of enzymes and secondary metabolites (Chisti, 1999; Durand, 2003; Vandenberghe et al., 2000). The basic requirement for any fermentation industry would be to produce enzymes with very little or no environmental impact, and the emphasis is given on the economic feasibility of the process. SSF and SmF are the two techniques which are being used across countries over time to obtain several key bioproducts (Ballardo et al., 2016; Mitchell et al., 2000, 1999; Vandenberghe et al., 2000). Micro-organisms like bacteria, fungi and algae have a significant role in extracting the desired product using this technique. Among these microbes, fungi are manifested for SSF due to its high adaptability to the natural environment compared to bacteria or algae (Mitchell et al., 1999). Both the techniques apply to a wide range of industries including biotech, chemical, fertilizer, food and pharma based on their individual requirements. The majority of industrial enzymes are produced using SmF, but recent developments show that production of these enzymes using SSF provide better yield and economic feasibility (Batool et al., 2015; Behara and Ray, 2016; Mitchell et al., 2000; Yazid et al., 2016).

In SmF substrate is a free flowing liquid usually molasses or broth, which is used up rapidly and has to be constantly replenished (Irfan et al., 2015; Mitchell et al., 1999). This technique is best suited for bacteria, as significant amounts of moisture content are required for microorganisms like bacteria during fermentation (Maghsoodi and Yaghmaei, 2010). SSF process involves cultivation of microorganism on solid substrate with minimal moisture content. SSF process is highly heterogeneous as it comprises a liquid phase containing a limited volume of water, a solid phase as insoluble substrate and gas phase that is the use of air for the supply of oxygen existing in between the particles (Yang et al., 2008; Suryanarayan, 2002). In SSF substrates are used slowly and effectively over a long period of fermentation and eukaryotic microorganisms like fungi have a greater potential for the production of therapeutic enzymes (Chow and Ting, 2014; Pandey, 2003). For example it is observed that the carbohydrate rich foods has high content of asparagine which would be effective to produce L-asparaginase (Lea et al., 2007), similarly there are large number sources of lipases from plants which include coconut, barley, oats,

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Table 1
Different types of semi-pilot industrial bioreactor used in Solid State Fermentation (SSF).

SSF bioreactor	Design	Advantages	Limitations	Reference
Koji fermenter	Tray bioreactor consists of stack of trays loaded with thin layer of substrate inoculated with microbes usually fungi. Tray fermenter usually belong to Group I without mixing and aeration.	This bioreactors uses the simple technology and can be operated with minimal physical parameters.	Control of temperature and moisture gradient in this bioreactors is troublesome. Use of tray bioreactor is labor intensive and largely unregulated. An alternate pre-heating model will be required	(Durand et al., 1988; Robinson and Nigam, 2003)
Zymotis	Packed bed bioreactors belong to Group II with forceful aeration and without mixing. In this group the air is circulated by using an external agency and the bioreactor that is considered for this process is packed bed bioreactor. The introduction of air through a sieve is the basic design feature of packed-bed bioreactor, which supports the substrate and holds it within the sieves.	This packed bed bioreactor with internal cooling plates can overcome problem of temperature gradient	As the bed is subjected to forced aeration the moisture content of the substrate is reduced which in turn effect in heat transfer across the bed. Due to the low water activity the improper aeration the uniform growth of the microorganism is not achieved	(Couto and Sanroḿan, 2006; Lüth and Eiben, 2003; Sangsurasak and Mitchell, 1998)
Rotating drum bioreactor	Rotary drum bioreactor falls under the category Group III, because of its continuous or intermittent mixing without aeration. When the rotation is neglected this bioreactor behaves similar to the tray bioreactor.	Since the rotation plays a major role in mixing, it is important to consider the height of the bed through which uniform mixing can be achieved. This helps in heat transfer between O_2 and CO_2 diffusion through the head space of the rotary drum bioreactor.	Discrete revolution is potentially less damaging to fungal mycelium than the uninterrupted revolution. The performance of rotating and stirred-drum bioreactors will depend robustly on the organization of the water and bed height that evaporates and the heat transfer between the bed and headspace.	(Vandenberghe et al., 2000; Mitchell et al., 2000; Schutyser et al., 2004)
[a]New design bioreactor	The newly designed bioreactor is considered under group IV with forceful aeration and continuous mixing	A rotation device is periodically used to mix the bed and at the same time, water is sprayed if necessary in order to address heat dissipation. Applicability to overcome most of the above mentioned disadvantages of other bioreactors	Above discussed limitations can be overcome by this new design bioreactor model in which it operates by controlling parameters (temperature, air flow rate, and agitation time).	

