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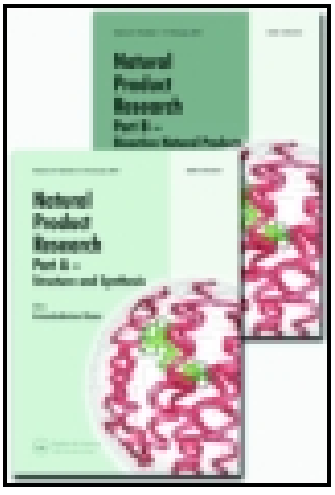

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REVIEW

Castanea sativa by-products: a review on added value and sustainable application

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Castanea sativa Mill. is a species of the family Fagaceae abundant in south Europe and Asia. The fruits (chestnut) are an added value resource in producing countries. Chestnut economic value is increasing not only for nutritional qualities but also for the beneficial health effects related with its consumption. During chestnut processing, a large amount of waste material is generated namely inner shell, outer shell and leaves. Studies on chestnut by-products revealed a good profile of bioactive compounds with antioxidant, anticarcinogenic and cardioprotective properties. These agro-industrial wastes, after valorisation, can be used by other industries, such as pharmaceutical, food or cosmetics, generating more profits, reducing pollution costs and improving social, economic and environmental sustainability.
The purpose of this review is to provide knowledge about the type of chestnut by-products produced, the studies concerning its chemical composition and biological activity, and also to discuss other possible applications of these materials.

Keywords: chestnut; *Castanea sativa*; by-products; sustainability; composition; review

1. Introduction

Castanea sativa Mill. is a species of the Fagaceae family that can be found in south Europe and Asia (China). In Portugal, chestnut trees are mainly used for nut production, representing a total area of about 35,000 ha with a production of about 19,000 tons per year (INE 2013). The nuts are consumed locally and exported, predominantly to Spain, Italy, France, Brazil, UK, USA and Switzerland (INE 2013). For the preservation of the national genetic heritage and high-quality products, specific regions (Terra Fria, Padrela, Soutos da Lapa and Marvão) were created with Protected Designation of Origin. Trás-os-Montes is the main Portuguese region of chestnut production (with more than 75% of all production), which is one of the most important economic resource in that area (INE 2013).

Chestnut is composed of fruit, pericarp (outer shell), integument (inner shell) and bur that surround the edible nuts.

These fruits are a highly appreciated seasonal nut (autumn) in the Mediterranean countries (Cruz et al. 2013), which is consumed raw or after cooking. Roasting or boiling is the most common cooking procedure. The cooking procedures change the sensorial and nutritional properties of chestnuts, improving its organoleptic properties, bioavailable nutrients and shelf life (de Vasconcelos, Bennett, Rosa et al. 2010; Cruz et al. 2013). According to Nazzaro et al. (2011), roasting best preserves the mineral and the total polyphenolic content of chestnut fruits.

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Other authors concluded that cooked chestnuts are a good source of organic acids and phenolics, with a significant amount of polyphenols, gallic and ellagic acid, and hydrolysable and condensed tannins (de Vasconcelos et al. 2007; Barreira et al. 2008; Gonçalves et al. 2010).

From a nutritional point of view, chestnut fruits can be used as an important source of dietary energy, due to its starch, carbohydrates and low fat contents (de Vasconcelos, Bennett, Rosa et al. 2010; Barreira et al. 2012). The mineral content is also very important, as it is critical for different metabolic processes, such as essential co-factors for enzymes related with digestion and absorption processes (Gonçalves et al. 2010; Cruz et al. 2013).

Oleic, linoleic and palmitic acids were the major fatty acids determined (about 85% of total content), which are related with health benefits (Borges et al. 2007; Barreira et al. 2012). Ruxton et al. suggested that *n*-3 and *n*-6 polyunsaturated fatty acids (PUFAs) help to prevent endothelial dysfunction, including the decrease in the production of pro-inflammatory mediators, such as tumour necrosis α-factor, and changing signalling pathways that regulate gene expression, such as nuclear factor-KB activity (Ruxton et al. 2004; Choque et al. 2014). PUFA intake is inversely associated with traditional biomarkers of cardiovascular disease (CVD) risk, glucose and low-density lipoprotein-cholesterol and fibrinogen and C-reactive protein (Livingstone et al. 2013). The severity of atherosclerosis might be reduced by consuming a diet rich in PUFAs (Penumetcha et al. 2012).

Vitamin E, mainly α-tocopherol form, was also present in chestnut, with its characteristic antioxidant and anti-inflammatory properties, acting as a chain-breaking antioxidant, preventing PUFA lipid peroxidation by reactive oxygen species (ROS) (Barreira et al. 2012, Mocchegiani et al. 2014; Niki 2014). According to epidemiological studies, a high intake of vitamin E can prevent neurodegenerative disorders (Engelhart et al. 2002; Morris et al. 2005). Mocchegiani et al. (2014) also suggested that vitamin E can be used for preventing ageing pathologies or to achieve healthy ageing and longevity without adverse effects. Aside from its beneficial health effects, vitamin E could be seen as a reliable authenticity marker, allowing the identification of different chestnut varieties according to their tocopherol and tocotrienol profiles (Barreira et al. 2009).

New applications for chestnuts are being tested. An example is the significant importance of chestnut fruits in coeliac disease as they are gluten free, ameliorating the response of the body's immune system to proteins (Demirkesen et al. 2010). Actually, it is easy to find new products in the market that are gluten free, such as breads made from chestnut flour (Demirkesen et al. 2010).

