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Achieving sustainable cultivation of tree nuts

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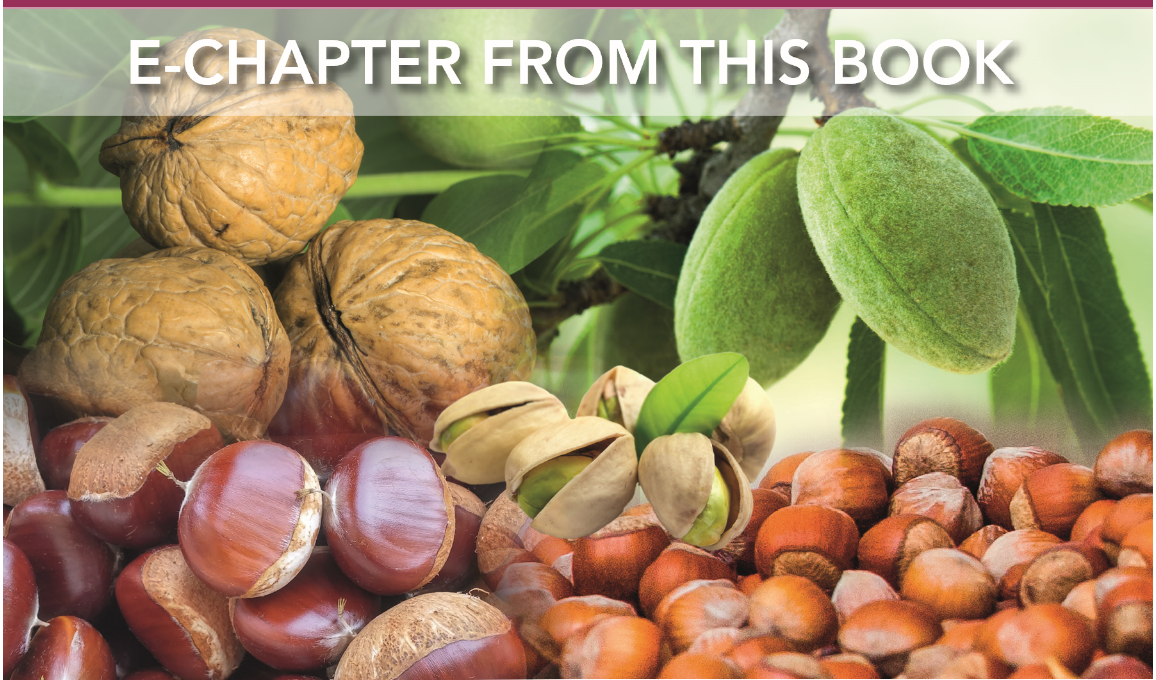

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Uses and health benefits of chestnuts

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1 Introduction

According to the WHO (http://www.who.int/dietphysicalactivity/fruit/en/), insufficient intake of fruit and vegetables on a global scale is estimated to cause approximately 14% of gastrointestinal cancer deaths, 11% of ischaemic heart disease deaths and 9% of stroke deaths; worldwide, 3.4 million deaths can be attributed to the low consumption of fruit and 1.8 million to diets low in vegetables (FAO, 2017). This information, combined with the increased literacy of consumers regarding the relationship between food and health, has gradually made consumers more aware of the relevance of diets on health and their respective impact on the environment and sustainability of the planet. Following extensive research supporting the benefits of the daily consumption of fruits and vegetables based on their supply of a range of nutritional compounds (vitamins, minerals, dietary fibre and later extended to several secondary plant metabolites), during the 1990s several countries initiated campaigns and recommendations to promote fruit and vegetable consumption. This was reinforced in 2003 by a joint action by the FAO and WHO

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that aimed to raise awareness and to boost fruit and vegetable production and consumption (400 g or five 80 g portions a day) to improve people's health and farmers' income. However, the inclusion of nuts in these references was minimal, relegating these fruits to a minor level. In the following sections it will be shown that in recent years there have been a number of research findings involving chestnuts, which support their importance and complementary role in our diet. There is readily available information focused on basic nutritional data along with more recent findings, which reveals the presence of bioactive compounds and their enzymatic metabolites, emphasizing the relevance of including chestnuts in the consumption pool of fruits and vegetables, as well as their respective health benefits. The following sections will also show that the higher consumption of chestnuts is a sustainable practice as this crop can be part of a more sustainable agricultural production system. Indeed, chestnut production, apart from being well adapted to soils of lower quality, requires less general resource input, such as water, labour and pest and disease management, when compared with other fruit crops; overall, it is better adapted to climate changes (Rackham, 1994; pers. comm.).

2 Recent research achievements

The production and consumption of chestnuts has steadily increased over the last few years, driven by an increased consumer awareness regarding food composition and the health benefits of a nut-rich diet. This has been reflected in the production area of *Castanea sativa* doubling over the last 20 years (1996–2016, the latest FAO data), from 299 911 to 602 718 ha, while the total recorded production showed a greater than threefold increase, from 678 446 t in 1996 to 2 261 589 t in 2016 (FAOstat, 2018) (Fig. 1). Similarly, from 2004 to 2012, there

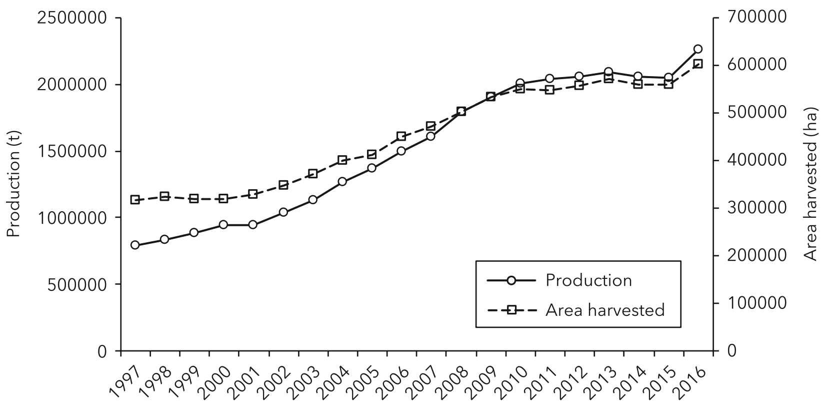

Figure 1 Evolution of production and harvested area of *C. sativa* from 1997 to 2016 in the world. Source: adapted from FAOstat (2018).

was an average increase in the global consumption of chestnuts of around 59% (Table 1) (Bento et al., 2016). Some *Castanea* species can strictly be used for their nuts; however, there is a wide range of species with other multipurpose uses that are worth noting (Table 2).

Research involving chestnuts is quite limited, but over the last two decades it has received increased attention based on the development of new equipment and consequent methodologies being focused on *C. sativa.* For *C. mollissima* and *C. crenata*, information is still very scarce despite the recent increase in the number of studies; for these two species and for *C. dentata* further studies are necessary given their potential crop expansion, consumption and uses.

Recent work involving *C. sativa* has focused on composition. Data indicate a considerable variation of moisture (41.9–64.4%), with the major component of dry nuts being carbohydrates, ranging from 42% up to 94.2% (Table 3) and starch being the most abundant carbohydrate. Other compounds, such as fat (0.7–5.37%) and protein (2.2–12.4%) also present a significant variation of their content. These variations are linked to cumulative differences between cultivars, climate and growing conditions and harvest timing.

Total phenolics are the major group of secondary plant metabolites in chestnuts. Over the last decade, the quantification of total phenolics and flavonoids in *C. sativa* has been evaluated in tree wood and bark, but also in leaves, flowers and pollen. The nut has been the focus of many studies, either as a whole or in separate fractions, such as the inner or outer skin.

Phenolics are present in a higher amount in chestnut wood (40.8 g GAE/g d.w.), bark (23.9–56.1 g GAE/g d.w.), leaves (413 mg GAE/g d.w.) and nut seed coat or testa (710 mg GAE/g d.w.), with catkins also containing a considerable amount of these compounds (251.6–327.2 mg/g) (Table 4).

Table 1 Chestnut consumption in 2004 and 2012 (t) and variation (%) between 2004 and 2012

Countries	2004 (t)	2012 (t)	Variation (%)
China	904 962	1 629 788	+80.1
South Korea	57 251	61 317	+7.1
Bolivia	52 758	57 000	+8.0
Turkey	41 798	52 603	+25.9
Italy	24 071	55 995	+132.6
Japan	48 625	31 159	−35.9
Greece	19 367	27 737	+43.2
Portugal	26 082	8408	−67.8
France	24 763	9300	−62.4
Spain	3282	8436	+157.0
World	*1 256 762*	*2 000 061*	*+59.1*

Source: adapted from Bento et al. (2016).

