

Composition of European chestnut (*Castanea sativa* Mill.) and association with health effects: fresh and processed products

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Abstract

Chestnut fruits are highly regarded and widely consumed throughout Europe, America and Asia. Various commercial forms are available, e.g. fresh and industrially processed. There have been various reviews on the composition of chestnut fruits but there has not been a comprehensive review of the different health benefits that this fruit can provide. This review is focused on the composition and associated health effects of European fresh chestnut (*Castanea sativa* Mill.) fruits and their home-processed and industrial products, e.g. boiled, roasted, frozen, and 'marron glacées'. We also expand the knowledge of chestnut uses by presenting data for other chestnut materials that have potential applications as new foods, as sources of antioxidants, and as sources of other useful bioactives. There is considerable literature data on nutrients in fresh chestnut fruits but less information on bioactive non-nutrients such as phenolics. Chestnuts are mostly consumed as processed forms, and the different types of processing clearly affect the nutrient and non-nutrient composition of the fruits. The benefits that this fruit can provide for human and animal health are numerous, but it is clear that improvements can be made for both production and quality of chestnut products, e.g. genetic selection and optimizing industrial processing.

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Keywords: *Castanea sativa*; home cooking; industrial processing; proximate analyses; phytochemicals; health

INTRODUCTION

Chestnut fruits are an important food in many European countries. In 2008 the production of these nuts was 22 000 t for Portugal, 55 000 t for Italy, 6258 t for France, 15 000 t for Spain, 55 800 t for North and South America, 925 000 t for China, 22 100 t for Japan and 80 000 t for Korea.¹ The same source showed that from 2005 to 2008 the production area of chestnut in Europe increased from 81 511 ha to 87 521 ha, whereas the production area decreased in America (from 42 160 ha to 40 190 ha) and in Asia (from 252 991 ha to 239 406 ha). There have been various reviews and book chapters on composition of chestnut fruits but no overall review of the composition and health effects of fresh and processed European chestnut fruits, which is the main focus of this work.

The compositional data presented in this review are from 102 cultivars (23 Portuguese, 69 Spanish, five Italian and five Greek) of *Castanea sativa* that have been previously studied. Since it would not be possible to show individual data we present ranges of the compounds found from all of these studies (Tables 2–6).

It is clear from several other studies that plant products are affected by various factors such as climatic conditions (CO₂, temperature, radiation and rainfall) and cultivation inputs (nutrient availability, minerals, and diseases and pests of the trees and of the fruits) and certainly the production of chestnuts is affected in a similar way. However, the focus of this review is on the raw materials composition, processing effects (home cooking and industrial) on the composition, and subsequent effects on health.

The European chestnut (*Castanea sativa* Mill.) probably had its origins in the eastern Mediterranean region over 90 million

years ago in the middle Cretaceous, later spreading throughout Europe during the Cenozoic period.² Later, between 900 and 700 BC, deliberate chestnut tree cultivation occurred in the Asian regions of the Caspian and Black seas. After this time chestnut cultivation quickly spread to Greece and later the Romans discovered the benefits of this nut tree.^{2,3} The genus *Castanea* belongs to the angiosperm family Fagaceae, which also includes other economically important tree species, e.g. *Quercus*.

Chestnut is geographically distributed in three major areas: Europe with *Castanea sativa* Mill., Asia with *Castanea creanata* Sieb. and Zucc. (Japan) and *Castanea mollissima* Bl. (China and Korea), and North America with *Castanea dentata* Borkh.^{4,5} Although the predominant cultivated species in Europe is *Castanea sativa* Mill., recently some hybrids resulting from the genetic crossing (rootstock) with other species of chestnut (*Castanea creanata* Sieb. and Zucc., and *Castanea mollissima* Blume) have been developed for improving nut production as well as increased resistance to ink disease and the chestnut tree cancer.⁶

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CHESTNUT USES AND CO-PRODUCTS

Fresh chestnut fruits are rarely consumed raw. They are processed in various ways, at home or on an industrial scale to improve the organoleptic properties (aroma, flavour, texture), digestibility of the fruits, i.e. making nutrients more bioavailable, and the shelf-life of various products from industrial processes. After collection all cultivars are ready for consumption; however, certain cultivars are more appreciated because of their organoleptic properties, although calibre and maturation time are also factors considered. Cultivars producing fruits with a polyspermy (the number of cotyledons/seeds inside the chestnut fruit) percentage over 12% are well accepted, but in general consumers have a noticeable preference for 'marron' chestnut fruits (monospermic). A calibre that does not exceed the 100 fruits kg⁻¹ is preferred, because larger chestnuts are more appreciated.^{6,7}

