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Research review paper

Bioactive phenolic compounds: Production and extraction by solid-state fermentation. A review

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ABSTRACT

Interest in the development of bioprocesses for the production or extraction of bioactive compounds from natural sources has increased in recent years due to the potential applications of these compounds in food, chemical, and pharmaceutical industries. In this context, solid-state fermentation (SSF) has received great attention because this bioprocess has potential to successfully convert inexpensive agro-industrial residues, as well as plants, in a great variety of valuable compounds, including bioactive phenolic compounds. The aim of this review, after presenting general aspects about bioactive compounds and SSF systems, is to focus on the production and extraction of bioactive phenolic compounds from natural sources by SSF. The characteristics of SSF systems and variables that affect the product formation by this process, as well as the variety of substrates and microorganisms that can be used in SSF for the production of bioactive phenolic compounds are reviewed and discussed.

Contents

1. Introduction — bioactive compounds

Bioactive compounds are extra nutritional constituents that naturally occur in small quantities in plant and food products (Kris-Etherton et al., 2002). Most common bioactive compounds include secondary metabolites such as antibiotics, mycotoxins, alkaloids, food grade pigments, plant growth factors, and phenolic compounds (Hölker et al., 2004; Kris-Etherton et al., 2002; Nigam, 2009). Phenolic compounds comprise flavonoids, phenolic acids, and tannins, among others. Flavonoids constitute the largest group of plant phenolics, accounting for over half of the eight thousand naturally occurring phenolic compounds (Harborne et al., 1999). Variations in substitution patterns to ring C in the structure of these compounds result in the major flavonoid classes, i.e., flavonols, flavones, flavanones, flavanols, isoflavones, and anthocyanidins. Fig. 1 shows examples of the most common naturally occurring flavonoids. Similarly to the flavonoids, phenolic acids constitute also an important class of phenolic compounds with bioactive functions, usually found in plant and food products. Phenolic acids can be divided in two subgroups according to their structure: the hydroxybenzoic and the hydroxycinnamic acids (Fig. 2). The most commonly found hydroxybenzoic acids include gallic, *p*-hydroxybenzoic, protocatechuic, vanillic and syringic acids, while

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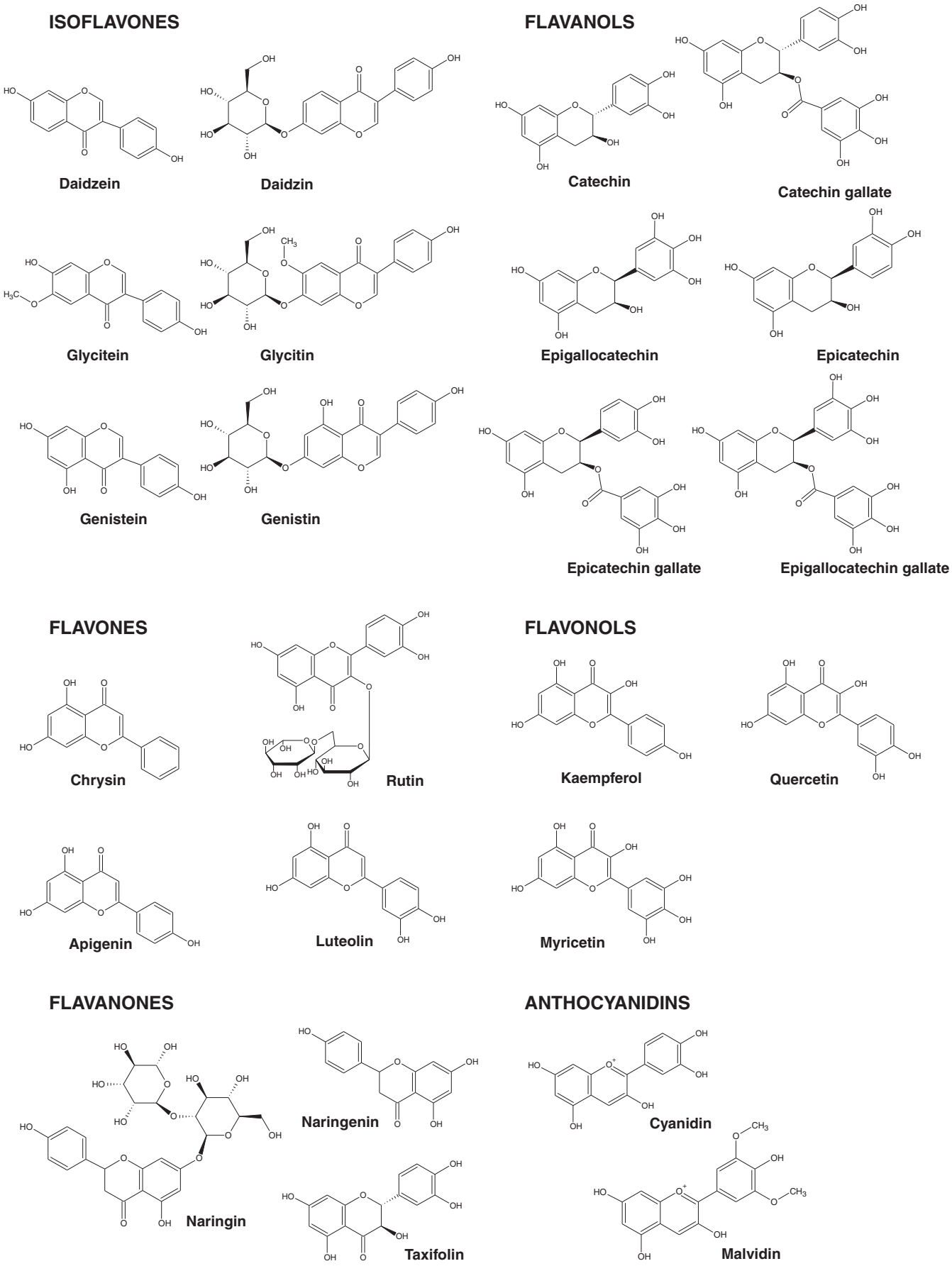

