Editorial

A new paradigm for waste management of organic materials

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In recent years, the proliferation of municipal solid waste management facilities using composting, anaerobic digestion or the combination of both technologies as the main stages for the treatment of organic wastes has increased in several developed or developing countries. These countries relied on landfill as main waste management scenario not so many years ago.

All such facilities (often referred as mechanical-biological treatment-MBT plants) require some mechanical pre-treatment to obtain recyclable materials and primarily organic waste, which is further treated using a biological technology. The resulting material is, in principle, a stabilized organic material with a variety of uses depending on its quality (e.g. agricultural or horticultural, restoration, etc.). The characteristics of the product also vary according to its origin: compost (when coming from source-separated organic fraction of municipal solid wastes), biostabilized (from mixed municipal solid wastes) or digested materials (from both sources).

However, following the ongoing developments of the circular economy and the principles of industrial ecology, a new question arises: Can anything else be obtained from organic wastes? In a world with limited sources, can wastes be really used as raw materials? The answers to these questions are starting to be clear in the positive sense, as some very recent developments show what we can obtain from a wide range of organic wastes and how. Using the traditional Solid-State Fermentation (SSF) concept: “the fermentation involving solids in absence (or near absence) of free water; with substrates that must possess enough moisture to support growth and metabolism of microorganisms” (Pandey, 2003), the biological transformations of wastes as substrates can lead to obtaining valuable bio-products, which are of special interest when they can substitute for non-renewable materials (e.g. polymers from petroleum) or transform traditional chemical processes into cleaner production strategies. Moreover, SSF also permits stabilization of the organic matter, resulting in a compost-like by-product. Therefore, SSF is a promising technology to change the organic waste old paradigm: from waste to product. Several examples of “what” and “how” SSF performs are explained below.

SSF: industrial and research overview

SSF processes have been used for centuries mostly in food production and related transformations both at domestic and industrial scales. This is the case of bread production (firstly dated on ancient Egypt), cheese production using *Penicillium roquefortis*, or the koji process involving *Aspergillus oryzae* growing in steamed rice, performed first in China and later in Japan. Tempeh and miso are also originated from fermented steamed and cracked legume seeds in many countries in South-East Asia. Pandey et al. (2008) presented the historical evolution of SSF applications in their book *Current developments in Solid State Fermentation* also mentioning the use of this process in other industrial applications among which composting and related solid waste treatments appeared towards the end of the 19th century. Rodríguez Couto and Sanromán (2006) devoted a review to the role of SSF in the food industry including traditional and promising applications.

Enzyme production is another of the main SSF developments at industrial scale. In addition to the use of filamentous fungi in these applications due to their natural occurrence in solid substrates, bacteria and yeasts have also many uses. Fungi have also been successfully used in mycotoxins production for medical uses.

However, as Pandey et al. (2008) pointed out, SmF (submerged fermentation) is still the preferred option instead of SSF. SSF is only considered if it is the only option or is by far the most favourable from an economic point of view. In this sense, SSF processes gained relevance when exploring the possibilities of waste valorisation using these low (or null) cost materials as raw matter. This is the case of agricultural residues used to produce single cell protein (SCP), ethanol or mushroom. Also some organic acids are produced by fermentation such as citric acid that has been produced by SSF for many years using different waste materials as carbon source, such as starchy agricultural wastes and molasses, or lactic with classical applications in food industry or also used in bioplastics production (polylactic acid). Mushroom production by SSF includes edible mushrooms (shiitake, oyster and champignon among others) and species used in medical and other applications.

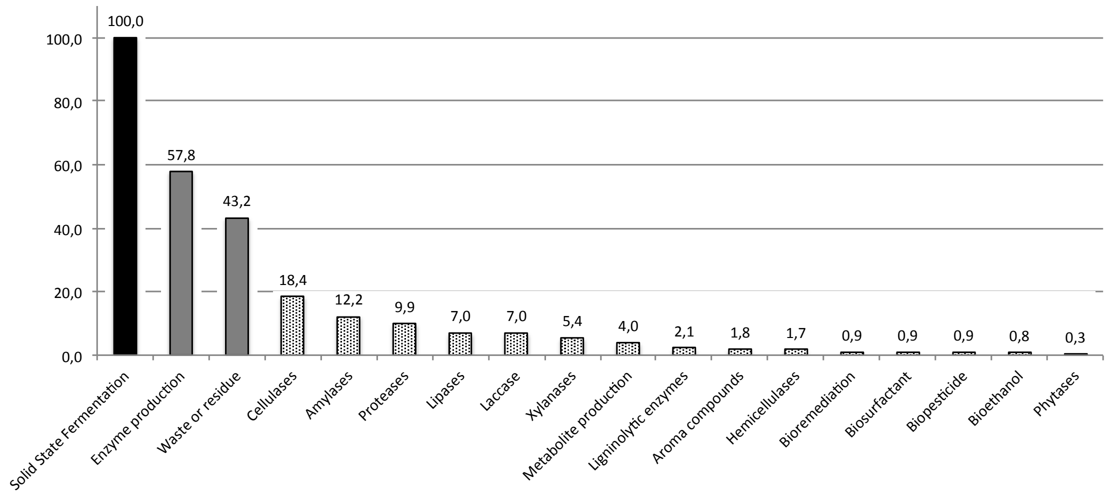
In the field of renewable energy, lignocellulosic residual materials such as crop residues, grasses, sawdust and wood chips have been used in ethanol production, with SSF playing an important role in the hydrolysis of cellulose by lowering costs and achieving higher process yield (Sun and Cheng, 2002). In fact, fungi produced cellulases are responsible for lignocellulosic materials pretreatment for ethanol production.