A prebiotic effect of chestnut has also been reported. Prebiotic is a food component that confers a health benefit on the host associated with modulation of the microbiota (Pineiro et al. 2008). Blaiotta et al. 2013 referred to chestnut as a functional fruit and prebiotic due to the presence of non-digestible components of the matrix. The authors verified that chestnut extracts improved the tolerance to gastric transit of lactobacilli, while chestnut fibre improved the tolerance to bile juice (Blaiotta et al. 2013).

The use of its starch as a valuable product could also be considered as a new application for chestnut in food industry. Starch is widely used in industrial applications such as paper, plastics, textile, food, pharmaceutical and cosmetic industries (Rodrigues & Emeje 2012). Rodrigues and Emeje (2012) described chestnut native starch as a high paste consistency and breakdown absence, associated with high amylose content and strong, elastic and stable gels. These properties give starch the ability to improve the texture of pasta noodles and provide viscosity, adhesion and binding properties in batters during production (Correia et al. 2012).

However, it should also be taken into account that seasonal variability, environmental conditions and storage time influence the nutritional composition and quality of chestnut (Fernandes et al. 2011). Their quality is measured by external factors such as colour, shape, size, surface blemishes and moulds, which are very important for consumer acceptance (Barreira,

Carocho, et al. 2013). For the preservation of chestnut fruit quality, and to protect them from insects and microorganisms, new methods are being studied, namely gamma and electron beam irradiation (Barreira, Carocho, et al. 2013). Irradiation proved to have beneficial effects, including reduction of loss during storage, shelf-life extension and improvement of microbiological and parasitological safety of foods (Rodrigues & Emeje 2012). A study conducted by Fernandes et al. tested chestnut samples conserved by irradiation and results proved that chemical and nutritional parameters were preserved, and antioxidant activity and total phenolic contents were maintained (Antonio et al. 2011; Fernandes et al. 2011). This method is also an environmentally friendly alternative to the use of fumigants, as it does not leave chemical residues on fruits or environment (Antonio et al. 2011).

Other industries are trying to use chestnut trees for different new functions. According to Alañón et al. (2012, 2013), its wood can be interesting for the wine industry. The authors described high levels of volatile phenols and phenolic aldehydes in chestnut wood, specifically vanillin and its derivatives that can be used in ageing processes (Alañón et al. 2012). The relation between time and phenolic composition of aged wines, stored in chestnut wood barrels, revealed it to be essential for the process. Wine phenolic compounds have a slow transformation and the microoxygenation process, suffered through the pores of chestnut staves during the ageing period (Alañón et al. 2013).

Chestnuts were also tested as a new adsorbent for cationic dyes (Sánchez-Martín et al. 2011). The adsorbent production used hydrolysable tannins, gallic and ellagic acids, to form complex structures through formaldehyde polymerisation (Sánchez-Martín et al. 2011). Sánchez-Martín et al. (2011) referred that gelified tannins from chestnuts were promising removers of cationic dyes. This could be very useful in solving pollution problems.

Chestnuts have an increasing economic value taking into account consumers and industrial interest. For all the referred reasons, it is possible to conclude that, although chestnut is considered an important source of essential elements for a healthy diet, new researches are being developed in order to find new chestnut applications for different industries, improving the sustainability of the chain in economic and social points of view.

The aim of this article is to review scientific information on chestnut by-products and identify phytochemicals with biological activity, predicting their future applications in food, pharmaceutical, nutraceutical or cosmetic industries, always focusing on sustainability and environmental protection.

2. *C. sativa* Mill. by-products

Several studies were conducted on chestnut by-products, namely leaf, shell and bur, revealing it to be a good source of phenolic compounds with marked biological activity, mainly antioxidant properties (Barreira et al. 2012).

The phenolic compounds are responsible for the properties of leaf extracts such as antibacterial, DNA protection and prevention, and treatment of oxidative stress-mediated diseases such as photoageing (de Vasconcelos, Bennett, Quideau, et al. 2010). Chestnut shell extracts also showed other applications beyond antioxidant properties. Vazquez et al. studied chestnut shell extracts as heavy metal adsorbents (Vázquez et al. 2012) and its potential use as phenol substitutes in adhesive formulation and as chrome substitutes in leather tanning, with good results (Husgafvel et al. 2013). Cost-efficient processing methods are needed, considering the economical and social viability and to decrease the impacts of these wastes. Many other benefits can be achieved through a sustainable management, based on efficient use of resources, materials and energy (Husgafvel et al. 2013). According to Nagalingam et al. (2013), manufacturers need to take responsibility for designing sustainable products and implementing cleaner production systems for 3R operations (Reuse/Remanufacture/Recycle).

2.1 *Phenolic compounds and antioxidant properties*

Nowadays, the consumers tend to prefer natural products (derived from natural sources); therefore, many studies are being developed in order to find new natural antioxidants and to replace synthetics, especially from food industry, associated with toxic and carcinogenic effects (Rechner et al. 2002). Phenolic acids are one of these cases, being investigated as new primary antioxidants for the prevention of oxidative processes (Roleira et al. 2010).

For a long time, infusions of chestnut leaves were used to treat cough, diarrhoea and rheumatic condition; chestnut shell had its main application as fuel and bur had no described application (Vázquez, Calvo, et al. 2009; Díaz Reinoso et al. 2012). Recent studies on chestnut by-product extracts concluded about the presence of high amounts of phenolic compounds with antioxidant activity (Almeida, Fernandes, et al. 2008; Barreira et al. 2008; Barreira et al. 2010). Barreira et al. (2008) confirmed that polyphenols and flavonoids were found in all studied samples of chestnut by-products, when extracted with water, in the following order of contents: shell > inner skins > flowers > leaves. The authors revealed that the antioxidant activity increased with the concentration, and even at low extract concentrations good results were obtained (Barreira et al. 2008). The results obtained with chestnut were better than those obtained with the leaf extracts of walnut and hazel (Barreira et al. 2008).