Home cooking

Previous analysis presented data on the modification of structure and digestibility of chestnut starch upon cooking, showing significant changes in the macromolecular structure of this polysaccharide.⁸ Bounous *et al.*⁹ studied the effect of different types of treatments (raw, dry, boiled, roasted and flour) on the nutritional composition of Italian chestnut fruits and the data obtained revealed that when boiled these nuts gain humidity but lose about 25% of energetic value, while by roasting the available sugars can increase by 25% and the energy levels increase significantly (200 kcal 100 g⁻¹). A recent study presented data on the processing effects of roasting and boiling on primary and secondary metabolite composition of Portuguese chestnuts showing an increase in protein content, insoluble and total dietary fibre for the roasted fruits, while the boiled chestnuts revealed lower protein but higher fat content.¹⁰ However, the same authors stated that the raw fruits presented higher content of malic acid compared with the cooked chestnuts.

Industrial processing

Chestnuts are available in various industrial forms, such as (i) frozen at -40 °C, (ii) sterilized in aluminium bags (116 °C for 30–35 min after vacuum sealing), (iii) tinned (with a preservative liquid), (iv) stored in flasks (with a preservative liquid), or (v) dried fruits. These forms are mainly used in gastronomy, commonly with roasted meats. The fruits destined for this purpose are peeled kernels with no presence of cracks, with good calibre, optimal storage capacity, and a good sanitary aspect after storage.^{11–13} Other products (purées, chestnut creams, flours, soups or yogurts) are generated from healthy but lower-quality chestnut fruits: lower calibre, polyspermic and broken. This is an alternative and economically profitable way of increasing the valorization of chestnut products and decreasing the levels of waste materials resulting from industrial processing.

Chestnut fruits are sold fresh during the production season and in hard-winter regions are often the only fresh product available. However, these fruits are now increasingly available as frozen products. Unfortunately there are only a few publications that describe the processing stages of industrial processing.^{14–16} Frozen chestnuts are one of the major forms of this food and therefore these fruits are available all year round to consumers. These studies showed that industrial processing has positive and negative effects on chestnut fruit nutrients. The positive effects on the fruits include the extension of the shelf life and increases from stage A (fresh) to stage D (frozen) in neutral

detergent fibre (NDF) (12.7–19.9 and 16.3–18.2 g 100 g⁻¹ dry matter (DM)), total phenolics (6.6–12.0 and 10.6–16.9 mg g⁻¹ fresh weight (FW)), Thr (4.9–6.8 and 3.6–7.9 mg 100 g⁻¹ FW) and Ala (3.3–6.5 and 4.0–5.7 mg 100 g⁻¹ FW) in 2006 and 2007, respectively, as well as in δ -tocopherol (0.3–0.4 μ g g⁻¹ FW in 2006) and γ -tocopherol (25.2–27.3 μ g g⁻¹ FW in 2007). The negative effects were reductions in the levels of total starch (53.8–51.3 and 54.9–51.0 g 100 g⁻¹ DM), Glu (14.7–9.2 and 13.9–10.9 mg 100 g⁻¹ FW) and ascorbic acid (6.4–5.4 and 7.2–5.1 mg 100 g⁻¹ FW) in 2006 and 2007, respectively, and also of fat (2.9–2.5 g 100 g⁻¹ DM in 2007).^{14–16}

Through industrial processing, and specifically generation of frozen chestnut products, the losses related to dehydration are drastically decreased, conferring to the fruits a long-term (out-of-season) availability and compositional stability. As part of industrial processing Hwang *et al.*¹⁷ previously analysed the physicochemical factors related to the automatic pellicle removal in 14 Korean chestnut (*Castanea crenata*) varieties. These authors stated the existence of a negative correlation between the tannin content of the integument and the peeling ratio.

The kernels used for the production of sweet chestnuts have to be, as previously described, in optimal condition after storage and have a good calibre. Some chestnut fruits are infiltrated with increasing concentrations of sugar solutions and conserved in flasks or metallic protected bags. Others can be added to bottles containing alcoholic beverages, allowing the sugar in the fruit to sweeten the liquor for a period of 6–12 months, e.g. brandies, cognacs or digestive liquors. In France, Italy, Switzerland and Spain the most appreciated transformed chestnut fruits are the 'marrons glacés'. The chestnuts are submerged in a sugar-rich solution and then covered with glucose. The fruits are then cooked in an oven at 300 °C for 1–2 minutes to crystallize the sugar.^{11,12} Other authors have performed nutritional and microbiological evaluations of freeze-dried chocolate-coated (dark and milk) Chinese chestnut (*Castanea mollissima*) fruits showing high contents of sucrose, protein, minerals and also moisture content suitable for industrial processing.¹³ According to these authors this type of processing allows the decrease of microbiological loads and therefore extending the shelf life of the chestnut products.