Fig. 1. Examples of naturally occurring flavonoids.

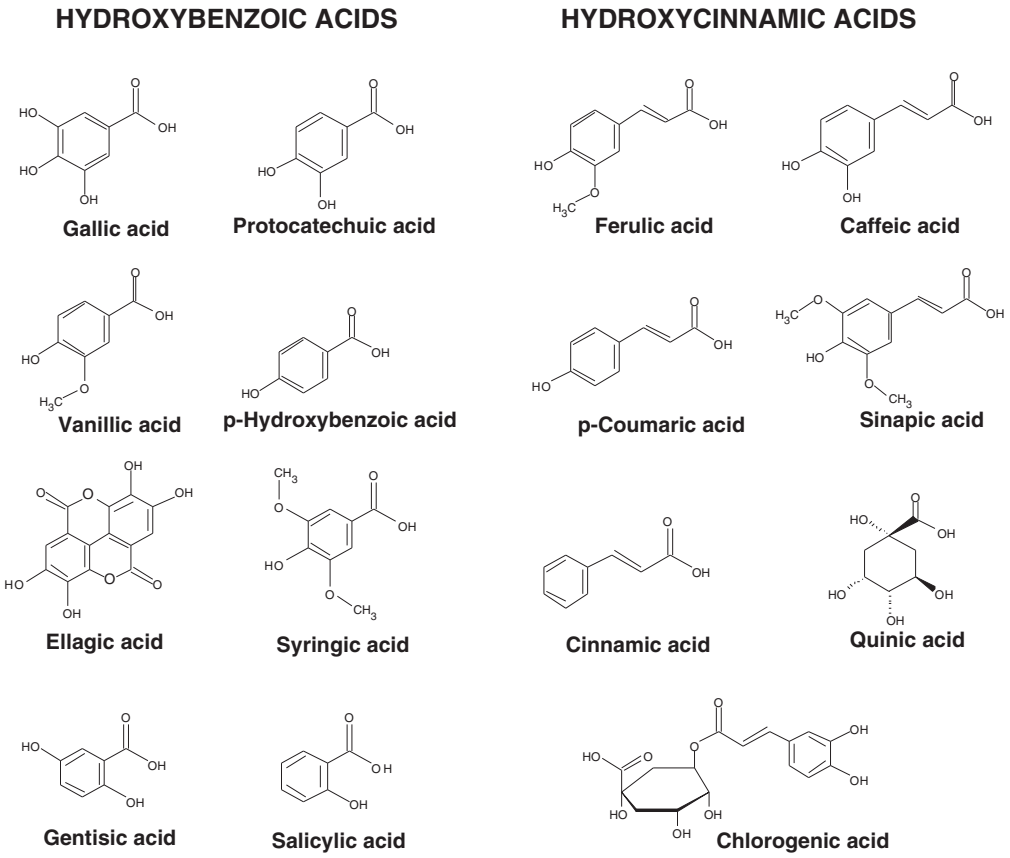

Fig. 2. Examples of naturally occurring phenolic acids.

among the hydroxycinnamic acids, caffeic, ferulic, *p*-coumaric and sinapic acids can be pointed out (Bravo, 1998).