Research in SSF can be seen through a search for the term “Solid State Fermentation” in the Web of Science® database. This search reports 1931 articles published from 1900 to 2014 (the first one published in 1972) that include the term Solid State Fermentation in the title. It is important to note that 60% of them have been published in the last 10 years. Recent research has led to 118 patents, 74% of them registered in the last 10 years. India, Brazil and China are clearly the countries with most publications in this field (57% of the articles published in the last 10 years). These general numbers suggest that SSF researchers are still finding new applications for this technology or are still optimizing existing processes.

Figure 1 shows the distribution (%) of different topics for those articles published in the last 10 years having the term “Solid State Fermentation” in the title. It can be observed that the main topic associated to SSF is “enzyme production” (57% of the articles). Indeed, cellulases, amylases, proteases, lipases, laccases and xylanases are the valuable final products that are being extensively studied in SSF processes. On the other hand, SSF using wastes is studied in 37% of the publications, increasing to 43% in the last 5 years, therefore indicating that SSF technology is also gaining interest as a waste valorisation process.

To a minor extent, but not to be underestimated, applications of SSF include the production of metabolites such as antibiotics (Iturin A or Meroparamycin), cholesterol lower agents (Lovastatin, Monacolin K or Compactin), anticancer agents (Antrodin C or Cordycepin) or antifungal agents (Griseofulvin). Downstream processes for the recovery and purification of these products are associated to expensive or complex processes, but as high-valuable and marketable products, this drawback should be overcome successfully.

Finally, other products in which researchers are focusing their efforts include production of aroma compounds, bioethanol, biosurfactants (surfactin, rhamnolipids or sophorolipids) and biopesticides (based on *Bacilus thuringiensis*).



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SSF limitations

Despite the increasing interest in SSF by the scientific community some challenges must be faced prior the full implementation of SSF processes at the commercial scale. Besides the classical SSF systems in the food industry and the well-known composting process, scarce SSF production processes are scaled up. The vast majority of the published papers in this field describe successful experiments at the lab scale, which use only a few grams of substrate. In addition, most of these studies are undertaken with a specific microorganism strain under sterile fermentation conditions. Only a few publications deal with the scale-up from the gram to the kilogram scale. According to a recent review by Thomas et al. (2013), few SSF processes have been developed at industrial scale: delignification of biomass, dyes bioremediation or *Jatropha* cake detoxification.

SSF is difficult to scale-up due to the three-phase heterogeneous nature of the substrate and the various gradients existing inside the reactor, such as temperature, pH, moisture, oxygen and biomass. The control of heat transfer is one of the major crucial issues in the design and operation of large-scale SSF fermenters. The heat generated due to the metabolic activities of microorganisms can lead to an increase in mass temperature when it is not properly removed, thus affecting the optimum growth of microorganisms. In fact, the absence of free water during the fermentation diminishes important points such as the accessibility to nutrients, the presence of a homogenous moisture content and pH. To help with these issues, solids agitation is possible in some reactors configurations such as rotating drums, but present a very high energy cost. There are a number of bioreactors that have been designed to overcome the problems of scale up, each with their own advantages and disadvantages. An extensive analysis on the design and operation of bioreactors in SSF has been published in the recent review by Thomas et al. (2013).

Downstream processing can be another limiting step if the valuable bioproducts have a high affinity for the solid matrix or if other not desired products are extracted together with the added-value product.

A different approach for an easily-scalable process is to perform fermentations at high temperatures using thermophilic microorganisms either at a controlled temperature or through a composting-like process.

Finally, the need for sterilisation increases production costs. When a non-sterile solid matrix is used, one aspect to consider is the interaction between microorganisms. In fact, when the inoculation with a specific strain is required, the quantity used as inoculum at the initial stage can determine the viability of the process. Competition and/or syntrophic relationships between microorganisms can affect the process yield and also they have to be considered in the scale-up.

Anyway, it is evident that SSF has a huge potential to transform organic wastes into raw materials for the production of bio-products, in the framework of circular economy.

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