Table 2 Origin of *Castanea* species and major uses

Origin	Species	Common name	Orchards	Predominant use
Europe	*C. sativa* Mill.	European or sweet chestnut	Europe, Asia Minor, North Africa	Nut, timber
Asia	*C. crenata* Sieb. et Zucc	Japanese chestnut	Japan, Korea	Nut
	C. mollissima Blume	Chinese chestnut	China	Nut
	C. seguinii Dode	–	China	Firewood
	C. davidii Dode	–	China	Firewood
	C. henryi (Skan) Rehd. et E. H. Wils	Willow leaf or pearl chestnut	China	Timber
America	*C. dentata* (Marsh.) Borkh	American chestnut	North America	Timber
	C. pumila Mill. var. *pumila*	Allegheny chinkapin	Southeast USA	Nut
	C. pumila Mill. var. *ozarkensis* (Ashe) Tucker	Ozark chinkapin	USA	Timber
	C. floridana (Sarg.) Ashe	Florida chinkapin	Southeast USA	Ornamental
	C. ashei (Sudw.) Ashe	Ashe chinkapin	Southeast USA	Ornamental
	C. alnifolia Nutt	Creeping chinkapin	Southern USA	–
	C. paucispina Ashe	–	Southern USA	–

Source: adapted from Mellano et al. (2012).

The presence of amino acids and vitamins has also been studied in *C. sativa* nuts (Table 5). Recent work has shown the variation in the amino acid content (from 2.3 mg/100 g to 8.7 g/100 g d.w.), while considerable variation of vitamins C and E has also been found, which depends on several factors, particularly cultivars and growth conditions. The quantitative and qualitative mineral profiles of chestnuts are affected by the same factors, which has received further clarification over the last few years (Table 6), with K identified as the major mineral. The mineral composition of leaves and catkins is known, with Ca being the major mineral present in both plant organs, which also contains interesting amounts of other important minerals (Portela and Louzada, 2012). Another topic of study has been the effect of cooking on several quality parameters of chestnuts, namely the chemical composition and antioxidant activity, with several, not always comparable, effects (see details in Section 5). Considering the number of compounds with possible positive biological activities, many authors have focused their research on evaluating the bioactive properties of this nut and related plant tissues and organs. Over the last two decades, several studies have shown the possible positive effects of chestnuts, including antioxidant activities and antimicrobial properties, with promising results as neuroprotective or anticancer agents. Considering only *C. sativa*

Table 3 Proximate analyses previously reported for chestnut fruits

Species	Moisture (g/100 g f.w.)	Total fat (g/100 g d.w.)	Crude protein (g/100 g d.w.)	Total ash (g/100 g d.w.)	Total starch (g/100 g d.w.)	Carbohydrates (g/100 g d.w.)	Crude energy (Kcal/100 g d.w.)	Reference
C. sativa	52–52.6	1.81–2.07	5.10–5.35	2.33–2.40	52.6–53.6	–	–	Mota et al. (2018)
	10.1	4.81	4.73	2.30	–	79.4	–	Wani et al. (2017)
	46.5–59.5	0.87–2.61	6.15–12.4	2.09–4.39	40.99–53.16	58.1–69.8	–	Mert and Ertürk (2017)
	56.7–62.64	2.06–2.58	3.52–6.39	2.43–2.68	–	88.9–91.5	–	Poljak et al. (2016)
	50.8–58.4	2.7–4.6	5.5–7.2	2.2–2.9	–	78.4–93.3	–	Özel (2015)
	49	2.3	5	2.3	–	92	410	Barreira et al. (2012a)
	53–54	0.7–0.8	2.4–3	0.8–1.1	–	42–43	184–189	Barreira et al. (2012b)
	52.8	2.95	5.0	2.23	–	60.3	–	Dinis et al. (2012a,b)
	49	2.0	4.0	2.0	–	92	402	Fernandes et al. (2011)
	50–60	1.88–4.71	4.51–9.89	1.69–2.56	–			Gonçalves et al. (2010)
	41.5		3.68	–	54.98	79.7		Glushkova et al. (2010)
	51.2–54.7	0.90–2.47	5.35–8.17	–	–	81.1–94.2	–	Öztürk et al. (2010)
	51.9–54.6	0.78–0.84	2.29–3.13	0.68–0.90	–	41.6–44.1	182.6–193.2	Barreira et al. (2009)
	41.9	2.1	2.2	–	–	52.4	237	Bellini et al. (2008)
	46–53	1.73–3.10	4.87–7.37	1.53–2.2	38.6–47.9	–	–	Borges et al. (2008)
	45.78–58.5	1.89–3.68	4.20–8.12	–	45.37–66.18	45.4–66.18	–	Cristofori et al. (2007)
	46.13–51.27	1.56–1.72	3.89–5.13	1.87–2.34	64.15–64.86	–	–	Vasconcelos et al. (2007)
	54	3	5.8	2.3	–	–	–	Pereira-Lorenzo et al. (2006)
	48.4–59.3	1.3–3	6.02–8.58	1.8–3	56.7–81.7	–	–	Míguelez et al. (2004)

(*Continued*)

Table 3 (*Continued*)

Species	Moisture (g/100 g f.w.)	Total fat (g/100 g d.w.)	Crude protein (g/100 g d.w.)	Total ash (g/100 g d.w.)	Total starch (g/100 g d.w.)	Carbohydrates (g/100 g d.w.)	Crude energy (Kcal/100 g d.w.)	Reference
	50.7–53.6	3.69–5.37	3.98–5.48	2.30–2.51	42.2–66.5	–	–	Sacchetti and Pinnavaia (2004)
	52.7–64.4	0.9–1.7	5.4–12.0	2.2–2.9	60.7	–	–	Sequeira et al. (2004)
C. mollissima	46.43–49.75	–	7.54–9.74	1.44–1.81	–	–	–	Yang et al. (2018)
	–	1.87–2.98	4.42–8.27	–	48.20–71.08	–	370–405	Hou et al. (2016)
	–	2.27	8.27	–	71.08	–	–	Li et al. (2016)
	34.2–63.6	4.3–10.2	6.1–12.2	0.8–2.2	45.7–62.8	51.2–81.6	–	Yang et al. (2015)
	31.9	–	3.88	–	40.8	65.49	–	Glushkova et al. (2010)
	43.95	1.11[a]	4.20[a]	1.67[a]	–	49.07[a]	–	McCarthy and Meredith (1988)
	57.6	0.9	4.4	1.1		34.6		Payne et al. (1983)
C. crenata	57.7–60.5[b]	0.3–0.8[b]	2.0–2.7[b]	1.0–1.6[b]	–	–	–	Jeong et al. (2012)
	36.8–44.15	–	4.42–4.88	–	36.09–56.32	68.56–88.43	–	Glushkova et al. (2010)
	39.1–67.3[b]	0.1–1.7[b]	2.2–5.3[b]	0.8–2.6[b]	–	28.7–53.8[b]	–	Seo et al. (2009)
C. dentata	43.7	1.32[a]	4.83[a]	1.58[a]	–	48.57[a]	–	McCarthy and Meredith (1988)
	33.7–47.0	8.4–10.2	9.1–10.2	1.1–1.9	–	32.4–42.3	–	Payne et al. (1983)

[a] Expressed as g/100 g d.w.
[b] Expressed as percentage.

Table 4 Content of phenolics (mg GAE/g d.w.) and flavonoids (mg GAE/g d.w.) previously reported for fruits and other chestnut tissues

Species	Tissue/organ	Total phenolics	Total flavonoids	Reference
C. sativa	Wood	40.8[a]	–	Sanz et al. (2010)
	Bark	23.9–56.1[a]	–	Comandini et al. (2014)
	Bark	24.01[b]	–	Chiarini et al. (2013)
	Leaves	412.96	82.87	Barreira et al. (2010)
	Leaves	1.4	0.33	Živković et al. (2009)
	Leaves	103[c]	54.5[c]	Barreira et al. (2008)
	Flowers	251.62–327.17[c]	27.93–31.60[d]	Sapkota et al. (2010)
	Flowers	298[c]	160[c]	Barreira et al. (2008)
	Pollen	64.02–103.80	–	Avşar et al. (2016)
	Peeled seed	0.59	0.007	Živković et al. (2009b)
	Outer brown peel	1.2	0.65	Živković et al. (2009b)
	Outer skin	510[c]	503[c]	Barreira et al. (2008)
	Inner skin	475[c]	330[c]	Barreira et al. (2008)
	Skin	709.96	901.59	Barreira et al. (2010)
	Fruits	1.60[b]	–	Wani et al. (2017)
	Fruits	1580–3673[e]	0.02[e]	Alasalvar and Bolling (2015)
	Fruits	5–32.82	–	Otles and Selek (2012)
	Fruits	16.2	–	Gonçalves et al. (2010)
	Fruits	0.42	0.17	Živković et al. (2009b)
	Fruits	3.73[c]	2.30[c]	Barreira et al. (2008)
C. mollissima	Fruits	43.77e	–	Liu et al. (2017)
	Fruits	2.24[c]	2.62[c]	Li et al. (2016)
	Fruits	20.4–27.7 × 10^{3}[f]	1.13–2.16 × 10^{3}[f]	Yang et al. (2015)
	Burs	3.31–7.12[e]	–	Zhao et al. (2011)
	Skin	136–147[c]	39–45[c]	Sato et al. (2010)
C. crenata	Leaves	256.98[c]	–	Woo et al. (2017)
	Shell	136.12–353.92[e]	367.43–459.09[e]	Seo et al. (2016)
	Shell	264.10–558.12[c] (extract)	47.41–166.28[c] (extract)	Ham et al. (2015)
	Skin	198–209[c]	69–76[e]	Sato et al. (2010)

[a] Expressed as g GAE/g wood.
[b] Expressed as g GAE/100 g d.w.
[c] Expressed as mg GAE/g d.w.
[d] Expressed as mg QE/g f.w.
[e] Expressed as mg GAE/100 g d.w.
[f] Expressed as mg/kg d.w.