In the last few years, great attention has been paid to the bioactive compounds due to their ability to promote benefits for human health, such as the reduction in the incidence of some degenerative diseases like cancer and diabetes (Conforti et al., 2009; Kim et al., 2009), reduction in risk factors of cardiovascular diseases (Jiménez et al., 2008; Kris-Etherton et al., 2002), antioxidant, anti-mutagenic, anti-allergenic, anti-inflammatory, and anti-microbial effects (Balasundram et al. 2006; Ham et al. 2009; Parvathy et al. 2009), among others. Due to these countless beneficial characteristics for human health, researches have been intensified aiming to find fruits, vegetables, plants, agricultural and agro-industrial residues as sources of bioactive phenolic compounds.

Usually, bioactive compounds are recovered from natural sources by solid–liquid extraction employing organic solvents in heat-reflux systems (Martins et al., 2010; Wang and Weller, 2006). However, other techniques have been recently proposed to obtain these compounds including the use of supercritical fluids, high pressure processes, microwave-assisted extraction and ultrasound-assisted extraction (Cortazar et al. 2005; Markom et al. 2007; Wang and Weller, 2006). Extraction/production of bioactive compounds by fermentation is also an interesting alternative that merits attention, since it is able to provide high quality and high activity extracts while precluding any toxicity associated to the organic solvents. In this process, bioactive compounds are obtained as secondary metabolites produced by microorganisms after the microbial growth is completed (Nigam, 2009). Studies on liquid culture show that the production of these compounds starts when growth is limited by the exhaustion of one key nutrient: carbon, nitrogen or phosphate source (Barrios-González et al., 2005).

The purpose of this article is to provide an overview of the bioactive phenolic compounds extraction and production by fermentation, more specifically by the solid-state fermentation technique. The current status of this technology, the microorganisms, substrates and cultivation conditions affecting the phenolic compounds formation are summarized and discussed.

2. Solid-state fermentation (SSF)

Fermentation processes may be divided into two systems: submerged fermentation (SmF), which is based on the microorganisms cultivation in a liquid medium containing nutrients, and solid-state fermentation (SSF), which consists of the microbial growth and product formation on solid particles in the absence (or near absence) of water; however, substrate contains the sufficient moisture to allow the microorganism growth and metabolism (Pandey, 2003). In recent years, SSF has received more interest from researchers since several studies have demonstrated that this process may lead to higher yields and productivities or better product characteristics than SmF. In addition, due to the utilization of low cost agricultural and agro-industrial residues as substrates, capital and operating costs are lower compared to SmF. The low water volume in SSF has also a large impact on the economy of the process mainly due to smaller fermenter-size, reduced downstream processing, reduced stirring and lower sterilization costs (Hölker and Lenz, 2005; Nigam, 2009; Pandey, 2003; Raghavarao et al., 2003). The main drawback of this type of cultivation concerns the scaling-up of the process, largely due to heat transfer and culture homogeneity problems (Di Luccio et al., 2004; Mitchell et al., 2000). However, research attention has been directed towards the development of bioreactors that overcome these difficulties.

Although many bioactive compounds are still produced by SmF, in the last decades, there has been an increasing trend towards the utilization of the SSF technique to produce these compounds since this process has been shown more efficient than SmF (Nigam, 2009).

Table 1
Examples of secondary metabolites produced with higher yield by solid-state fermentation than by submerged fermentation (Hölker et al., 2004).

