Biochemical Engineering Journal 81 (2013) 146–161

Contents lists available at ScienceDirect

Biochemical Engineering Journal

journal homepage: www.elsevier.com/locate/bej

Review

Current developments in solid-state fermentation

Leya Thomas [a], Christian Larroche [b], Ashok Pandey [a,*]

[a] Biotechnology Division, CSIR-National Institute of Interdisciplinary Science and Technology, Trivandrum 695 019, India
[b] LGCB, Polytech Clermont Ferrand, University Blaise Pascal, 63174 Aubiere, France

ARTICLE INFO

Article history:
Received 22 July 2013
Received in revised form
14 September 2013
Accepted 15 October 2013
Available online 24 October 2013

Keywords:
Solid-state fermentation
Bioprocess design
Enzyme production
Modeling production kinetics
Agro-industrial residues
Other industrial products

ABSTRACT

Solid-state fermentation (SSF) is a three-phase heterogeneous process, comprising solid, liquid and gaseous phases, which offers potential benefits for the microbial cultivation for bioprocesses and products development. Over the last two decades, SSF has gained significant attention for the development of industrial bioprocesses, particularly due to lower energy requirement associated with higher product yields and less wastewater production with lesser risk of bacterial contamination. In addition, it is eco-friendly, as mostly utilizes solid agro-industrial wastes (resides) as the substrate (source of carbon). This article aims to present and analyze the current development on SSF taken place mainly during the last five years, linking the developments with earlier two papers published in this journal in 2003 (Pandey, 2003 [1]) and in 2009 (Singhania et al., 2009 [2]). The article reviews the current state-of-art scenario and perspectives on the development of bioprocesses and products in SSF and also discusses microbes employed in these processes, the types of bioreactors used for these and also presents the modeling and kinetics aspects.

Contents

* Corresponding author. Tel.: +91 471 2515279; fax: +91 471 2491712.
E-mail addresses: pandey@niist.res.in, ashokpandey56@yahoo.co.in (A. Pandey).

1369-703X/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.bej.2013.10.013

1. Introduction

Solid-state fermentation (SSF) has continued to built up credibility in recent years in biotech industries due to its potential applications in the production of biologically active secondary metabolites, apart from feed, fuel, food, industrial chemicals and pharmaceutical products and has emerged as an attractive alternative to submerged fermentation [1,2]. Bioremediation, bioleaching, biopulping, biobeneficiation, biological delignification, etc. are the major applications of SSF in bioprocesses, which have set another milestone. The human quest for eco-friendly and green processes in place of chemical processes for the production of industrial products has turned the industrial manufacturing strongly 'bio-based'. SSF has attained much relevance in this context during the last one decade as SSF processes offer potential environmental benefits [3]. Yet another very relevant concern, though of generic nature, in this regard is the economic feasibility and sustainability of the bioprocesses, where also SSF offers potential benefits, as it utilizes low-cost agro-industrial residues as the substrate, which is very attractive for bioprocessing.

SSF has been defined as the bioprocess carried out in the absence, or near-absence of free water; however, the substrate must possess enough moisture to support the growth and metabolic activity of the microorganism. The solid matrix could be either the source of carbon (and other nutrients), or it could be an inert material to support the growth of the microorganisms on it (with impregnated growth solution).

As has been advocated, the potential of SSF is to provide the cultivated microorganism an environment as close and in vicinity as possible to natural environment where usually they exist and from where they are isolated. This apparently is the main factor why microbes perform well and give higher products yields in SSF when compared with the liquid fermentation carried out in a closed bioreactor, even if with optimal conditions for growth and activity. As mentioned above, the use of agro-industrial residues and by-products as feedstock in SSF processes on one hand adds economic value to these wastes, or by-products, and on other hand it solves the problem of their disposal, which otherwise would cause pollution [3].

There has been substantial improvement in the fundamental understanding the biochemical engineering aspects, particularly on mathematical modeling and design of bioreactors (fermenters) during the last decade, which has helped in developing several designs for the SSF bioreactors. These have also helped in better understanding of heat and mass transfer effects, leading to better design of process and product developments.

We had earlier reviewed the development of SSF and attributed its growth and developments as the timely need due to environmental and economic benefits it offered. The paper presented the detailed perspectives in 2003 [1], which was followed by another in 2009, describing the developments taken place chiefly in five years since the publication of 2009 [2]. The present article focuses on SSF process and product developments mainly from the last five years since the publication of 2009 article and provides an update to our previous reviews.

2. Critical aspects of SSF

SSF is governed by a large number of factors, each of which is critical for the technical and economic feasibility of the process development. While several of these are of generic nature, they still hold a significant impact and need to be considered in a holistic manner. These included the selection of microorganism and substrate, optimum physical–chemical and biological process parameters and also purification of the desired products, which have been a challenge for SSF. In general, fungal and yeast cultures have been considered as the most suitable microorganisms for SSF processes. This has been essentially based on the theoretical concept of water activity, as fungi and yeast have lower water activity requirements, typically around 0.5–06 a_w. Bacterial cultures have higher water activity requirement (around 0.8–09 a_w), which tend them not suitable for SSF processes. However, it is now well established that this theoretical concept was not correct as a large number of bioprocesses have been described, which are bacterial-based. The choice of the microbe should apparently be linked with the selection of the substrate and product aimed at.

The identification of the physiology of the microorganisms and the physico-chemical factors where it grows leads to the development of process parameters, which are required for its optimal growth and activity. These factors include temperature, pH, aeration, water activity and moisture, bed properties, nature of solid substrate employed, including the particle size, etc. These must be optimized based on factorial design experiments and response surface methodology so as to identify the critical factors and their interactions. Modern biotechnological tools involving artificial neural network (ANN) and genetic algorithm offer potential advantage for the optimization of bioprocesses.

Understanding of heat and mass transfer effects are among the most critical aspects of SSF, which need attention. These pose challenge for the design and operation of bioreactors and their scale-up for the commercialization of SSF processes. The heterogeneous nature of the substrate (agro-industrial residues) poses problem in kinetics and modeling studies, which are mandatory information for the development of design of the bioreactors and its operation [1,2,4].

The substrates used in SSF differ greatly in composition, chemical nature, mechanical properties, particle size (including inter- and intra-particle spaces), water retention capacity, surface area, etc. These factors affect the overall process design and product development. During the last five years, there have been significant developments on these aspects, which would be discussed later in this review.

3. Industrial products developed by SSF

3.1. Enzymes

The field of industrial enzymes is now experiencing major research and development initiatives, resulting in the development of a number of new products and an improvement in the process and performance of several existing products. With environmental and cost issues in conventional chemical processes being subjected to considerable scrutiny, biotechnology is gaining rapid ground as it offers several advantages over conventional technologies. Industrial enzymes represent the heart of biotechnology. The global market for industrial enzymes is estimated at $3.3 billion in 2010. This market is expected to reach $4.4 billion by 2015, a compound annual growth rate (CAGR) of 6% over the 5-year forecast period. Technical enzymes are valued at just over $1 billion in 2010. This sector will increase at a 6.6% compound annual growth rate (CAGR) to reach $1.5 billion in 2015. The highest sales of technical enzymes occurred in the leather market, followed by the bioethanol market. The food and beverage enzymes segment is expected to reach about $1.3 billion by 2015, from a value of $975 million in 2010, rising at a compound annual growth rate (CAGR) of 5.1% [5].

Industrial enzymes have been among the various products produced most successfully at commercial level by SSF. Efforts have continued to study the production of different enzymes in SSF with the ultimate aims to obtain high production of the enzyme at lesser cost from new microbial sources, improved media