Table 5 Content of amino acids and vitamins previously reported for chestnut fruits

Species	Free amino acids	Vitamin E (as tocols)	Vitamin C (as ascorbic and dehydroascorbic acid)	Reference
C. sativa	–	16.42–16.53[a]	–	Delgado et al. (2016)
	–	739–854[b]	–	Carocho et al. (2014a)
	–	43[c]	–	Kalogeropoulos et al. (2013)
	–	4347–5388[d]	–	Barreira et al. (2012a)
	–	1.09[a]	–	Barreira et al. (2012b)
	–	1039–1213[b]	–	Carocho et al. (2012)
	374.55[a]	–	–	Gonçalves et al. (2012)
	–	–	400–693[e]	Barros et al. (2011)
	–	960.7–1201.5[b]	–	Fernandes et al. (2011)
	–	4.33–23.95[f]	8.76–12.87[c]	Vasconcelos et al. (2010)
	–	4188–5719[d]	–	Barreira et al. (2009)
	67.45[c]	–	–	Vasconcelos et al. (2009)
	–	72[g]	–	Bellini et al. (2008)
	5.5–8.7[h]	–	–	Borges et al. (2008)
	–	–	0.028–0.128[h]	Dimitri et al. (2008)
	–	–	30.8–36.3[c]	Pena-Méndez et al. (2008)
	–	–	45.2–164.3[e].	Ribeiro et al. (2007)
	261.97–420.84[c]	–	–	Vasconcelos et al. (2007)
C. mollissima	7.67[i]	–	$0.59–1.34 \times 10^{3}$[e]	Li et al. (2016)

[a] Expressed as mg/100 g d.w.
[b] Expressed as μg/100 g d.w.
[c] Expressed as mg/100 g f.w.
[d] Expressed as ng/g f.w.
[e] Expressed as mg/kg d.w.
[f] Expressed as μg/g f.w.
[g] Expressed as mg/kg f.w.
[h] Expressed as g/100 g d.w.
[i] Expressed as mg/g d.w.

Table 6 Content of minerals previously reported for fruits and other chestnut tissues

Species	Ca	Mg	Na	K	P	Zn	B	Fe	Cu	Mn	Reference
C. sativa fruits	2040–2937[a]	1364–1852[a]	245–526[a]	10633–15871[a]	1741–1879[a]	54–85[a]	–	–	–	–	Özel (2015)
	0.55[b]	0.54[b]	–	9.36[b]	1.13[b]	8.91[a]	7.07[a]	25.91[a]	8.22[a]	36.61[a]	Gonçalves et al. (2012)
	13.2[c]	27.6[c]	1.7[c]	351.1[c]	–	0.7[c]	–	0.8[c]	0.3[c]	0.8[c]	Bellini et al. (2008)
	40.8–50.6[d]	63.3–93.3[d]	–	473–974[d]	104–148[d]	–	–	5.33–10.87[d]	1.30–2.53[d]	3.07–8.00[d]	Borges et al. (2008)
	0.032–0.067[e]	–	–	–	0.10–0.14[e]	–	–	–	–	–	Dimitri et al. (2008)
	43–230[d]	70–160[d]	6–41[d]	761–1271[d]	107–191[d]	1.8–9.1[d]	–	0.4–5.7[d]	0.6–3.8[d]	0.7–5.5[d]	Ertürk et al. (2006)
	0.026–0.072[e]	0.049–0.100[e]	0.003–0.017[e]	0.789–1.130[e]	0.068–0.305[e]	10.0–19.0[f]	–	13.5–23.8[f]	5.5–10.3[f]	17.0–124.6[f]	Pereira-Lorenzo et al. (2006)
	37.1[d]	67.2[d]	2.7[d]	1202.7[d]	181.6[d]	1.1[d]	–	3.3[d]	0.7[d]	–	Sequeira et al. (2004)
	23[c]	32[c]	3[c]	378[c]	50[c]	0.44[c]	–	0.71[c]	0.208[c]	0.563[c]	McCarthy and Meredith (1988)
C. sativa catkins	16.6[b]	3.52[b]	–	8.1[b]	1.70[b]	66[a]	9.0[a]	28[a]	10.0[a]	1041[a]	Portela and Louzada (2012)
C. sativa leaves	9.3[b]	2.00[b]	–	7.0[b]	1.54[b]	25[a]	8.8[a]	53[a]	8.0[a]	880[a]	Portela and Louzada (2012)
C. mollissima	287–1038[a]	–	–	–	17–43[a]	15–36[a]	–	6–23[a]	7–15[a]	–	Yang et al. (2015)
	86.22[e]	96.44[e]	4.49[e]	79033[e]	114.33[e]	5.07[e]	–	2.71[e]	2.37[e]	5.17[e]	Glushkova et al. (2010)
	18[c]	84[c]	3[c]	447[c]	96[c]	0.87[c]	–	1.41[c]	0.363[c]	1.601[c]	McCarthy and Meredith (1988)
C. crenata	13.6–20.3[e]	28.7–32.7[e]	5.2–6.9[e]	257.3–380.7[e]	49.7–68.1[e]	0.1–0.5[e]	–	1.0–3.7[e]	–	1.2–4.4[e]	Jeong et al. (2012)
	41.14–86.08[e]	88.84–96.36[e]	3.39–429[e]	893.67–1034.67[e]	135.00–173.67[e]	2.08–10.36[e]	–	2.04–3.34[e]	0.592.28[e]	3.674.55[e]	Glushkova et al. (2010)
	24[c]	79[c]	3[c]	504[c]	96[c]	1.16[c]	–	1.52[c]	0.390[c]	2.164[c]	McCarthy and Meredith (1988)

[a] Expressed as mg/kg d.w.
[b] Expressed as g/kg d.w.
[c] Expressed as mg/100 g f.w.
[d] Expressed as mg/100 g d.w.
[e] Expressed as g/100 g d.w.
[f] Expressed as ppm.

(Table 7), almost all plant tissues have been studied with regard to health-promoting properties. Flower and pollen, tree bark and all nut parts (bur, seed coat or testa, shell and kernel) show diverse effects, with the most common being an interesting antioxidant activity against several oxidative radicals recorded for nuts. Besides those studies, some of the most relevant recent work shows the neuro- and cardioprotective effects of bark, the antitumoral and anti-inflammatory effect of flower extracts, the anti-angiogenic properties of shell or the antidiabetic effect of burs and seed coat or testa.

For *C. mollissima*, recent work has also focused on the composition of these nuts (Table 3). These recent investigations are complementary to a few previous studies, showing moisture content between 34.2% and 63.6%, while carbohydrates can range from 34.6% to 81.6%. Minor components, such as fat and protein, range from 0.9% to 10.2% and from 4.2% to 12.2%, respectively. As for *C. sativa*, some researchers have quantified the phenolic and flavonoid fraction present in *C. mollissima* (Table 4). Both phenolics and flavonoids can be found in higher amounts in the seed coat or testa (as much as 147 mg GAE/g f.w. and 45 mg GAE/g f.w., respectively), while burs and nuts have a lower amount, respectively, of phenolics and flavonoids. As for *C. sativa*, the mineral profiles of *C. mollissima* are highly variable, but K is the major mineral, although some authors refer to Ca as being at the highest levels (Table 6). For *C. crenata* and *C. dentata*, the existing information is scarce, with no recent work available for *C. dentata*. Although, these studies show a moisture content ranging from 39.1% to 67.3% for *C. crenata*, for *C. dentata*, the moisture range is lower (33.7–47.0%). As for other chestnuts, carbohydrates are the major components (28.7–88.4% in *C. crenata* and ranging from 32.4% to 48.6% in *C. dentata*). The fat content is higher for *C. dentata* (1.32–10.2%) than in *C. crenata* (0.1–1.7%), a pattern also found for protein (2.0–5.3% and 4.83–10.2% in *C. crenata* and *C. dentata*, respectively). For these two species, further studies are lacking and information is scarce. Total phenolics and flavonoids have been quantified in *C. crenata*, and show a higher amount of those compounds (up to 209 mg GAE/g f.w.) in skin, for phenolics and 459.1 mg GAE/100 g d.w. in shell, for flavonoids, while the mineral content of *C. crenata* has been recently described, indicating a predominance of K and P. The mineral composition of leaves and catkins of *C. dentata* is known, with an interesting amount of important minerals, and K being the major mineral present in both plant organs (Cho and Jo, 2003).