Product	Microorganism
6-pentyl-alpha-pyrone	*Trichoderma harzianum*
Bafilomycin B1 + C1	*Streptomyces halstedii K122*
Benzoic acid	*Bjerkandera adusta*
Benzyl alcohol	*Bjerkandera adusta*
Cephamycin C	*Streptomyces clavuligerus*
Coconut aroma	*Trichoderma sp.*
Ergot alkaloids	*Claviceps fusiformis*
Giberellic acid	*Giberella fujikuroi*
Iturin	*Bacillus subtillis*
Ochratoxin	*Aspergillus ochraceus*
Oxytetracycline	*Streptomyces rimossus*
Penicillin	*Penicillium chrysogenum*
Rifamycin-B	*Amycolatopsis mediterranei*
Tetracycline	*Streptomyces viridifaciens*

Table 1 shows several examples of bioactive secondary metabolites that demonstrated significantly higher yields obtained by SSF than by SmF. Besides the higher yields, SSF has also been reported as a technique able to produce secondary metabolites in shorter times than SmF, without the need of aseptic conditions, and with capital costs significantly lesser.

Several important factors must be considered for the development of a successful bioprocess under SSF conditions. Some of the most important include the selection of a suitable microorganism strain and the solid support to be used. A variety of microorganisms, including fungi, yeasts and bacteria may be used in SSF processes; however, due to the low moisture content in the fermentation media, fungi and yeasts are the most commonly used microorganisms due to their ability to growth in environments with this characteristic. However, the choice of the microorganism to be used in SSF depends on the desired end product. Filamentous fungi have great potential to produce bioactive compounds by SSF, and therefore, they are the most commonly used microorganisms for this purpose (Aguilar et al., 2008; Nigam, 2009; Topakas et al., 2003a). Filamentous fungi have also received great attention due to their ability in producing thermostable enzymes of high scientific and commercial value, such as amylases, pectinases, xylanases, cellulases, chitinases, proteases, lipases, β-galactosidases, and others (Christakopoulos et al., 1990; Martins et al., 2002).

The right selection of the solid substrate is also of great importance for an efficient and economical production of the compound of interest. Mostly the production yields of secondary metabolites can be improved with a suitable choice of substrate or mixture of substrates with appropriate nutrients (Nigam, 2009). As a whole, the support material must present characteristic favorable for the microorganism development and be of low cost. These characteristics are easily found in many residual natural materials proceeding from agricultural and agro-industrial activities. In addition, the use of these residues as carbon sources through SSF provides an important way to reduce the fermentation cost and avoid environmental problems caused by their disposal, being an economical and interesting solution for countries with abundance of these materials. Several of these residues, including coffee pulp and husk, sugarcane and agave bagasses, fruit pulps and peels, corn cobs, among others, have been used as supports and/or substrates for the production of valuable compounds by SSF, such as enzymes (Guimarães et al., 2009; Mamma et al., 2008; Oliveira et al., 2006; Sabu et al., 2005), organic acids (John et al., 2006; Sharma et al., 2008; Vandenberghe et al., 2000), antibiotics (Adinarayana et al., 2003; Ellaiah et al., 2004), flavor and aroma compounds (Medeiros et al., 2006; Rossi et al., 2009; Sarhy-Bagnon et al., 2000), and bioactive compounds (Hernández et al., 2008; Vattem and Shetty, 2003). Table 2 summarizes some of the most recent studies in SSF, the microorganisms and solid supports employed. Note that a large variety of solid supports have been used in these processes, and fungi are the most used microorganisms.

The process variables including pretreatment and particle-size of substrates, medium ingredients, supplementation of growth medium, sterilization of SSF medium, moisture content, water activity (a_w), inoculum density, temperature, pH, agitation and aeration, have a significant effect on the efficiency of SSF processes (Nigam and Pandey, 2009). Among these, the moisture content and a_w have an important role in SSF, and have been studied, described, and revised by several authors. Generally, the substrates have a water content oscillating between 30 and 85%. Lower values may induce the sporulation of the microorganism, while more elevated levels may reduce the porosity of the system, which can produce oxygen transfer limitation, and increase

Table 2
Recent studies of solid-state fermentation using different microorganisms and solid supports.