Phenolic acids (ellagic and gallic acid), flavonoids (rutin, quercetin and apigenin) and tannins were the main phenolic compounds reported (de Vasconcelos, Bennett, Quideau, et al. 2010; Díaz Reinoso et al. 2012; Vázquez et al. 2012).

Phenolics could be divided into two classes: benzoic acid derivatives, such as gallic acid, and cinnamic acid derivatives, such as coumaric, caffeic and ferulic acid (Dai & Mumper 2010). A direct relationship has been found between the content of total phenolics in the extracts and the antioxidant capacity of plants (Ferreira et al. 2007). Phenolic compounds are involved in the defence process against deleterious oxidative damage, protecting against oxidative stress-related diseases. Oxidative stress occurs when the balance between the production and elimination of ROS, reactive nitrogen species (RNS) and reactive sulfur species (RSS) is compromised, leading to an overproduction of oxidative species (Craft et al. 2012). The main targets of pro-oxidants, such as ROS, RNS and RSS, are proteins, DNA and RNA molecules, sugars and lipids (Lu et al. 2010; Craft et al. 2012).

The antioxidant activity can be effective in different ways: inhibition of free radical oxidation reactions avoiding the formation of free lipid radicals; interrupting the propagation of the autoxidation chain reaction; as singlet oxygen quenchers; through synergism with other antioxidants; as reducing agents which convert hydroperoxides into stable compounds; as metal chelators that convert metal pro-oxidants (iron and copper derivatives) into stable products and as inhibitors of pro-oxidative enzymes (lipoxygenases) (Sies 1997; Min & Boff 2002; Pokorný 2007; Valko et al. 2007).

A large amount of flavonoids were detected in chestnut by-product extracts (Calliste et al. 2004; Díaz Reinoso et al. 2012; Vázquez et al. 2012). Flavonoids are abundant polyphenols in our diets and are composed of flavonols, anthocyanins, isoflavonoids, flavanones and flavones, according to the oxidation state of the central C ring (Dai & Mumper 2010). Some of the most important flavonoids are catechin, catechin-gallate, quercetin and kaempferol, which reveal good antioxidant properties as the phenolic hydroxyl groups are attached to ring structures (Sroka 2005). Flavonoids are able to activate antioxidant enzymes, reduce α-tocopherol radicals, inhibit oxidases, mitigate nitrosative stress and increase levels of uric acid and low-molecular-weight molecules (Sroka 2005; Prochazkova et al. 2011). According to Valko et al. (2007), flavonoids can enhance nitric oxide status and improve endothelial function, which are important properties for the prevention of CVDs. Quercetin is one of the most abundant natural flavonoids and can be found in onions, tea and apples (Scalbert et al. 2005). Studies on quercetin showed its

relation in the increase of antioxidant capacity of blood plasma (Rao & Parthasarathy 1996) and its direct effect on ROS scavenging, with major implications on the prevention of *tert*-butyl hydroperoxide effects, a compound that can induce breakage in DNA chains (Silva et al. 2008). Neuroprotective effects were also reported (Silva et al. 2008). A combination between quercetin and phospholipids such as lecithin proved to increase its ability to cross the blood–brain barrier and exert its protective effect on the brain (Dajas et al. 2003).

Tannins were present in chestnut wood, bark and shell, providing the possibility to be used in the formulation of adhesives, in leather tanning and as a source of antioxidant compounds for food application (Vázquez, González-Alvarez et al. 2009; Comandini et al. 2014). These compounds are polyphenolic secondary metabolites of plants, usually subdivided into two groups: hydrolysable and condensed tannins. Condensed tannins (proanthocyanidins) are oligomers or polymers of flavan-3-ol linked through an interflavan carbon bond (Dai & Mumper 2010). The biological activity of tannins should be related to a high concentration of ortho-phenolic hydroxyl groups (Haslam 1974). Hydrolysable tannins are mainly associated with gallic or ellagic acid residues and condensed tannins with ring B phenolic hydroxyls.

2.2 *Extraction methods*

According to different authors, extracts present better properties than pure molecules for the achievement of bioactive compounds based on the additive and synergistic effects implicated in its properties (Liu 2003; Calliste et al. 2004). Many studies are being conducted on *C. sativa* by-product extracts, revealing a good content of total polyphenols (Barreira et al. 2008; Vázquez et al. 2008; Barreira et al. 2010; Díaz-Reinoso et al. 2011; Díaz Reinoso et al. 2012; Vázquez et al. 2012; Almeida et al. 2013).

The solubility of polyphenols is influenced by the chemical nature of the plant sample, as well as the polarity of the solvents used. Different solvents such as water (Calliste et al. 2004; Barreira et al. 2010), methanol (Calliste et al. 2004), ethyl acetate (Basile et al. 2000; Calliste et al. 2004) and ethanol-aqueous solutions (Almeida, Fernandes, et al. 2008; Almeida, Valentão, et al. 2008; Mujić et al. 2011) are suitable agents for the extraction of phenolics from *C. sativa* leaves, but the polarity of the solvent influences the antioxidant activity of the extract. Ethanol is considered a good solvent for polyphenol extraction and safe for human consumption (Shi et al. 2005) being a GRAS (generally recognised as safe) compound. Ethyl acetate (low polarity) can also be used as a good solvent for the extraction of polyphenols, as it has the ability to extract polyphenols dissolved in the lipid fraction of food. Its low boiling point makes the solvent easy to remove and reuse, making it very promising for a sustainable process (Shi et al. 2005). Calliste et al. (2004) used ethyl acetate for the extraction of phenolic compounds from the extracts of chestnut leaves, obtaining antioxidant properties equivalent to quercetin and vitamin E, but lower than those obtained with other solvents. Water is a biorenewable non-toxic solvent, normally used for the extraction of antioxidant compounds from chestnut by-products (Díaz-Reinoso et al. 2011). However, the high residual volumes could compromise the environmental benefits and concentration costs (Díaz-Reinoso et al. 2011).