Studies have been performed evaluating the enzymatic hydrolysis of chestnut products (steamed fruit and purée) with mixtures of α -amylase and amyloglucosidase in order to develop the fruits as sources of glucose for different fermentation of distilled spirits and glucose syrups.^{12,18} Other authors have evaluated the potential of the fruits to produce chestnut-based chips¹⁹ and the effect of drying conditions on chestnut flours and fruits.^{20,21}

Other chestnut tissue products

The Romans first discovered the high potential of chestnut trees not only for fruit production but also use of the bark, leaves and flowers in pharmacopoeia. One of the founders of pharmacopoeia, Dioscoride Pedanio, who worked in Nero's court, attributed to chestnut astringent, antitoxic, stomatic and tonic characteristics.²

Chestnut flower honey has been much appreciated since early times by the Romans, positively described for its pleasant and mildly bitter taste.² Chestnut honey is also used for dressing chronic wounds, burns or skin ulcers because of its antibacterial activity. Recent studies of chestnut honey reveal significant contents of compounds with antioxidant and antimicrobial activities such as phenolics, flavonoids and quinoline alkaloids (Fig. 1).^{22–26}

Chestnut trees are tannin-rich, with high levels of both procyanidins (condensed tannins) and ellagitannins (hydrolysable tannins). This property has been exploited by using the wood for wine barrels and addition of wood chips directly to the wine; the leaching of these tannins from the wood provides the characteristic organoleptic properties in matured wines and brandies.^{27,28} The bark and wood of chestnut trees are the prime sources of tannins for leather processing, transformation of hides and skins into leather and as retanning agents.²⁹ During the tanning process polyphenols are involved in the introduction of additional cross-links into collagen, which binds the active groups of the tanning agents to groups of the collagen of the skin.³⁰

The chestnut shell resulting from the fruit peeling process is used in some countries as fuel (Spain) and is also a rich source of phenolics and antioxidants.^{17,31–34} These antioxidants and other components present in shells, wood and leaves are used in animal feeds (for details see section on 'Health effects: animals') and could also be used as additives to human foods, allowing the recycling and decrease of vegetable waste together with a more environmentally friendly food production.^{31–33,35}

PROXIMATE COMPOSITION OF CHESTNUT FRUITS

Recommended daily intake (RDI) values

The RDI values for macronutrients, minerals and vitamins are shown (Table 1) so that these values can be compared with the compositional data for chestnut fruits, to further demonstrate their nutritional benefits as part of a healthy balanced diet.³⁶ In order to compare the RDI values with the composition of specific components identified in chestnuts, we have estimated the percentage contribution from consuming 100 g FW of chestnut fruits as follows: using the DM data from Table 2 we calculated the mean of all the ranges (47.65 g DM in 100 g fresh chestnuts) and used this to convert the means of the ranges of the individual nutrients, energy, vitamins and minerals to an FW basis and then used these values to compare with the RDI values (calculating the percentage contribution to the RDI).

Basic composition

Various simple^{9,37} and detailed studies (Tables 2–6) have analysed the chemical composition (proximate analyses) of chestnut fruits.

Chestnut fruits contain various nutrients (starch, free sugars, proteins, lipids/fat), vitamins and minerals that are important for health (Tables 2–6). Chestnut fruits are mainly composed of carbohydrates: primarily starch (Table 2). The free sugar sucrose (saccharose) can be up to one-third of the total sugars. Previous analyses revealed the presence of various mono- and disaccharides (glucose, fructose, sucrose and maltose) (Table 2) that are very important for the assessment of chestnut fruit commercial quality.^{16,38–40} Previous studies in Spanish and Italian chestnut cultivars have shown high contents of starch and, additionally, studies have been performed on Italian chestnuts to evaluate the specific contents of amylose and amylopectin,^{8,39,41} which account for 33% and 67% of the starch content, respectively. Both of these forms of starch have positive health effects, providing energy (catabolism of both amylose and amylopectin into glucose) and positive effects on gut functions due to bacterial catabolism of amylopectin-derived dextrins into short-chain fatty acids (SCFA).^{8,42}

The popularity of dietary ingredients used to improve human health has increased in the last few decades.⁴³ One of the most