Microorganism	Solid support	Reference
Fungi		
Aspergillus niger	Creosote bush leaves, variegated Caribbean agave, lemon peel, orange peel, apple pomace, pistachio shell, wheat bran, coconut husk, pecan nutshell, bean residues	Orzua et al., 2009
Aspergillus niveus	Sugarcane bagasse	Guimarães et al., 2009
Aspergillus oryzae	Red gram plant waste	Shankar and Mulimani, 2007
Aspergillus sojae	Crushed maize, maize meal, corncob	Ustok et al., 2007
Bjerkandera adusta; Ganoderma applanatum; Phlebia rufa Trametes versicolor	Wheat straw	Dinis et al., 2009
Phanerochaete chrysosporium	Rice straw	Yu et al., 2009
Penicillium sp.	Soybean bran	Wolski et al., 2009
Rhizopus chinensis	Combination of wheat bran and wheat flour	Sun et al., 2009
Sporotrichum thermophile	sesame oil cake	Singh and Satyanarayana, 2008a
Trichosporon fermentans	Rice straw	Huang et al., 2009
Yeasts		
Baker yeast AF37X	Sweet sorghum	Yu et al., 2008
Saccharomyces cerevisiae	Mahula flowers	Mohanty et al., 2009
	Corn stover	Zhao and Xia, 2009
Bacteria		
Nocardia lactamdurans	Wheat bran, rice, soybean oil cake, soybean flour	Kagliwal et al., 2009
Bacillus sphaericus	Wheat bran	El-Bendary et al., 2008
Bacillus subtilis	Wheat bran	Gupta et al., 2008
Pseudomonas aeruginosa	Jatropha curcas seed cake	Mahanta et al., 2008
Streptomyces sp.	Coffee pulp	Orozco et al., 2008

the risk of bacterial contamination (Pérez-Guerra et al., 2003). According to Raimbault (1998), the water requirements of microorganism may be better defined in terms of a_w rather than water content in the solid substrate. The a_w can be defined as the relationship between the vapor pressure of water in a system, and the vapor pressure of the pure water. In other words, a_w indicates the available or accessible water for the growth of the microorganism, and affects the biomass development, metabolic reactions, and the mass transfer processes (Bellon-Maurel et al., 2003; Gervais and Molin, 2003).

The establishment of the most suitable conditions for use of the process variables is of relevance to achieve elevated process yields. The use of experimental design statistical methodology may be a useful tool to define such conditions performing a minimal number of experiments. Recently, several works report the use of statistical analysis to maximize the product formation through the establishment of the best SSF operational conditions. Such works include the production of enzymes such as α-amylase (Reddy et al., 2003), inulinase (Xiong et al., 2007), phytase (Singh and Satyanarayana, 2008b), protease (Reddy et al., 2008), xylanase (Senthilkumar et al., 2005), and laccase (Liu et al., 2009), biosurfactants (Mukherjee et al., 2008) and organic acids such as citric acid (Imandi et al., 2008).

Finally, the selection of the most appropriate downstream process for the obtained product is also crucial when SSF processes are performed. The product obtained by SSF may be recovered from the solid fermented mass by extraction with solvents (aqueous or other solvents mixtures). The type of solvent and its concentration, as well as the ratio of solvent to the solid and pH are important variables that influence in the product extraction. In addition, since the metabolites diffuse throughout the solid mass during the culturing, long extraction-times may be required for complete product recovery. The cost of purification depends on the quality of the obtained extract. For example, the presence and concentration of inert compounds in the extract increase the cost of purification and therefore the cost of recovery is increased. Particularly those secondary metabolites which are used in bulk in the pharmaceutical and health industry and whose purity is governed by stringent regulations need to go through specific purification strategy (Nigam, 2009).

3. Uses of SSF for bioactive phenolic compounds production

3.1. Phenolic content increase in food products

Food quality is not only a function of nutritional values but also of the presence of bioactive compounds exerting positive effects on human health (Cassano et al., 2008). Phenolic compounds, also referred as polyphenols, are considered to be natural antioxidants and represent an important group of bioactive compounds in foods (Dueñas et al., 2005). These compounds are present in all plant foods but their type and levels vary enormously depending on the plant, genetic factors and environmental conditions (Kris-Etherton et al., 2002).

In the last years, SSF has been employed to increase the content of phenolic compounds in certain food products, thus enhancing their antioxidant activity. For example, black beans are well known for their high nutritional value containing isoflavones, vitamin E, saponins, carotenoids and anthocyanins (Choung et al., 2001). In a recent study on the bioprocessing of these beans to prepare koji using SSF with different food-grade filamentous fungi (in particular *Aspergillus sp.* and *Rhizopus sp.*), an enhancement of the antioxidant properties of the beans was observed, which might be related to the increase of phenol and anthocyanin contents (Lee et al., 2008). Nevertheless, the enhancement of the antioxidant activity of the black bean koji varied to each microorganism used. Similarly, SSF of grass peas cooked seeds using *Rhizopus oligosporus* caused an increase in the phenolic compounds content which significantly improved the antiradical properties of the seeds (Starzynska-Janiszewska et al., 2008).