3 General uses of chestnuts

Sweet chestnuts used to be called the ‘bread-tree’, providing staple food with nutritious and health-giving properties for people in the Mediterranean and Europe. Chestnuts are widely recognized for their nutritive value (Wani et al., 2017) and distinctive flavour and taste (Ertan et al., 2015). These nuts are rich

Table 7 Health effects previously reported for extracts of fruits and other chestnut tissue/organ

Tissue/organ	Negative	Beneficial	References
Pollen	Allergy		Sánchez-Monge et al. (2006)
Pollen		Antimicrobial and antioxidant activities	Avşar et al. (2016)
Pollen		Anti-inflammatory	Avşar et al. (2016)
Bark		Preventive neuroprotective effects	Brizi et al. (2016)
Bark		Anticancer agent	Lenzi et al. (2017)
Bark		Antioxidant activity	Chiarini et al. (2013)
Bark		Cardioprotective effect	Chiarini et al. (2013)
Bark		Antimicrobial activity	Chiarini et al. (2013), Živković et al. (2009a)
Flowers		Antitumor effects	Carocho et al. (2014b)
Flowers		Antimicrobial activity	Carocho et al. (2014b)
Flowers		Antioxidant activity	Carocho et al. (2014c,d), Barreira et al. (2008), Jukić et al. (2013), Sapkota et al. (2010)
Flowers		Anti-inflammatory	Jukić et al. (2013)
Leaves		Antibacterial activity	Quave et al. (2016), Basile et al. (2000)
Leaves		Antioxidant activity	Almeida et al. (2008), Barreira et al. (2008), Vella et al. (2018)
Leaves		Allelopathic activity	Basile et al. (2000)
Leaves		Antimicrobial activity	Živković et al. (2009a)
Fruits		Antioxidant activity	Barreira et al. (2008, 2010, 2011), Akbulut et al. (2017), Antonio et al. (2011), Carocho et al. (2012, 2014a), Dimitri et al. (2008), Dinis et al. (2012a,b), Galiñanes et al. (2015), Kalogeropoulos et al. (2013), Kirbaslar et al. (2012), Mujić et al. (2009), Otles and Selek (2012), Wani et al. (2017), Zeković et al. (2009), Živković et al. (2010)
Fruits		Antimicrobial activity	Kirbaslar et al. (2012), Živković et al. (2010)
Burs		Antidiabetic	Grdović et al. (2012)
Shell		Anti-angiogenic	Sorice et al. (2016)
		Anti-inflammatory	Sorice et al. (2016)
Skin		Antidiabetic	Tsujita et al. (2008)

in carbohydrates, minerals, vitamins, protein and fibre, and low in fat content (see Tables 3–6), which make them highly suitable for human nutrition and well-being (Liu et al., 2017; Mert and Ertürk, 2017).

Most chestnuts are sold fresh in autumn in the Mediterranean region (Delgado et al., 2016). However, the high tannin content in the nut is responsible for its astringent bitterness and lower palatability (Wani et al., 2017), making it highly suitable for processing and an array of novel uses. Chestnuts can be home processed or can undergo industrial processes in order to improve its organoleptic properties (aroma, flavour, texture) and digestibility (Vasconcelos et al., 2010). In the market, chestnuts are available in different industrial forms such as boiled, roasted, frozen at −40°C, dried or crystallized as the typical 'marrons glacés' (Vasconcelos et al., 2010). They can also be found as 'cured chestnuts', which involves immersing the nuts in cold water (hydrocooling) or hot water (thermohydrotherapy) to prolong the shelf life, a process that can result in changes to the chemical composition (Neri et al., 2010). Chestnuts are also used as an ingredient in many different bread and cake recipes (Dall'Asta et al., 2013), soups or other edible foods (Vossen, 2000) and gluten-free beers (Chenlo et al., 2009), a diversity of uses that are expanding. For example, in the Canary Islands, chestnuts are one of the ingredients used in the typical sweet 'morcillas' (Ríos-Mesa et al., 2011). In addition, novel products have been developed, such as yoghurt with candied chestnut (Sakin-Yilmazer et al., 2014). Chestnut flowers are also an important source of nectar and pollen for honey (Vasconcelos et al., 2010). Chestnut honey possesses a distinctive aroma and is very rich in K, Ca and Mn (Küçük et al., 2007) and has high antibacterial and antioxidant activities enabling its use for dressing chronic wounds, burns or skin ulcers (Vasconcelos et al., 2010). Moreover, chestnut flower extracts possess antimelanogenic effects, making them highly suitable for use in food, cosmetic and pharmaceutical applications (Sapkota et al., 2010).

4 Specific nutritional features

Folk tradition and the recognized nutritional value of chestnuts have led to them being widely consumed, especially in Europe, America and Asia (Vasconcelos et al., 2010). In some regions of such continents, chestnuts are still used as a potato substitute due to their high starch content (Vossen, 2000; Vasconcelos et al., 2007; Borges et al., 2008; Korel and Balaban, 2008; Silva et al., 2016). Although differences can be found among species/cultivars (Míguelez et al., 2004; Sequeira et al., 2004; Ertürk et al., 2006; Cristofori et al., 2007; Borges et al., 2008), origin (Míguelez et al., 2004; Ertürk et al., 2006; Cristofori et al., 2007; Yang et al., 2015), year of harvest (Sequeira et al., 2004), genetic factors (Borges et al., 2008) and/or fruit processing (Hou et al., 2016; Li et al., 2016), starch is the most abundant carbohydrate constituent of chestnuts, accounting for almost 50% of the total composition (Table 3). Amylose and amylopectin are the main types of starch in these nuts (Vasconcelos et al., 2010) and are a critical part of the functional and physico-chemical properties of starch (Muzzaffar et al., 2016). When compared with other staple starch foods such as potatoes, the starch content is approximately double or triple in chestnuts (Sato et al., 2017), making them a very popular and appreciated nut with potential health benefits. Moreover, the chestnut starch content exhibits lower gelatinization (56.1°C) and peak viscosity (79.5°C) temperatures, which compare favourably with corn starch, especially in applications where lower processing temperatures are needed (Cruz et al., 2013). Associated with a high starch content, chestnuts are also rich in sugars (Borges et al., 2008; Korel and Balaban, 2008; Vasconcelos et al., 2010), making this fruit an energetically valuable nut. Among the simple sugars chestnuts contain a high content of sucrose, which can be up to one-third of the total sugars (Vasconcelos et al., 2010) and is advantageous when compared with potatoes, wheat and walnuts (Künsch et al., 1999), for example. These complex (starch) and simple (sugar) carbohydrates are responsible for the sweetness (Pereira-Lorenzo et al., 2006; Yang et al., 2015) and palatability of chestnuts (Yang et al., 2015), which make them suitable for human and animal diets. On the contrary, the ash content of chestnuts is considered low, accounting for 0.8–4.4 g/100 g d.w. in various species (Table 3).

Water is also an important component in chestnuts and acts as an indicator of the shelf life of fresh nuts (Yang et al., 2015). In general, fresh chestnuts contain about 50% moisture (Table 3), which makes them highly suitable for industrial processing (Míguelez et al., 2004) but has a negative impact on their storage ability (Borges et al., 2008). Comparing the most cultivated *Castanea* species, McCarthy and Meredith (1988) found that *C. sativa* exhibits the highest moisture content, followed by *C. mollissima* and *C. dentata*. However, Glushkova et al. (2010) recorded the highest moisture content (50.4–55.4%) for two interspecific hybrid cultivars (*C. crenata* × *C. sativa*), and the lowest value (31.9%) for *C. mollissima*, while intermediate values (36.8–44.1%) were found for *C. crenata* and *C. sativa* cultivars. According to Pereira-Lorenzo et al. (2006) and Neri et al. (2010), the moisture content of chestnuts tends to change with the chestnut origin, which is probably due to the different growing and climate conditions between regions.

Chestnuts are also characterized by a low fat content (Table 3) but of relatively high quality, ranging from 0.7 to 10 g/100 g d.w., depending on the species/cultivar (Míguelez et al., 2004; Mert and Ertürk, 2017). Compared with other nuts, for example, hazelnut, macadamia, pecan or almond, chestnuts exhibit the lowest fat content (Alasalvar and Bolling, 2015). However, the fat-soluble bioactive compounds, such as tocols and phytosterols, are present in chestnuts in higher amounts, when compared with fat-rich nuts. Despite the low fat content, chestnuts contain a high amount of essential fatty acids

(Künsch et al., 1999; Borges et al., 2007; Poljak et al., 2016), either saturated or unsaturated, which has been linked to several processes involved in health and chronic diseases (Benatti et al., 2004). Among them, linoleic and linolenic acids are the most important unsaturated fatty acids (Künsch et al., 1999; España et al., 2011). The beneficial effects of fatty acids on human health are well known, as anticancer (Vasconcelos et al., 2010) and neuroprotective (Künsch et al., 1999) compounds, and they are also associated with protection against cardiovascular diseases (Braga et al., 2015).