[a] The design for this has been discussed in Section 2.

almond, papaya etc. (Seth et al., 2014). Here the idea is to bring into account similar kinds of products that will be available from the agricultural residues (Pandey et al., 1999). A filamentous fungus plays a significant role in SSF as the morphology of it can help the microorganism to grow deep into the soil thereby reducing contamination level and also limiting the choice of the microorganism (Kumar and Sobha, 2012; Kumar and Ray, 2014; Meng et al., 2015; Vandenberghe et al., 2000). SSF has one specific advantage over SmF on the fact that the wastes that are produced after the fermentation process can be used as a fuel for other processes (Yang et al., 2008; Ballardo et al., 2016).

For a simple comparison between the various types of bioreactors that are being used and into what category the new design will fall into and the advantages and disadvantages of each type are discussed in Table 1. Kinetics is an essential part of any process and it can be considered that a good design has the best kinetic description of the process, it is important because a good kinetic model would help in the increase of productivity, it would help to understand the capabilities of the bioreactor in a much better sense, it would also bring about a better final outcome and play a vital role while considerations are made on the scaling up of any bioreactor (Ali and Zulkali, 2011; Rodríguez-fernández et al., 2015).

This paper shall deal with the study of the difference between the SSF and SmF bioreactors with a greater focus on the SSF bioreactors along with the challenges that would be faced in the process of scaling up the bioreactor to the industrial scale, an introduction to a new design model will be shown along with a brief idea of the kinetics that are involved in the development of the SSF bioreactor.

1.1. Comparison of SmF and SSF bioreactors

Enzymes are usually produced through Submerged Fermentation technique, but this method has several disadvantages such as moderate product yield, high cost and it generates a significant amount of wastewater effluent (Abd-elhalem et al., 2015). Solid State Fermentation is extensively used in various processes such as bioremediation, biodetoxification of different hazardous compounds, production of various therapeutic enzymes and secondary metabolites and as an effective alternative to Submerged Fermentation. A comparative study of SSF and SmF can be done using the Fig. 1 (Chang and Chang, 2014; Roy et al., 2006; Ali and Zulkali, 2011; Subramaniyam and Vimala, 2012) and also the effect of different factors on these bioreactor types are given in Table 2 (El-Bakry et al., 2015; Doriya et al., 2016; Patnala et al., 2016). Recent studies show that SSF is an effective alternative to SmF since the rate of substrate consumption and resistance to substrate concentration gradient is high in SSF (Pandey, 1992; Modi et al., 1994; Singhania et al., 2009; Zhang et al., 2015). Although these results are currently for the laboratory case study, it is expected that the new design that shall be discussed later in this paper has a tendency to improve it to the industrial scale level. From biological aspect SSF play as terrestrial habitat for fungi and spores which are produced from these fungi and show higher growth rates than SmF (Colla et al., 2014; Singhania et al., 2009; Pandey et al., 1999). As seen in case of most of the available enzymes, the production through SSF has always shown a higher productivity than in the SmF, a small list of the same has been displayed in Table 3, and as done in some of the previous studies it has been observed that in the overall economic analysis, SSF has been much better than the conventional SmF in almost every aspect including the equipment, raw material and final product cost (Castilho et al., 2000; Hölker et al., 2004; Viniegra-González et al., 2003). An example on the economic investigation of lipase production in SSF and SmF has revealed that SSF is economically feasible due to the cheap agricultural materials used as a substrate (Colla et al., 2014; Hölker and Lenz, 2005; Selvakumar et al., 1998;