Two different filamentous fungi (*Aspergillus oryzae* and *Aspergillus awamori*) used in SSF were very effective for the improvement of phenolic content and antioxidant properties of wheat grains. In this study, fermented wheat grains were considered to be antioxidant richer and healthier food supplement compared to non-fermented wheat grains (Bhanja et al., 2009). Soybean products fermented by SSF with *Trichoderma harzianum* showed stronger antioxidant activity than unfermented products, which was probably related to the markedly higher contents of phenolic acids, flavonoids and aglycone isoflavone with more free hydroxyl groups achieved during SSF (Singh et al., 2010). Chemical composition and bioactivity of stale rice were also improved by SSF with *Cordyceps sinensis* (Zhang et al., 2008).

Besides to increase the antioxidant activity of certain foods, bioconversion of phenolic compounds by SSF may also promote other alterations in the food properties, with influence on human health. An example of this is the SSF of mung beans (also known as green beans) with *Rhizopus oligosporus*. This process has been demonstrated as being able to mobilize the conjugate forms of phenolic precursors naturally found in mung beans and improves their health-linked functionality. According to Randhir and Shetty (2007), SSF of mung beans significantly increased the phenolic content enhancing the antioxidant activity of the beans. This antioxidant activity enhancement contributed to the α-amylase inhibition (which is relevant for the diabetes controlling), as well as for the inhibition of the *Helicobacter pylori* growth (linked to peptic ulcer management).

3.2. Production and extraction of bioactive phenolic compounds from agro-industrial residues

Another valuable application of SSF is for the production or extraction of bioactive phenolic compounds from agro-industrial residues. Large amounts of these materials, including seeds, peels, husks, whole pomace, among others, are generated every year in the form of wastes, and are poorly valorized or left to decay on the land. Recently, increased attention has been given to these materials as abundantly available and cheap renewable feedstocks for the production of value-added compounds. In this sense, a number of them have been used as solid substrates in SSF processes for the production of different bioactive phenolic compounds (Hernández et al., 2008; Robledo et al., 2008; Vattem and Shetty, 2003; Zheng and Shetty, 2000).

Pomegranate wastes, for example, contain a significant amount of phenolic compounds, including anthocyanins (derived from delphinidin, cyanidin and pelargonidin), hydrolysable tannins (catechin, epicatechin, punicalin, pedunculagin, punicalagin, gallic and ellagic acid esters of glucose) (Cuccioloni et al., 2009; Gil et al., 2000), and several lignans (isolariciresinol, medioresinol, matairesinol, pinoresinol, syringaresinol, and secoisolariciresinol) (Bonzanini et al., 2009) can be mentioned. These phenolic compounds confer antioxidant, anti-mutagenic, anti-inflammatory and anticancer activities to the pomegranate wastes (Gil et al., 2000; Naveena et al., 2008; Negi et al., 2003). In recent studies, pomegranate husks were successfully used as support and nutrient sources for ellagic acid production by SSF with *Aspergillus niger* GH1 (Aguilar et al., 2008; Hernández et al., 2008). This process is economically interesting since from each ton of waste, it is possible to produce 8 kg of ellagic acid by SSF (Robledo et al., 2008). This process is also quite profitable from an industrial point of view, considering the commercial price of this acid and the low cost and abundance of the husks.

Cranberry pomace, the by-product of the cranberry juice processing industry, has also been pointed out as a good source of ellagic acid and other phenolic compounds (Vattem and Shetty, 2003; Zheng and Shetty, 1998, 2000). Bioprocessing of this waste by SSF with *Lentinus edodes* was useful to increase the ellagic acid content, being also an interesting alternative for the production of bioactive compounds

(Vattem and Shetty, 2003). In India, Teri pod (*Caesalpinia digyna*) cover, the solid residue obtained during processing of the pod for recovery of oil, is a readily available agro-industrial by-product. This material contains tannin that can be used as substrate for microbial conversion to gallic acid. Bioconversion of tannin to gallic acid from the powder of Teri pod cover was successfully performed by SSF with the fungus *Rhizopus oryzae* (Kar et al., 1999).