Table 1 summarises the relation between phytochemical extract from chestnut by-products with different solvents and their biological activity.

According to Calliste et al. (2004), high phenolic polymers and tannins from chestnut leaves can be found in water fractions and the ratio of tannins/other phenolic compounds is responsible for the radical-scavenging capacity. Comparing the amount of total phenolic compounds obtained using different extraction methods, it is possible to conclude that the experiment realised by Barreira et al. is the one that showed highest values. Also, these authors used water as solvent, which has less environmental impact than other solvents, mainly, organic solvents.

Table 1. Extraction methods, identified phytochemicals and reported biological activities of *C. sativa* by-product extracts.

Ref.	Extraction method	Identified phytochemical	Biological activities	Antioxidant assays
Leaves				
Díaz Reinoso et al. (2012)	Acidified water; >90 min; 50°C	Phenolic acids and flavonoids: Gallic acid, protocatechuic acid, hydroxybenzoic acid, vanillic acid, rutin, quercetin and apigenin **Total phenols:** 90 mg GAE/g	Antioxidant capacity; radical-scavenging capacity similar to BHA	DPPH; TEAC; free radical-scavenging activity
Barreira et al. (2008)	50 mL of water; 30 min; boiling temperature	Polyphenols and flavonoids **Total phenols:** 510 mg GAE/g	Antioxidant capacity; Lipid peroxidation inhibition	DPPH; inhibition of β-carotene bleaching; inhibition of erythrocyte haemolysis; reducing power; inhibition of lipid peroxidation using TBARS
Calliste et al. (2004)	Ethyl acetate fraction; water/acetone (1:2); 60°C	High level of total phenolic compounds; flavonols; isoquercitrin (quercetin 3-glucoside), phenolic acids derived from benzoic acid Total phenols: 291 mg GAE/g	Antioxidant capacity; high antioxidant potentials equivalent to quercetin and vitamin E	Radical-scavenging activity against ABTS radical scavenging; TEAC; DPPH; free radical-scavenging activity.
Díaz-Reinoso et al. (2011)	Acidified water; 25°C; 90 min; ultrafiltration membranes (5 and 10 kDa)	Flavonoids (rutin, quercetin, apigenin) Phenolics (vanillic acid) **Total phenols:** 46 mg GAE/g	Antioxidant capacity; antioxidant properties similar to Trolox and BHA	DPPH; TEAC; FRAP
Barreira et al. (2010)	Water; room temperature; 1 h	Phenolic compounds and flavonoids **Total phenols:** 413 mg GAE/g	Antioxidant capacity	TBARS; inhibition of β-carotene bleaching; reducing power; DPPH; content of total phenols and flavonoids
Almeida, Fernandes, et al. (2008)	Ethanol/water (7:3); 10 min; 40°C	Phenolic compounds and flavonoids **Total phenols:** 284 mg GAE/g	Antioxidant capacity; antioxidant properties similar to Trolox, mannitol and ascorbic acid	Radical-scavenging activity
Shell				
de Vasconcelos, Bennett, Quideau, et al. (2010)	Acetone/water (7:3); 20°C; 48 h	Phenolic compounds (gallic and ellagic acid), condensed tannins; ellagitannins (castalagin, vescalagin, acutissiminA and acutissimin B) **Total phenols:** 136.35 mg GAE /100 g	Antioxidant capacity; neither tocopherols nor carotenoids/chlorophylls were detected	Folin–Ciocalteu; acid/1-butanol method; HPLC analyses of phenolics

(*Continued*)

Table 1. (*Continued*)

Ref.	Extraction method	Identified phytochemical	Biological activities	Antioxidant assays
Vázquez, González-Alvarez, et al. (2009)	2.5% Na_2SO_3 or 2.5% NaOH–2.5% Na_2SO_3 aqueous solution; temperature: 70–90°C	Phenolic compounds, flavonoids and condensed Tannins **Total phenols:** 18.83 g GAE/100 g	Antioxidant capacity; 70–90°C implied an increase in the extraction yield	FRAP, Folin–Ciocalteu, tannin content,
Bur Vázquez et al. (2012)	Methanol/water (50–90%); 25–75°C; 30–120 min	Phenolic compounds Gallic acid esters of glucose, ellagic acid and quercetin-3-_-D-glucoside **Total phenols:** 36.32 g GAE/100 g	Antioxidant capacity; optimal extraction conditions: 50% solvent concentration; 75°C; 75°min	Folin–Ciocalteu; FRAP, DPPH; ABTS
Conde et al. (2011)	Non-isothermal autohydrolysis; ethyl acetate/water (1:3); 20 min; 220°C	Phenolic compounds: gallic acid esters of glucose, ellagic acid; 4-hydroxybenzoic acid, vanillic acid, syringic acid, *p*-coumaric acid; ferulic acid Flavonoids (quercetin, rutin and apigenin) **Total phenols:** 0.61 g GAE/g	Antioxidant capacity; re-dissolution of extracts in water reduced the phenolic content by 50% Antioxidant capacities similar to synthetic compounds	DPPH; TEAC; FRAP; β-carotene bleaching method; reducing power; ORAC-FL assay

Chestnut shell extracts confirmed their richness in total phenolic compounds, mainly phenolic acids and tannins (condensed and hydrolysable), as described in Table 1.