Chestnuts are considered to be an excellent source of dietary fibre (Mert and Ertürk, 2017), which does not appear to be influenced by cultivar or origin (Borges et al., 2008). According to Pereira-Lorenzo et al. (2006), chestnuts contain a similar amount of fibre to the majority of nuts, but lower than hazelnuts. The presence of fibre in chestnuts make them more attractive to consumers since it is associated with favourable health effects, for example, in the intestine by influencing metabolic activities (Gonçalves et al., 2010). Dietary fibre also promotes, apart from other properties, cardiovascular health (Sathe et al., 2009), cholesterol reduction, regulation of insulin and metabolism of blood lipids (Prosky, 2000).

The protein content of chestnuts is considered to be moderate (Poljak et al., 2016), with some differences among species/cultivars (Mert and Ertürk, 2017), which is associated with the nature of the soil the chestnuts are grown in (Míguelez et al., 2004; Poljak et al., 2016). Considering the recommended daily intake (RDI) of protein, the protein content of these nuts represents approximately 9.2% of the RDI for females and 7.6% of the RDI for males (Vasconcelos et al., 2010), which highlights the relevance of these nuts in the human diet. Although the protein content in chestnuts is in the range of 2.0–8.6 g/100 g d.w. (Table 3) and is comparatively lower than other tree nuts such as peanuts (25.8 g/100 g d.w.), almonds (21.3 g/100 g d.w.) and hazelnuts (15.0 g/100 g d.w.) (Ros, 2010); it is considered to be high quality due to the presence of important amino acids (Vasconcelos et al., 2010). Aspartic acid and glutamic acid were detected as the main protein-derived amino acids (Vasconcelos et al., 2010) present in chestnuts. Borges et al. (2008) also identified arginine as one of the most predominant amino acids in different chestnut cultivars from various Portuguese regions. Other amino acids, such as γ-aminobutyric acid (GABA), occur naturally in chestnuts at a concentration of 188 nmole/g d.w. (Oh et al., 2003), making them extremely relevant for the human diet. This non-proteinogenic amino acid is considered to be effective in lowering blood pressure and heart rate (Oh et al., 2003). GABA has also been regarded as an important neurotransmitter inhibitor in the mammalian central nervous system (Bettler et al., 2004), which is relevant for the maintenance of cerebral activity (Gonçalves et al., 2012). In addition, GABA can also be helpful in some anxiety and neurological disorders such as Huntington's chorea, and

Parkinson's and Alzheimer's diseases (Gajcy et al., 2010). The protein content, as well as the amino acid profile of chestnuts, indicates the high nutritional quality of these nuts (Yang et al., 2018) with positive health effects on the brain and energy metabolism (Lau and Tymianski, 2010).

In addition to investigating the composition, recent approaches to chestnut analysis have revealed the content of total phenolics and flavonoids, not only in nuts but also in other plant tissues, including tree bark or burs (Table 4). As for many other nuts, like almonds (Milbury et al., 2006), these bioactive compounds appear to be present preferentially in the seed coat or testa, rather than in the kernel itself. This should be taken into consideration, not only from a consumer's point of view, regarding the intake of those health-promoting compounds, but also from a research-driven assessment, as compounds of interest are found in low added-value by-products. Some of the phenolics of interest in chestnuts are gallic and ellagic acids, with the content in *C. sativa* cultivars ranging between 3.46 and 9.07 g and 2.71 and 9.64 g/100 g d.w., respectively (Vasconcelos et al., 2007), with strong evidence regarding the positive effects on cardiovascular function, and anticarcinogenic and antiplasmodial activity (Okuda, 2005). Chestnut catkins, also a by-product, are nowadays regarded as an interesting source of compounds. Indeed, catkins of *C. sativa* contain soluble sugars, with special reference to fructose, but also glucose and sucrose, organic acids (quinic, oxalic, malic and shikimic acids) and about 27 phenolic compounds, with the predominance of trigalloyl-HHDP-glucoside, followed by pentagalloyl glucoside (Carocho et al., 2014c). According to Jukić et al. (2013), dehydrodigallic acid dimethyl ester is the major phenolic in chestnut catkins, which has a considerable amount of gallic acid derivatives. Flowers of *C. crenata* also contain sugars, with a predominance of sucrose and maltose, and organic acids (malic, citric, oxalic and succinic acids). Amino acids are also found in interesting amounts in flowers of *C. crenata*, with a higher content of aspartic acid and proline, and these plant organs are also rich in vitamin C (Cho and Jo, 2003).

Chestnuts are also rich sources of vitamins, particularly vitamins C and E, mainly tocols (Table 5), which are responsible for their beneficial health effects with respect to antioxidant and antimicrobial properties (Table 7). Vitamin E has also been associated with reducing the risk of cancer and cardiovascular diseases (Vasconcelos et al., 2010). In addition, such nuts are characterized by considerable amounts of other vitamins such as vitamin A, which has multiple actions in the human body, and B vitamins including thiamine, riboflavin, niacin and folate (Vasconcelos et al., 2010). These B vitamins are essential for brain health and act against neurological diseases. Chinese chestnuts contain a higher amount of vitamin A, riboflavin, pantothenic acid and pyridoxine, while European chestnuts are high in vitamin C and thiamine, and Japanese chestnuts are rich in niacin. Portuguese cultivars of *C. sativa* exhibit an interesting amount of vitamin C and, although their content varies significantly among samples (Vasconcelos et al., 2009; Barros et al., 2011), a clear relationship between the content of vitamin C and the antioxidant activity (Barros et al., 2011) has been recorded. There are a limited number of studies focusing on the presence of vitamins in *C. crenata*, *C. dentata* and *C. mollissima*, while for *C. sativa*, some work has been performed over the last few years to elucidate the extent of the presence of vitamins, namely C and E, in nuts of this species.

Chestnuts are also a good source of minerals (Table 6), that when deficient in the diet, may have a severe impact on human health (Belitz and Grosch, 1999; FAO/WHO, 2004). Ca, Mg, Na, K, P, Zn, B, Fe, Cu and Mn have been found in nuts of *C. sativa*, mainly in recently performed studies, while for *C. crenata* and *C. mollissima* information is still very limited. Although the content of macronutrients, particularly K (the most abundant one), P, Mg and Ca found in Portuguese *C. sativa* cultivars (Borges et al., 2008) are comparable with those of other cultivars (Pereira-Lorenzo et al., 2006), and even for Chinese ones (McCarthy and Meredith, 1988), values for micronutrients (Fe, Zn, Cu or Mn) appear to change substantially among cultivars (Borges et al., 2008).

5 Effects of cooking on quality

Chestnuts can be consumed raw but are usually processed. Consumer preference is either boiling or roasting (Silva et al., 2001), but other alternatives exist, such as frying or curing. As for any other food commodity, cooking may change the quantitative and qualitative composition of the chestnut, which will ultimately result in variations in actual nutrient intake by consumers. Considering these facts, several authors have focused their research on the effect of different cooking methods on chestnut composition (Table 8). This issue has been thoroughly reviewed by Zhu (2016) and will be briefly addressed here, considering proximate composition and also bioactive compounds. For one of the major components of chestnuts, that is carbohydrates, cooking considerably alters its quantity as well as other parameters. For *C. sativa*, insoluble, soluble and total fibre increases with roasting, but boiling only increases soluble and total fibre (Gonçalves et al., 2010). In *C. mollissima*, boiling reduces the amount of reducing sugars, sucrose, glucose and fructose (Li et al., 2016), a fact attributed to the solubilization of those carbohydrates. Starch is also markedly affected by cooking and decreases upon roasting and boiling as recorded in *C. mollissima* (Li et al., 2016), whereas the increase found for some cultivars of *C. sativa* (Silva et al., 2016) led to changes in the structure of starch. Indeed, roasting and boiling have proven to lead to the fusion of individual granules, and gelatinization occurring with the formation of elongated clusters (Silva et al., 2016). These changes can be responsible for the modification of starch properties, ultimately influencing sensory, rheological

Table 8 Effects of cooking on compositional and bioactive characteristics of chestnut