Green coconut husk, an abundant agro-industrial residue in Brazil, is a potential source of ferulic acid, from which vanillin can be obtained via microbial conversion. In a recent study, the cultivation of the basidiomycete *Phanerochaete chrysosporium* under SSF in this residue caused the production of lignolytic enzymes that released ferulic acid from the coconut husk cell wall and subsequently, vanillin was obtained with high yield by the ferulic acid conversion (Barbosa et al., 2008). In fact, the action of enzymes such as α-amylase, laccase and β-glucosidase, tannin acyl hydrolase, ellagitanin acyl hydrolase, among others, plays an important role in the mobilization of bioactive phenolic compounds during SSF (Cho et al., 2009; Robledo et al., 2008; Zheng and Shetty, 2000). The enzymes responsible for the degradation of lignocellulosic residues are mainly produced by fungi, since these microorganisms have two extracellular enzymatic systems: a hydrolytic system that produces hydrolases able to degrade polysaccharides, and an oxidative ligninolytic system, which degrades lignin and opens phenyl rings, increasing the free phenolic content (Sánchez, 2009). Table 3 summarizes some enzymes produced during SSF by lignocellulolytic fungi in several agro-industrial residues.

The enzyme β-glucosidase (β-D-glucoside glucohydrolase) catalyzes the hydrolysis of glycosidic linkages in alkyl and aryl β-D-glucosides, as well as glycosides containing only carbohydrate residues (Vattem and Shetty, 2003). This enzyme has been described as being able to hydrolyze phenolic glycosides to release free phenolic acids. Some studies have suggested that crude *Lentinus edodes* β-glycosidase has higher capacity to release free phenolic acids from cranberry pomace than the commercial β-glycosidase (Vattem and Shetty, 2003; Zheng and Shetty, 2000). Such capacity was related to the possible presence of other enzymes such as esterases, in the crude β-glycosidase solution. These enzymes might help the cleavage of inter-sugar linkages, releasing the corresponding glycosides that were hydrolyzed liberating phenolic aglycon moieties.

During SSF of soybean with *Bacillus pumilus* HY1, Cho et al. (2009) reported a significant increase in the contents of flavanols and gallic acid, and a decrease in the amounts of isoflavone glycosides, malonylglycosides and flavanol gallates. This phenomenon was associated with bacterial β-glucosidase and esterase activities. Similarly, the improvement in the antioxidant potential of fermented rice has been associated with phenolic compound increases by β-glucosidase and α-amylase activities during SSF (Bhanja et al., 2008). Recently, elagitannin acyl hydrolase has been related with the bioconversion of elagitannin into ellagic acid during SSF of pomegranate husks (Robledo et al., 2008).

Agricultural or forestry refuses including cereal and vegetable wastes such as straw, bagasse, stover, cobs, husks, among others, are lignocellulosic materials composed mainly of cellulose, hemicellulose and lignin. The lignin fraction in these materials contains numerous phenolic components, mainly acids such as ferulic, *p*-coumaric, syringic, vanillic and *p*-hydroxybenzoic (Mussatto et al., 2007), which can be recovered by SSF. Filamentous fungi like the white-rot fungi *Phanerochaete chrysosporium, Trametes versicolor, Trametes hirsuta* and *Bjerkandera adusta* have ability to degrade lignin since they produce a large range of enzymes necessary to break down this structure. As fungi grow on these agro-industrial residues, they utilize the polysaccharides after lignin degradation in order to grow and reproduce. This has the effect of increasing the nutritional value of the agro-industrial substrates that are generally low. After SSF the materials can be used as an animal feed or soil fertilizer (Nigam et al., 2009). The main extracellular enzymes participating in lignin degradation are lignin peroxidase (LiP), manganese peroxidase (MnP) and laccase (Philippoussis, 2009).

3.3. Production and extraction of bioactive phenolic compounds from plants

Plants produce a wide variety of bioactive compounds with significant applications in the health and food areas (Sarikaya and Ladisch, 1999; Ventura et al., 2008). Such compounds include a variety of flavonoids, phenolic acids, lignans, sallicylates, stanols, sterols, glucosinolates, among others (Hooper and Cassidy, 2006). In fact, plants are considered to be excellent sources of phenolic compounds with very interesting nutritional and therapeutic applications (Li et al., 2008; Trouillas et al., 2003). Among these compounds, a strong correlation between antioxidant activity and the total phenolic content in the plants has been observed, suggesting that phenolic compounds could be the major contributor of their antioxidant capacity (Li et al., 2008).