Barreira et al. (2008) analysed five different chestnut extracts with several biochemical assays, including inhibition of oxidative haemolysis in erythrocytes and inhibition of lipid peroxidation. Chestnut skins (inner and outer) revealed a good antioxidant capacity and a high content of polyphenols and flavonoids, demonstrating a direct correlation between antioxidant capacity and the concentration of these bioactive compounds (Barreira et al. 2008). Shell extracts showed a high capacity to protect against oxidative damage of erythrocyte cell membranes, avoiding haemolyses (Barreira et al. 2008). The solvent was water at boiling point. In different studies, these authors found an interesting total phenolic content (>100 mg/g of extract) and a good radical-scavenging activity for all extracts, except for chestnut fruit (Barreira et al. 2008; Barreira et al. 2010).

In another study, Vázquez, González-Alvarez, et al. (2009) used many organic and aqueous solvents for the extraction of phenolics from shell extracts. According to these authors, the solvents with highest yields and the best antioxidant activities were aqueous sodium sulfite and a mixture of sodium hydroxide and aqueous sodium sulfite at 90°C, with values ranging between 2.5% aqueous sulfite hydroxide (13.4 g GAE/100 g extract) and sodium sulfite and sodium hydroxide (2.5%) at 90°C (188.4 g GAE/100 g extract). The authors concluded that the extraction yields increased with the polarity of the solvent and the temperature (from 70 to 90°C) (Vázquez et al. 2008; Vázquez, González-Alvarez, et al. 2009).

Recently, de Vasconcelos, Bennett, Quideau, et al. (2010) analysed the phenolic and tocopherol compositions of chestnut outer and inner shells. A good content of total phenolics with low molecular weight were determined, but neither tocopherols nor carotenoids/chlorophylls were detected (de Vasconcelos, Bennett, Quideau, et al. 2010). Inner shell showed the highest levels of total phenolics (de Vasconcelos, Bennett, Quideau, et al. 2010). The authors evaluated different solvents, and the efficient extraction of total phenolics, total condensed tannins and low molecular weight phenolics was obtained with acetone:water (70:30; v/v) at 20°C. According to this study, the extraction efficiency could be resumed as: acetone > methanol > ethanol > water (de Vasconcelos, Bennett, Quideau, et al. 2010).

Considering chestnut bur extracts, Vázquez et al. (2012) evaluated the influence of different extraction conditions: different solvents (methanol/ethanol) and concentrations (50–90%), temperatures (25–75°C) and extraction times (30–120 min) to determine the total phenolic content and antioxidant activity. The authors concluded that the best extraction conditions were obtained with 50% methanol/water extract at 75°C during 75 min. However, ethanolic extracts also presented a good antioxidant activity (26.11 g GAE/100 g extract) at 75°C and only 30 min of extraction (Vázquez et al. 2012). The ethanolic extract has the advantage of being safe for food application which highlights chestnut bur as a valuable product for edible applications.

2.3 *Potential applications*

This review describes some applications of chestnut products, and in particular, those that may promote the health of its consumers.

2.3.1 *Chestnut leaf extracts*

Diabetes and DNA protection. The interaction between ROS, from metabolic pathways, and other genotoxic agents, such as radiation (UV, X-ray and gamma), plant toxins and viruses can cause DNA damage. This oxidative form of DNA accumulates in non-replicating cells, such as neurons or myocytes, showing relatively strong association with cancer, atherosclerosis, diabetes and ageing process (Bjelland & Seeberg 2003; Muid et al. 2014).

The progression of diabetes is associated with oxidative stress and decreased concentrations of glutathione in its reduced state (GSH) (Jia et al. 2009). Rains et al. suggested that oxidative stress plays a role in the development of insulin resistance, impairing glucose tolerance and β-cell, and mitochondrial dysfunction (Burcelin et al. 2008; Rains & Jain 2011). According to Opara (2004), antioxidant supplements can be used as adjunct therapy for control of blood sugar in diabetic patients. As such, Mujić et al. (2011) studied the capacity of leaf extracts of *C. sativa* in DNA protection in β-cells. A diabetogenic agent streptozotocin (STZ) was mixed with an ethanolic extract of *C. sativa* leaves. STZ normally leads to generation of ROS and toxic amounts of nitric oxide participating in DNA damage and insulin-producing β-cell death (Lenzen 2008; Jia et al. 2009). The antioxidant properties of the referred extract showed significant ability to prevent oxidative stress in rat pancreatic β-cells. Chestnut extracts increased cell viability after STZ treatment and inhibited lipid peroxidation by lowering the malondialdehyde levels. According to the authors, chestnut extracts could increase the rate of GSH biosynthesis and/or GSH regeneration from oxidised glutathione by glutathione reductase, and the decrease of GSH oxidation, mainly by improving cellular antioxidant defences (Mujić et al. 2011). In cells treated with STZ together with the chestnut extracts, GSH concentrations increased, proving the beneficial effect of these extracts in the progression of diabetes (Mujić et al. 2011).