Species	Type of processing	Highlights	Reference
C. sativa	Boiling and roasting	Roasting increased protein and fibre, as well as gallic acid and total phenolics and lowered fat contents. Boiling increased fat, gallic and ellagic acids contents. Cooking increased citric acid contents, reducing malic acid.	Gonçalves et al. (2010)
	Roasting	Depending on cultivar, variations in fat, starch and sugars, as well as individual fatty acids.	Künsch et al. (2001)
	Boiling and roasting	Depending on cultivar and type of processing, variations of total and individual amino acids and minerals.	Gonçalves et al. (2012)
	Boiling, roasting and curing	Decrease in total phenolics and antioxidant activity with cooking. Depending on type of processing, variations in specific polyphenol compounds, minerals and trace elements.	Nazzaro et al. (2011)
	Pan and microwave roasting	Increase in carbohydrate content and antioxidant activity.	Wani et al. (2017)
	Boiling and roasting	Depending on cultivar and type of processing, variations in vitamin C, antioxidant activity, gallic and ellagic acid content.	Barros et al. (2011)
C. mollissima	Boiling, roasting and frying	Reduction in fat, protein, sugars, amino acids, total polyphenols, total flavonoids and organic acid with cooking.	Li et al. (2016)
	Frying	Decrease in total phenolics and flavonoids, ascorbic acid and reduction of antioxidant activity.	Hou et al. (2016)

and chemical characteristics, but also digestibility (Noda et al., 2008). The protein content appears to be more resistant to cooking than other chestnut components. In fact, previous work shows that roasting or boiling of the *C. sativa* or *C. mollissima* nut only slightly alters the protein content (Gonçalves et al., 2010, 2012; Li et al., 2016; Wani et al., 2017). Although without an apparent effect on protein content, changes in the amount of total amino acids and their composition occur with cooking (Gonçalves et al., 2012; Li et al., 2016), possibly due the degradation of peptides and proteins and to Maillard reactions (Gonçalves et al., 2012). One of the amino acids that is most affected is L-aspartic acid (Li et al., 2016), which is one of the most abundant in chestnuts

(Vasconcelos et al., 2010), although several others are also affected (Gonçalves et al., 2012; Li et al., 2016). Considering that amino acids are biologically active, with several functions in the body, variations of their content alter the possible health-related effects of these compounds. Although having a low fat content, chestnuts present fat-soluble bioactive compounds in higher amounts than fat-rich nuts, as well as essential fatty acids, which are linked to several processes involved in health and chronic diseases. The fat fraction of chestnuts decreases upon boiling, frying or roasting (Gonçalves et al., 2010; Li et al., 2016). However, it appears that boiling leads to fewer changes, probably due to the lower temperature of the process (Das et al., 2013). Despite limited information, the fatty acid profile also appears to be slightly modified after roasting (Künsch et al., 2001), an effect that can change the nutritional value of chestnuts and is a topic that deserves further investigation.

Besides the effect on composition, cooking may also result in changes to the content of bioactive compounds, such as phenolics or vitamins. Some work has highlighted the negative effect of roasting, boiling or frying on total phenolic content (Barros et al., 2011; Nazzaro et al., 2011; Hou et al., 2016; Li et al., 2016), with a parallel reduction on the antioxidant activity. This decrease may be due to the fact that temperature leads to the oxidation of phenolics. However, an increase of the total phenolic content and antioxidant activity has also been found (Gonçalves et al., 2010; Wani et al., 2017), which may be linked to the release of tightly bound phenolics that, in this way, can be extracted and quantified (Liu et al., 2017). The vitamin content of chestnuts is also altered by cooking procedures. Although studies are lacking on this specific topic, a considerable decrease in the amount of vitamin C after cooking has been recorded (Barros et al., 2011; Li et al., 2016), and is probably linked to the conversion of ascorbic acid to dehydroascorbic acid, which was further degraded to 2,3-diketogulonic acid. Data regarding other important vitamins present in chestnuts is limited and should be considered an important major research line, but changes are to be expected, although dependent on time and conditions, as recorded for vitamin E (Delgado et al., 2016). Considering the health-promoting capacity of the vitamins present in chestnuts, all changes, either increasing or decreasing these compounds are of great importance to producers and consumers. Knowledge of their behaviour under certain cooking conditions, besides being a major research theme, can also be an added-value factor for this nut.

Other chestnut components are also affected by cooking, namely organic acids and minerals. The organic acid content decreases considerably after boiling, roasting or frying (Ribeiro et al., 2007; Li et al., 2016), but interestingly, Gonçalves et al. (2010) showed that individual organic acids are affected differently: cooking increased the content of citric, gallic and ellagic acids, while reducing the malic acid content. These variations of the content and organic acid profile after cooking must be considered from two points of view: from an organoleptic perspective and for improving health, as they are linked to the sensory characteristics of nuts (Vaughan and Geissler, 1997), while presenting antioxidant activity with a protective role against various diseases (Silva et al., 2004). Finally, the mineral content is known to decrease after cooking, with the exception of P, Fe, Cu and Mn (Gonçalves et al., 2010), although other studies show that Ca may not be lost (Künsch et al., 2001). The work of Nazzaro et al. (2011) shows a more complex pattern of cooking effects on chestnut minerals, with increases or decreases recorded for different minerals.

6 Post-harvest handling and storage

Due to their high moisture and sugar content (Attanasio et al., 2004; Jermini et al., 2006; Gounga et al., 2008, 2017), chestnuts are characterized by a short shelf life (Gounga et al., 2008). They are extremely susceptible to damage during storage (Ertan et al., 2015), which is reflected in important economic losses. Moreover, the peeled chestnut tends to be more perishable when compared with the intact nut (Gounga et al., 2008).

Weight loss is one of the major problems in chestnut preservation (Antonio et al., 2011; Ertan et al., 2015) as it promotes the condensation and growth of fungi (Antonio et al., 2011) with a negative influence on its availability and certain nutritional and physical properties of the nuts. Mencarelli (2001) reported weight losses of around 1% in fresh chestnuts after 1-day storage at 20°C and 70% relative humidity (RH). In studies where the recently harvested Portuguese varieties (Judia, Longal and Martaínha) were evaluated, a weight loss of up to 26% between the end of October and January at room temperature (13°C, 65% RH) was observed for the Judia variety; however, when kept under a modified atmosphere (1.7°C, 88% RH, 7% O_2 and 14% CO_2) the weight loss was only 6.6% up to the end of April, and even lower (1.3%) in the Martaínha variety (VALCAST project data, 2008). Data from the same project with the Lada variety, showed a weight loss variation from 35.9% at room temperature to as low as 1.4% under a modified atmosphere (1.7°C, 88% RH, 7% O_2 and 21% CO_2). Thus, apparently an increase in the CO_2 concentration of up to 21% can reduce weight loss, which has a tremendous impact on the yield of the processing industry, as it needs to process chestnuts from harvest up to a few months later. Similar findings were reported by Gounga et al. (2008) in *C. mollissima* peeled nuts, where a moisture loss of about 25% was observed following storage for 6 days at 30°C and 80% RH. Optimizing storage conditions is thus essential to reduce the incidence of nut decay and loss of quality attributes. According to Jermini et al. (2006), the most suitable conditions for preserving chestnuts ranged from 0°C and 2°C with a high RH of around 90%. The same conclusion was reached by Ertan et al. (2015) who found that buried nuts of *C. sativa* in the orchard had deleterious effects on their quality when compared with storage under low temperatures and high RH. These authors also concluded that temperature is the key factor in the preservation of chestnut quality. However, these methodologies are not always effective in suppressing fungal spoilage and need to be supplemented. One of the most common methods in the past consisted of the application of fungicides (Lee et al., 2016b) but the potential harm to health and environmental risk led to it being banned (Carocho et al., 2013). Thus, it is crucial to use novel technologies that do not cause environmental harm or negatively affect health.

Among the alternative methodologies, the use of electron beam irradiation has gained interest as it is considered to be a safe, cheap and environmentally friendly technology that is able to minimize the detrimental problems that can occur during the chestnut post-harvest process (Carocho et al., 2013). Another promising technology for the preservation of chestnuts consists of using a natural coating (Gounga et al., 2008), which acts as a barrier to water loss and gas exchange (Lin and Zhao, 2007), hence minimizing nut deterioration and, at the same time, acts as a carrier of health-promoting compounds. Gounga et al. (2008) investigated the application of this technology on fresh-roasted chestnuts and concluded that the use of a whey protein isolate-pullulan (WPI–Pul) coating combined with freeze-drying and low temperature storage was responsible for reducing microbial growth in nuts, thus extending the shelf life. According to Gounga et al. (2007), the use of a WPI–Pul coating enhanced the sensory attributes of fresh and dried chestnuts. Additionally, the use of chitosan coatings on Chinese chestnuts reduced respiratory rates with positive effects on shelf life (Tian et al., 2009). More recently, Gounga et al. (2017) tested chocolate as a new chestnut coating and the results are very promising. In fact, the results suggest that this new type of coating was very effective in controlling microbial growth in addition to being well accepted by consumers. Moreover, it adds value to chestnuts.

Another technology largely used in fresh fruits is modified atmosphere packaging (MAP), which is still under investigation in chestnuts. Panagou et al. (2006) observed that this technology combined with low temperature storage preserves chestnut quality, especially during long-term storage. Treatment with CO_2 under higher pressure has also been mentioned as a promising strategy for extending the shelf life of chestnuts (Navarro, 2012).