Phenolic compounds are widely distributed in plants, usually being found in higher concentrations in leaves and green steams (Bennett and Wallsgrove, 1994; Hyder et al., 2002). These compounds are considered natural defense substances, and their concentration in each plant may be influenced by several factors including physiological variations, environmental conditions, geographic variation, genetic factors and evolution (Figueiredo et al., 2008). The large

Table 3
Enzymes produced during solid-state fermentation by lignocellulolytic fungi in several agro-industrial residues.

Enzyme (s)	Substrate	Microorganism	Reference
β-glycosidase	*Lentinus edodes*	Cranberry pomace	Zheng and Shetty, 2000
	Rhizopus oligosporus	Flour-spplemented guava waste	Correia et al., 2004
	Aspergillus oryzae	Rice	Bhanja et al., 2008
α-amilase	*Aspergillus oryzae*	Rice	Bhanja et al., 2008
Polygalacturonase	*Aspergillus niger*	Wheat and soy brans	Castilho et al., 2000
Xylanase	*Aspergillus niger*	Apple pomace and cotton seed powder	Liu et al., 2008
	Sporotrichum thermophile	Corn cobs	Topakas et al., 2003b
Cellulase	*Aspergillus niger*	Bran and cotton seed powder	Wang et al., 2006
Hemicellulase			
Glucoamylase			
Pectinase			
Acidic proteinase			
Laccase	*Lentinus edodes*	Corn	D'Annibale et al., 1996
	Pleurotus pulmonarius	Wheat bran and wheat straw	Marques de Souza et al., 2002
		Wheat straw	Lang et al., 1996
	Pleurotus sp.	Wheat straw	Baldrian and Gabriel, 2002
	Pleurotus ostreatus		
Glycosidase	*Aspergillus niger*	Grape	Huerta-Ochoa et al., 2003

biodiversity of plants existent, provides a great exploration field for researches on bioactive phenolic compounds and their biological properties (Shetty and McCue, 2003; Skerget et al., 2005; Tellez et al., 2001; Yesil-Celiktas et al., 2009).

Mexico is one of the world's richest countries in plant biodiversity, with a variety estimated between 22,000 and 30,000 species (Villaseñor, 2003; Villaseñor et al., 2007). The scientific and most common names of some plants that have been studied in SSF processes include *Larrea tridentata* (gobernadora or creosote bush), *Flourensia cernua* (hojasén or tarbush), *Jatropha dioica* (sangre de drago or dragon's blood), *Euphorbia antisyphylitica* (candelilla) and *Turnera diffusa* (damiana). These plants dominate some semiarid areas of northern Mexico and southwestern United States, as well as some desert regions of Argentina (Rzedowski and Huerta, 1994). Extracts from *Larrea tridentata* using organic solvents have shown great potential regarding biological properties, namely, antioxidant and antifungal activities (Abou-Gazar et al., 2004; Vargas-Arispuro et al., 2005). These biological properties were related to the presence of certain lignans, which are phenolic compounds characterized by having a diphenolic ring containing a 2,3-dibenzylbutane structure formed from the oxidative dimerization of two cinnamic acid residues. *Larrea tridentata* has also been used as a source of a valuable lignan named nordihydroguaiaretic acid (Hyder et al., 2002), known for its biological properties including anticancer and antiviral activities (Cui et al., 2008; Hwu et al., 2008; Vargas-Arispuro et al., 2005). It has been demonstrated in a recent study that *Larrea tridentata* was a potential source for gallic acid and tannase production by SSF using *Aspergillus niger* Aa-20 (Treviño-Cueto et al., 2007). High concentrations of gallic and ellagic acids were also obtained by *Aspergillus niger* PSH during SSF of tannin-rich aqueous extracts from *Larrea tridentata* impregnated in polyurethane foam (Ventura et al., 2008). *Aspergillus niger* GH1 has also been reported as being a fungi with great ability to hydrolyze ellagitannins into ellagic acid during SSF using *Larrea tridentata* as substrate (Aguilera-Carbo et al., 2009).

4. Concluding remarks and future perspective

SSF is a clean technology with great potential for application on the production or extraction of biologically active compounds from natural sources. The agro-industrial residues reuse in this area is of particular interest due to their availability, low cost, and characteristics that allow obtaining different bioactive phenolic compounds, besides being an environment friendly alternative for their disposal. Another interesting application for SSF is to increase the bioactive phenolic compounds content in food products. This area has great potential to expand in a near future due to the increased consumer desire to improve health through food.

Acknowledgments

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