Antibacterial and allelopathic activity. The development of resistance to antibacterial agents and the limited availability of effective antifungal agents have led researchers to investigate novel chemical structures. Phenolic compounds are known to be synthesised by plants in response to microbial infection (Cowan 1999), which are being tested against growth and by-products of bacteria (Gram-positive and Gram-negative, spore and non-spore formers, spoilage and pathogenic), moulds and yeasts due to their antimicrobial and antioxidant activities (Raccach 1984). Phenolics can act by interacting with the microorganism's cell membrane or cell wall (Taguri et al. 2006). The interaction with membrane proteins of bacteria by means of hydrogen bonding through their hydroxyl groups can cause changes in membrane permeability and cell destruction (Tian et al. 2009). Phenolics can also penetrate into bacterial cells and promote the coagulation of the cell content. In another way, phenolic compounds as natural antimicrobials could improve the shelf life of different products, inhibiting the growth of pathogenic microorganisms (Rains & Jain 2011).

Antibacterial and allelopathic activities were verified in an ethyl acetate-soluble fraction of the aqueous extract from *C. sativa* leaves (Basile et al. 2000). This extract was tested against Gram-positive and Gram-negative bacteria showing antibacterial activity against seven bacteria: *Escherichia coli*, *Klebsiella pneumoniae*, *Enterobacter aerogenes*, *Staphylococcus aureus*, *Proteus vulgaris*, *Psuedomonas aeruginosa* and *Enterobacter cloacae* (Basile et al. 2000). Quercetin and rutin were the most active flavonoid compounds in the antibacterial test, showing that the aglycone moiety is perhaps responsible for the activity (Basile et al. 2000). Different authors tried to explain its ways of action as antibacterial agents (Mirzoeva et al. 1997; Cushnie & Lamb 2005). Plaper et al. (2003) suggested that quercetin binds to *E. coli* DNA gyrase and inhibits the enzyme's ATPase activity. According to the authors, quercetin inhibits gyrases through two different mechanisms based on interaction with DNA or with ATP-binding site of gyrase (Plaper et al. 2003). In another study on the antibacterial activity of these flavonoids, Mirzoeva et al. (1997) proposed that quercetin caused an increase in permeability of the inner bacterial membrane and a dissipation of the membrane potential, inhibiting bacterial motility. Bacterial virulence and motility are related, as motility can guide bacteria to its sites of adherence and invasion (Cushnie & Lamb 2005). Rutin, another flavonoid present in the leaf extracts of chestnut, can act by selectively promoting *E. coli* topoisomerase IV-dependent DNA

cleavage and inducing the SOS response of the *E. coli* strain (Raccach 1984). This activity is suggested to lead to a response and growth inhibition of *E. coli* cells, as topoisomerase IV is essential for cell survival (Bernard et al. 1997).

The allelopathic effect was tested against *Raphanus sativus* seed germination (Basile et al. 2000). Quercetin, rutin and apigenin present in the extract caused a decrease in the percentage of seed germination, root and epicotyl growth proving that the biological activity of *C. sativa* can modulate the development of other plants (Basile et al. 2000). Extracts of *C. sativa* leaves showed a great potential to be used in the development of antibacterial agents and in allelopathic activities (Basile et al. 2000).

Skin effects. Skin is constantly exposed to different light radiations. UV radiation from sunlight can cause short- and long-term damages (Matsumura & Ananthaswamy 2004). Some of the adverse effects that are visible after a few hours of exposure to sunlight are redness and burning due to the release of substances that cause vasodilation and erythema, and long-term effects include photoageing with a loss of elasticity and blotchy appearance, and various skin tumours (Matsumura & Ananthaswamy 2004). UV irradiation causes skin damages, involving the generation of ROS and RNS, with consequent oxidative and nitrosative stress (Shindo & Hashimoto 1997).

These reactive species interact with proteins, lipids and DNA, resulting in structural and functional modifications in the cutaneous tissue (Matsumura & Ananthaswamy 2004). ROS and UV irradiations are also involved in skin diseases such as erythema, cancer, psoriasis, acne, cutaneous vasculitis, allergic or irritant contact dermatitis and photoageing (Matsumura & Ananthaswamy 2004; Sander et al. 2004; Mehrotra et al. 2005, Okayama 2005). Dermatitis is a polymorphic inflammation of the skin characterised by redness, itching, swelling and blistering, with formation of crusts and scales during the healing process (Rios et al. 2005). Phenolics and terpenoids are considered to be the most effective inhibitors against contact dermatitis (Rios et al. 2005). Many of these compounds act not only by non-specific mechanisms such as antioxidants, but also may act via specific mechanisms such as the inhibition of the mediators implicated in the immune response, showing anti-inflammatory properties and being able to alleviate symptoms of skin inflammation and contact hypersensitivity (Rios et al. 2005; Nichols & Katiyar 2010).

UV radiation promotes wrinkle formation and loss of tissue elasticity (Lin et al. 2003). According to Choi et al. (2010), ageing is a natural process that is closely related to the oxidative stress, which leads to the imbalance between free radicals and antioxidant defence in skin. As such, the important role of antioxidants in protecting against ROS is believed to prevent the ageing process and skin diseases (Almeida et al. 2013). Topical application of antioxidants such as vitamins C and E has proven to be effective in the protection of skin against UV-mediated damage (Lin et al. 2003). A recent study evaluated the topical applications of ethanol/water extracts from *C. sativa* leaves (Almeida et al. 2010; Almeida et al. 2013). A strong absorption at 280 nm could forecast a possible effectiveness of chestnut leaf extract topical administration to prevent UV radiation-induced skin damage (Almeida et al. 2010). The extract was mainly composed of phenolic compounds such as chlorogenic acid, ellagic acid, rutin and quercetin. An *in vivo* patch test was performed in 20 volunteers and results were very promising (Almeida et al. 2010). Transepithelial water loss (TEWL) is considered to be the first choice to evaluate slight skin reactions, as it detects disrupted epidermal barrier that results in a higher loss of transepidermal water (Aramaki et al. 2001). As such, no differences were observed for TEWL measurements compared with purified water at 2 h after patch removal (Almeida et al. 2013). The same extract was evaluated under stability studies in order to prove its efficacy overtime.