Chestnuts might also be affected by several fungi and insect worms, namely elephant weevil, *Balaninus elephas*, and chestnut tortrix, *Cydia splendana* (Chenlo et al., 2009), which are responsible for the rapid deterioration of nuts (Ertan et al., 2015) resulting in decreased value and consequently their acceptance by consumers. Gao et al. (2011) estimated the annual losses of chestnuts due to pests during storage as 35–50% of total production. In order to reverse the high perishability of chestnuts and to minimize post-harvest losses, different methodologies have been used. Traditionally, freezing, cold storage and drying are used to extend the shelf life of chestnuts (Gounga et al., 2008; Sakin-Yilmazer et al., 2014; Delgado et al., 2018) and to ensure year-round availability (Moreira et al., 2015; Lee et al., 2016b). However, such methodologies require proper storage conditions, namely a lower temperature, associated with adequate ventilation and relative air humidity in order to maintain the physical properties of fruits, such as colour or texture, and to preserve their nutritional and sensory properties (Panagou et al., 2006).

7 Chestnut co-products

The agricultural and industrial processing of chestnuts generates large quantities of waste material, mainly bur, shell, leaves and curing wastewater (Braga et al., 2015; Squillaci et al., 2018). The valorization of these products has been a new challenge for the chestnut value chain contributing to environmental (Pinto et al., 2017) and economic sustainability (Braga et al., 2015). In fact, such agro-industrial wastes, after valorization, can be used by other industries, such as pharmaceutical, food or cosmetics (Sapkota et al., 2010; Aires et al., 2016; Vella et al., 2018) due, in part, to the production of active molecules (Nazzaro et al., 2012; Squillaci et al., 2018).

Some examples of how the valorization of such co-products can be achieved are reported in the work of Aires et al. (2016) and Santos et al. (2016). The former shows how chestnut peels can be used to produce pomaces with high amounts of tannins, which can be used as phenol substitutes in the formulation of adhesives or as antioxidant supplements in food, cosmetic or pharmaceutical formulations. Santos et al. (2016) suggested the beneficial use of shell extracts on lettuce properties. According to these authors, the composting shell and seed coat or testa of the chestnut can potentially be used as growing media for lettuces as an alternative to non-renewable organic substrates as it results in increased yield and antioxidant capacity of lettuces. The use of rejected fruits by the industry, especially those of small size, can also be converted into different products (Delgado et al., 2017), making this crop even more profitable. In addition, application of chestnut co-products in the cosmetic industry is still an area under development. The growing demand for natural products that are environmentally friendly and are of benefit to health has caused an increased interest in chestnut extracts (Ribeiro et al., 2015), in part, due to its antioxidant properties (Sapkota et al., 2010). Almeida et al. (2015) indicated that the use of leaf extracts of chestnut in skincare products can contribute to the prevention and minimization of oxidative stress in the skin, which could otherwise result in photoageing, some dermatosis and cancer. Pinto et al. (2017) concluded that *C. sativa* bur extract could be a promising cosmetic ingredient in topical hydrogels. More recently, Squillaci et al. (2018)

suggested the beneficial use of chestnut shell extracts in cosmetic preparations as it showed anti-inflammatory activity, skin hydration capacity and the ability to protect collagen from degradation. Other parts of the fruit can also be used for other applications. For example, chestnut shell extracts can be used in the manufacture of shoe and sole leather due to the high level of tannins (Braga et al., 2015). Another example of alternative applications of chestnut shell extracts includes its use as a heavy metal adsorbent (Braga et al., 2015) or a source of fermentable sugars for biofuel production (Vella et al., 2018).

Although the main use of chestnuts is for human consumption, chestnuts are also being tested as a component of animal feed (Borges et al., 2008; Vasconcelos et al., 2010). De Jesús et al. (2016) proved that the incorporation of chestnuts into the diet of Celta pigs reduced the saturated and monounsaturated fatty acid content of such feed, enabling the production of healthier dry-cured meat products. Similar to these conclusions, Ferreira-Cardoso (2002) concluded that adding chestnuts to the diets of pigs had positive effects on the energy requirements of pigs and increased the sensorial taste of the meat and ham. Lee et al. (2016a) showed that the use of a small percentage of chestnuts (5%) in the feed could be useful for reducing the negative presence of tannins in the feed.

8 Health benefits of eating chestnuts

Chestnut consumption has been perceived as beneficial for health; however, nowadays there is a misleading association between nut intake and nut high fat content, which could contribute to weight gain (Vadivel et al., 2012). Chestnuts contain a low amount of fat, being a good alternative to other fat-rich nuts, without the weight gain effect but with the benefits of all the active compounds present in the fat fraction of this nut. The essential fatty acids found in chestnuts are linked to an array of biological processes (plasma lipid levels, cardiovascular and immune function, insulin action, and neuronal development and visual function) (Benatti et al., 2004) and their intake can result in decreased cholesterol levels and prevent coronary heart disease (CHD) (Garcia et al., 1992). Indeed, studies have shown that extracts of chestnut can actively reduce the oxidation of low-density lipoprotein (LDL), which is a key step in the pathological basis of cardiovascular disease (CVD) (Hansson, 2005). The intake of phytosterols and dietary fibre is also linked to the reduction of cardiovascular issues (Jesch and Carr, 2017). For phytosterols, an inverse dose–response relationship between their intake and LDL cholesterol concentration has been established (Ras et al., 2014), for an intake of up to 3 g/day, with mechanisms including inhibition of cholesterol ester hydrolysis, competition with cholesterol for solubilization or transport across the apical membrane of enterocytes (Jesch and Carr, 2017).

With regard to fibre, studies have confirmed the hypolipidaemic and cardioprotective effects in humans (Anderson et al., 2000; Naumann et al., 2006). Although the mechanism by which positive effects are achieved has not been elucidated, it may include interaction with and fermentation of fibre by gut bacteria, delayed gastric emptying, increased muscle glucose transporter type 4 expression and glucose uptake, decreased absorption of dietary fats and increased excretion of faecal cholesterol (Jesch and Carr, 2017). Dietary fibre has also been linked to beneficial effects for diabetes, cancer mechanisms and potential therapeutic agents in diseases such as various forms of colitis, antibiotic-associated diarrhoea and colon cancer (Prosky, 2000). Furthermore, it stimulates *Bifidobacterium* and *Lactobacillus* in the intestine (Blaiotta et al., 2013), which are also responsible for reducing serum total and LDL cholesterol (Jesch and Carr, 2017). Nut intake, including chestnuts, is linked to protection against type 2 diabetes and related metabolic syndromes, with those actions connected to decreases in oxidative damage and inflammatory biomarkers in blood lipids and the content of fatty acids, dietary fibre, vegetable proteins and polyphenols (Amarowicz et al., 2017). Chestnut ingestion also has positive effects on cancer prevention, due to its bioactive compound composition. For this cancer-preventive action, some major compounds are likely to contribute, such as fatty acids, especially omega-3 (Hardaman, 2002), but also vitamin C (Wenzel et al., 2004), vitamin E, and gallic and ellagic acids (Mertens-Talcott et al., 2006; Veluri et al., 2006; Geleijnse and Hollman, 2008). Compared with fresh nuts, ellagic acid can register a greater than twofold increase when chestnuts are boiled, with up to 12.2 mg/kg d.w. (Gonçalves et al., 2010) that can be transformed into urolithin metabolites by some species of intestinal bacteria, which play a major role in cardiovascular protection, and anti-inflammatory and anticarcinogenic properties (Selma et al., 2014). Vitamin C functions in the human body are also linked to bone, teeth and blood vessel formation, wound healing and is necessary for metabolic functions, activation of the B vitamin, folic acid, conversion of cholesterol to bile acids and conversion of tryptophan to serotonin (Chambial et al., 2013). Being a joint source of vitamins C and E, chestnuts are of paramount health importance. Vitamin E is a strong antioxidant, acting in the chain-breaking reactions during peroxidation of unsaturated lipids, LDL and other cell membrane components, reducing the risk of cancer and cardiovascular diseases (Vasconcelos et al., 2010). Chestnuts are also rich in B vitamins that, when deficient, can result in developmental abnormalities, haematologic status, iron absorption, gastrointestinal development (Powers, 2003), cognitive disorders and anaemia (Morris et al., 2007).