Solvent selection and pH value proved to be critical, influencing functional stability and *in vivo* effectiveness (Almeida et al. 2010). A negative effect of heating was reported (Almeida et al. 2010). The increase of temperature from 20 to 40°C in storage led to a decrease in the efficacy of the extract, due to the interference on the stability of some polyphenolic compounds (Almeida et al. 2010). According to Almeida et al. (2010), the best conditions determined for the stability of a topical formulation containing an extract of *C. sativa* leaves were a hydroalcoholic extract and the storage at 20°C.

Recently, another study characterised an antioxidant surfactant-free topical formulation containing an ethanolic *C. sativa* leaf extract (Almeida et al. 2013). Physical, microbiological and functional stability for 6-month storage at 20°C and 40°C and pH 5 were confirmed (Almeida et al. 2013). No changes in pH and DPPH-scavenging activity were observed, when stored at 20°C (Almeida et al. 2013). The formulation increased skin hydration and the effect lasted for a minimum of 4 h after application (Almeida et al. 2013). The increased temperature (40°C) caused some modifications in the rheological properties of the formulation and decreased the effectiveness of the antioxidant properties of the extract (Almeida et al. 2013). This fact was related with changes in rutin contents, which are less stable to heating. As rutin was the main phenolic compound of the extract, the decrease of the antioxidant properties may be inferred. Because of all of the possible variations, specific storage conditions were recommended. The authors suggested that the topical formulation can be used in the prevention or treatment of oxidative stress-mediated dysfunctions. *C. sativa* leaf extracts can be safe and stable for use in topical formulations, and could be relevant for topical application in the prevention and treatment of oxidative stress-mediated diseases and photoageing (Almeida et al. 2013).

Other studies on the potential use of by-product plant extracts (*Medicago* spp.) and fruits (*Bryonia dioica*, *Tamus communis*) containing phenolic compounds, for topical application, revealed successful results according to safety and antioxidant properties (Barreira, Pereira, et al. 2013; Rodrigues et al. 2013).

2.3.2 *Potential application of chestnut shell extracts*

Chestnut shell, an agro-residue, may be subjected to different treatments in order to improve its efficiency as heavy metal adsorbent.

Potential use as heavy metal adsorbent. The use of by-products or waste materials from industrial operations and agriculture as biosorbents, for the removal of toxic heavy metal ions from aqueous streams, is being studied (Demirbas 2008; O'Connell et al. 2008; Bilal et al. 2013). Copper, lead, zinc and cadmium are heavy metals commonly found in industrial effluents (Garg et al. 2007). They are of specific concern due to their toxicity, tendency to bioaccumulate and persistent nature (Garg et al. 2007). From a healthy and economic perspective, it is very important to remove these metals from the wastewaters before their discharge and to try to separate them for recovery and reuse (O'Connell et al. 2008). Biosorption is seen as a new alternative to the existing conventional technologies for the removal and recovery of metal ions and contaminants from aqueous effluents. This technology shows great advantages compared with conventional treatments for its high efficiency, low cost, regeneration of biosorbents and possibility of metal recovery. The use of these low-cost biosorbents, such as cellulosic waste materials, is recommended since they are easily available, cheap, renewable and show high affinity for heavy metals (Sud et al. 2008).

From a sustainable point of view, this new application for agro-industrial waste materials could lead to an environmental improvement and decrease the costs related to the bioaccumulation of the heavy metals in water and land.

Chestnut shell showed a great potential for use as a heavy metal adsorbent (Vázquez, Calvo, et al. 2009). A study using acidic formaldehyde pre-treated chestnut shell as adsorbent reported on the influence of initial cation concentration, temperature and pH for optimum Pb^{2+}, Cu^{2+} and Zn^{2+} removal from an aqueous solution (Vázquez, Calvo, et al. 2009). Chestnut shell was pre-treated with formaldehyde in acid medium to polymerise and immobilise the water-soluble phenolic compounds (Vázquez, Calvo, et al. 2009). The maximum pre-treated chestnut shell adsorption capacity was obtained for lead ions, and the order of ion affinity was $Pb^{2+} > Cu^{2+} > Zn^{2+}$ (Vázquez, Calvo, et al. 2009). Adsorption capacity increased with increasing temperature and pH (Vázquez, Calvo, et al. 2009). Temperature may contribute to changes in pore size of the adsorbent or to the enhancement in the chemical affinity of the adsorbent for lead ions (Meena et al. 2008). In terms of pH values, metal binding could be reduced due to the increasing competition among protons for the same binding sites that metals can use. Therefore, if the functional groups of the shell were protonated hindrance to metal ion uptake is lower (Lima et al. 2007; Krishnani et al. 2008). Functional groups of the shells involved in metal uptake were supposed to be carboxyl, carbonyl, amino and alcoholic groups (Vázquez, Calvo, et al. 2009).

Another study on chestnut shell adsorbent capacity used activated carbon, prepared from chestnut shell as adsorbent, for the removal of copper ions from aqueous solutions (Özçimen & Ersoy-Meriçboyu 2009). They arrived at the same conclusions of the previous study: an increase in temperature, pH and surface area leads to an increase in the adsorbent efficiency of the chestnut shell due to its high surface area and porosity (Özçimen & Ersoy-Meriçboyu 2009).

Potential use as phenol substitutes in adhesive formulation. Plywood industry utilises adhesives composed of phenol–formaldehyde (PF), urea–formaldehyde and melamine–urea–formaldehyde (Olivares et al. 1988). PF adhesive is the most commonly used due to its high weather and water resistance, making it suitable for exterior applications, providing high resistant to moisture and good temperature stability (Çetin & Özmen 2002). The major problems in the use of PF adhesives are the composition of petrochemicals, nonrenewable materials from fossil fuel and phenol costs (Çetin & Özmen 2002; Zhang et al. 2013). The use of natural products, such as tannins and lignin as phenol substitutes in adhesive formulations, is being studied, based on their structural similarity and high reactivity towards aldehydes and other chemicals, promoting economic and environmental benefits (Hoong et al. 2011).

It has been reported that tannins from chestnut shell, under different conditions, could be used as potential phenol substitutes in adhesive formulation (Vázquez, González-Alvarez, et al. 2009). Vázquez et al. evaluated different alkaline compounds (such as sodium hydroxide, sodium sulfite and sodium carbonate), different concentrations and different temperatures (70–90°C) in the extraction of tannins from chestnut shell. Its extracts showed, for all extraction conditions used, total phenol content and antioxidant activity, being the best properties and extraction yields presented by 2.5% sodium sulfite at 90°C, together with the 2.5% sodium hydroxide and 2.5% sodium sulfite at 90°C. Also, the increase of temperature from 70 to 90°C results in an increase in the extraction yield (Vázquez, González-Alvarez, et al. 2009).

According to these data, tannins from chestnut shell extracts may have a potential use as phenol substitutes in adhesive formulations, decreasing the related costs and contributing to better environmental sustainability.

Potential use as chrome substitutes in leather tanning. Leather industry comprises the transformation of raw putrescible animal skin into useful materials (Falcão & Araújo 2011). Tanning process can avoid the degradation of the skin by stabilising its collagen structure (Sundar et al. 2002; Marsal et al. 2012). Social concerns and environmental considerations, such

as the disposal of solid chrome leather wastes as well as the chromium salt containing treatment baths, which constitute a significant pollution parameter for wastewaters, have prompted research into chromium-free tannage (Sundar et al. 2002). The treatment of tanning wastewater represents one of the major problems in the leather industry, mainly because of more stringent effluent limits imposed for pollution control (Pizzi 2008).

Vegetable tannins are natural materials which have been considered as a suitable eco-friendly option to replace chromium (Subramani et al. 2006). The molecular weight of tannins must be between 500 and 3000 Da, as higher molecular weights are unable to penetrate into the fibre structure of the skin and tend to be water insoluble (Tang et al. 1992). An example of natural tannin source for leather tanning is chestnut wood (Tang et al. 1992).

Recently, Vázquez, González-Alvarez, et al. (2009) proposed chestnut shell tannins as chrome substitutes for leather tanning. The authors extracted the tannins using water and different alkaline aqueous solutions. The extraction yield found for chestnut shell (8.7–49.4%) reached the values described for commercial pecan nut tannins (42–43%) (Vázquez, González-Alvarez, et al. 2009). Also, the extracted tannins were of a condensed type and their average molecular weights were suitable to be used in leather tanning which means that it could be used for this purpose (Vázquez, González-Alvarez, et al. 2009).

3. Future perspectives

C. sativa by-products seem to have many beneficial effects in different fields, particularly in pharmaceutical, food, cosmetics and leather industry, due to the presence of specific functional groups of phytochemicals. However, conditions and solvents used for the extraction could affect the type of biological compounds extracted and its safety.

From a sustainable point of view, chestnut by-product extracts could provide in the near future a way of recycling for chestnut-processing companies, developing cost-efficient processing methods, decreasing the negative impacts of wastes on the environment and providing other economical advantages for companies. European Commission policies have three main goals, 'more value – less impact – better alternatives' (Behrens et al. 2007).

Besides Europe, with *C. sativa* Mill., chestnut is geographically distributed in other major areas: Asia with *Castanea crenata* Sieb. and Zucc. (Japan) and *Castanea mollissima* Bl. (China and Korea) and North America with *Castanea dentata* Borkh. The reutilisation impact of these wastes as valuable products could be huge, with benefits for the environment, pollution costs and economy at a world level (Lang et al. 2006).

More studies need to be conducted to provide the potential use of these by-products at industrial scale, always taking into account the toxicity of the extracts and the cost involved.

4. Conclusion

This review summarises the state-of-the-art and future prospect of *C. sativa* Mill. by-products: leaves, shell and bur. Chestnut is one of the most frequently consumed fruit in Europe and large amounts of by-products are produced during its processing. Therefore, the establishment of effective use of chestnut by-products is important. Different suggestions are presented for the management of its utilisation. One is the use of these by-products as bioactive substances. It is reported that the phytochemicals identified in chestnut by-products were phenolic compounds, flavonoids and tannins. Most of them were reported to exhibit beneficial properties in many diseases such as diabetes, cancer, CVD, neurodegenerative diseases due to their antioxidant and antimicrobial activities. Another is the use in leather industry, in adhesives and in topical formulations for the prevention and treatment of skin oxidative stress-mediated diseases. It is necessary to identify the active substance in shell extracts. Feasibility will be high if the large-

scale experiments for industrialisation prove these effects, as it will have economic benefits and help in reducing the disposal costs of these by-products.

Conflict of interest

The authors declare that there are no conflicts of interest.

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