Furthermore, a well-balanced intake of minerals, that are almost entirely obtained from vegetables and fruits, is of great importance to human health. As mentioned before, chestnuts are a very good source of macro-elements, such as Ca, P, K, Mg and S, but also of micro-elements (Fe, Cu, Zn and Mn)

(Vasconcelos et al., 2010), that are linked to several health-related effects, and have been thoroughly reviewed by Martínez-Ballesta et al. (2010) and will be briefly detailed here. Calcium has been linked to reducing colon cancer and preventing the risk of pre-eclampsia, while suboptimal Ca intake can result in osteoporosis, hypercholesterolaemia and high blood pressure. Potassium is related to the transmittance of nerve impulses, heart muscle contraction and deficiency of this mineral can result in muscular difficulties, skin problems and alkalosis. Phosphorus, besides being essential for the production of ATP, GTP and CP, also regulates the activity of a number of proteins via phosphorylation reactions, and its deficiency results in bone pain, irregular breathing, fatigue, anxiety, numbness, skin sensitivity and changes in body weight. For magnesium, the described results of low intake are ageing and age-related disorders, such as diabetes, metabolic syndrome, hypertension and several cardiovascular conditions. Regarding the micro-elements, Fe deficiency is termed hypochromic anaemia, as this element is linked to the synthesis of haemoglobin and myoglobin. Copper, a mineral linked to enzyme function, can, when lacking in the body, result in anaemia, leukopenia and neuropenia, and skeletal disturbances. Zinc deficiency negatively affects the efficacy of the immune system, taste and smell senses, while impairing DNA synthesis, and causing hair loss and hypochromic anaemia. Finally, deficiencies in Mn intake lead to a reduction of cholesterol and red blood cells, while causing mucopolysaccharide abnormalities. Chestnuts have a major distinctive characteristic: they are gluten-free nuts and can therefore be used for the preparation of numerous products for gluten-sensitive, wheat allergy and celiac disease patients. In this way, these patients can benefit from all the health-related compounds present in chestnuts, without suffering from symptoms like diarrhoea, irritable bowel syndrome, malabsorption syndrome, weight loss and autoimmune diseases (Vasconcelos et al., 2010).

The chemical composition of chestnuts can change due to a number of factors, including genetic factors and environmental conditions (Míguelez et al., 2004; Pereira-Lorenzo et al., 2006; Borges et al., 2008; Poljak et al., 2016; Mert and Ertürk, 2017) suggesting different uses. For example, the presence or absence of some compounds can be of interest for processing purposes or health uses. Borges et al. (2008) in a study with eight sweet chestnut cultivars from three Portuguese areas identified two cultivars linked to health-promoting benefits, due to the presence of a high linoleic acid content (cv. Lada) or unsaturated fatty acids (cv. Aveleira).

Besides the nut itself, other chestnut organs or derived products have been referred to as having a beneficial health effect, either when consumed as-is or used as ingredients in other foods. Chestnut flowers have been referred to as one of the best sources of nectar and pollen for honeybees early in the summer (Kolayli et al., 2016). Pollen from chestnuts has also been studied and revealed interesting results, as it displays antioxidant and antimicrobial activity (Avşar et al., 2016; Karadal et al., 2018) and exhibits good ability to protect hepatocytes from oxidative stress (Yıldız et al., 2013). In this study it was shown that the inclusion of chestnut pollen in the human diet reduces oxidative stress, with the pollen as a suitable alternative for the treatment of hepatocellular pathologies.

For a long time, honey has been associated with health-promoting effects due to high-quality natural compounds (Ajibola et al., 2012). Chestnut honey is considered one of the most delicious and is of high quality (Castro-Vázquez et al., 2010) due to its colour, aromatic physical properties (does not crystallize easily) and composition (particularly the natural volatile compounds related to the original nectar), when compared with blossom honey (Kolayli et al., 2016). Traditionally, it has been used in wound healing due to the high phenolic content and flavonoids (Alissandrakis et al., 2011; Meteoglu et al., 2015), and if impregnated with carboxymethyl cellulose sodium hydrogel paste can be a competitive candidate as a therapeutic dressing for diabetic ulcer wound healing, due to its potential to inhibit and kill bacteria (Park et al., 2017). Chestnut honey has also been used in the treatment of colds, reflux, gastritis and other disorders of the upper respiratory tract and gastric system (Kolayli et al., 2016). These effects are sustained by the strong antioxidant activity (Bertoncelj et al., 2007; Sarikaya et al., 2009; Kolayli et al., 2016; Karadal et al., 2018), which introduces the possibility of reducing health problems related to oxidation damage and associated diseases. Apart from the antioxidant activity, chestnut honey exhibits antimicrobial activity and can inhibit the growth of numerous bacteria and fungi (Kuncic et al., 2012; Karadal et al., 2018). Chestnut honey has also been reported to have antihyaluronidase and antiurease properties. However, excess hyaluronidase activity can cause hyaluronic acid deficiency, and its breakdown products can be harmful to the organism, with the inhibitors of this enzyme offering potential use for the treatment of several diseases, such as cancer and rheumatoid arthritis (Sunitha et al., 2013; Selenge et al., 2014). On the other hand, antiurease activity can be important, as excess urease activity is linked to the development of urolithiasis, pyelonephritis, hepatic encephalopathy, hepatic coma, urolithiasis and urinary catheter encrustation in humans and animals. Its inhibition is also important when dealing with *Helicobacter pylori* in gastric diseases (Kolayli et al., 2015). Chestnut honey differs significantly from floral honey, in phenolic composition, and in the recorded antioxidant and antimicrobial activity (Güneş et al., 2017). The major phenolic found in chestnut honeys is caffeic acid, followed by *p*-hydroxybenzoic acid or protocatechuic acid, depending of the origin of the honey, while floral honey contains higher amounts of protocatechuic acid. Chestnut honey has also been proven to have a higher amount of total phenolics when compared with floral honeys, as well as enhanced bioactive properties, namely an antioxidant effect, using the CHROMAC and ABTS methods, and antibacterial effects against *Staphylococcus aureus* and *Escherichia coli* (Güneş et al., 2017).

Propolis, another bee product that can originate in chestnuts, has garnered increased interest over the last few years, as it has beneficial properties for human health. As with other chestnut products, it exhibits antioxidant and antimicrobial activity (Sarikaya et al., 2009; Karadal et al., 2018). However, chestnut-based propolis also has an interesting effect against hereditary spherocytosis (HS), a type of anaemia characterized by microcytic and hyperchromic red cells, spherical in shape and without central pallor (Moreira et al., 2011). In this study, propolis extracts decreased the fragility of the erythrocyte membrane, with the effect related to the phenolic content of propolis. Furthermore, chestnut propolis also exhibits a monoamine oxidase inhibiting effect, an approach often used in the treatment of depressive disorders and some neurodegenerative illnesses, such as Parkinson's and Alzheimer's diseases, and may be effective in protecting humans against depression and similar diseases (Yıldız et al., 2014).

Extracts of the outer brown peel, leaf and catkins (male flowers) of chestnuts have shown an interesting ability to protect liposomes from peroxidation, as the phenolics of their extracts intercalate into the membranes to remove lipid peroxides (Živković et al., 2009b). Phenolic extracts prepared from chestnut leaf, catkin and spiny burs also prevented oxidative stress-induced β-cell (Rin-5F) death, a phenomenon with a central role in the onset of diabetes. The extracts increased cell viability by protecting DNA from oxidative damage and by enhancing the natural antioxidant system, while improving the cell's redox status, and inhibiting lipid peroxidation (Mujić et al., 2011). Chestnut catkins have been studied as an ingredient in Portuguese pastry and cheese, with the aim of creating functional foods. Carocho et al. (2015a,b) processed the Portuguese 'Serra da Estrela' cheese and Portuguese traditional cakes 'económicos', into functional products showing high phenolic content and higher antioxidant activity, which leads to an increase in consumer intake of the bioactive compounds present in chestnut flowers. Chestnut leaves have been traditionally used for teas in the treatment of coughs and diarrhoea (Calliste et al., 2005), lower back pain and stiff joints or muscles (Díaz-Reinoso et al., 2011; Reinoso et al., 2012) with their effect probably linked to the presence of phenolic compounds, namely ellagic acid and gallic acid derivatives (Živković et al., 2009c).

Bud extracts and bud preparations form a new category of plant products. Also based on the use of *Castanea* spp. as herbal medicines in homeopathy and in modern phytotherapy, old macerations of buds sampled from fertile long shoots (sleeping and breaking stages) from *C. sativa* and *C. crenata* were found to be a good source of vitamins, terpenes and polyphenolic compounds, which are responsible for the popularized effects on stagnant and vascular fluids or against recurrent cystitis and for its curative and restorative properties (Donno et al., 2014).

9 Future trends in research

The recent upward trend in chestnut production and consumption has been supported by recent research findings regarding its nutritional value and beneficial health effects, as well as improved knowledge and awareness of the stakeholders in the value chain that are willing to improve the use of either fresh or processed chestnuts. Although chestnut production is mainly focused on the production of fresh fruit and timber, the recent advances in food technology and health status have shown other neglected potentialities of this crop.

In the area of food science and technology, there are endless opportunities to explore other food and non-food products derived or obtained from chestnut production which will create added value in this value chain. Thus, further research should be aimed at developing novel products or new recipes from traditional chestnut products. For instance, honey and herbal teas from chestnut leaves, buds and catkins need further investigation, based on their potential health benefits and for added value in the chestnut value chain.

Concepts such as 'organic food', 'zero-kilometre food' or 'family farming' have an increasingly bigger role on the world's agricultural stage and could represent a big opportunity for producers to develop new market opportunities and expand the culture of this crop.

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