Table 1. Reference daily intake (RDI) values for macronutrients, vitamins and minerals.³⁶

	RDI	
	Females (19–50 years)	Males (19–50 years)
Carbohydrates (g d ⁻¹)	130	130
Total Fibre (g d ⁻¹)	25	38
Fat (g d ⁻¹)	20–35 ^a	
Fatty acids		
Linoleic	12	17
α -Linolenic	1.1	1.6
Energy (kcal d ⁻¹)	2016–2202 ^b	2254–2566 ^b
Protein (g d ⁻¹)	38	46
Vitamins (mg d ⁻¹)		
A	0.7	0.9
C	75	90
E	15	15
Thiamine (B1)	1.1	1.2
Riboflavin (B2)	1.1	1.3
Niacin (B3)	14	16
Pantothenic acid (B5)	5	5
Pyridoxine (B6)	1.3	1.3
Folate	0.4	0.4
Minerals (mg d ⁻¹)		
Ca	1.0	1.0
Cu	0.9	0.9
Fe	18	8
Mg	320	420
Mn	1.8	2.3
P	700	700
Se	0.055	0.055
Zn	8	11
K	4700	4700
Na	1500	1500

^a Percent of energy.

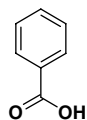
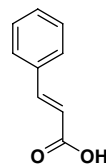
^b Low active individuals of 1.65 m of height and body mass index (BMI) of 18.5 kg m⁻² and 24.99 kg m⁻².

common, associated with positive health effects, is dietary fibre that consists of the remnants of edible plant cell polysaccharides, lignin and other substances resistant to digestion by the alimentary human enzymes. Dietary fibre is associated with stimulation of *Bifidobacterium* and *Lactobacillus* in the intestine, decrease in cholesterol levels, reduction of the risk of cardiovascular diseases, positive regulation of insulin response, increase in anticancer mechanisms and positive effects on metabolism of blood lipids.⁴⁴ When dietary fibre is fermented by colonic bacteria, SCFA are produced and these contribute to the maintenance of colonic integrity and metabolism. They are also potential therapeutic agents in diseases such as various forms of colitis, antibiotic-associated diarrhoea and colon cancer.⁴⁵ From the data presented in Table 2 the mean of total carbohydrates 100 g⁻¹ fresh chestnut fruits (starch, NDF, acid detergent fibre (ADF) and free sugars) was estimated to be 44.7 g. This represents approximately 34% of the RDI for females and males and therefore chestnuts are a good source of dietary carbohydrates and fibre.

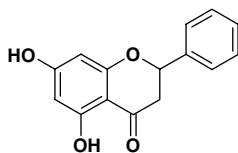
Previous studies of Portuguese cultivars have revealed that chestnuts contain very small amounts of crude fat content that is low in saturated fatty acids and high in unsaturated fatty acids

A. HONEY PHYTOCHEMICALS

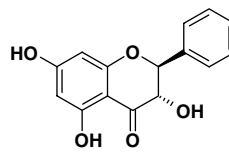
Benzoic acid

*t*-Cinnamic Acid

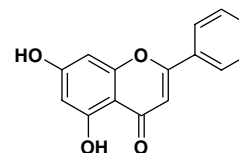
Pinocembrin



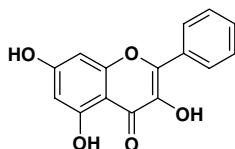
Pinobanksin



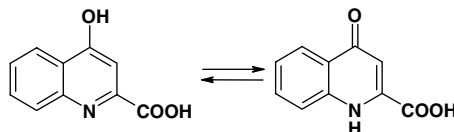
Chrysin



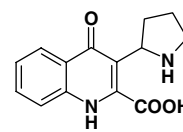
Galangin



Kynurenic acid and tautomer



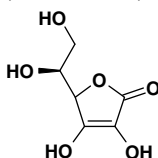
3-Pyrrolidinyl kynurenic acid



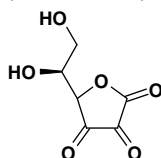
B. ANTIOXIDANT VITAMINS

Vitamin C

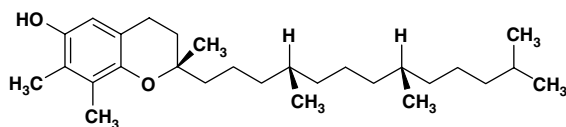
Ascorbic acid (reduced form)



Dehydroascorbic acid (oxidized form)

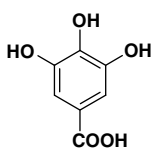


Vitamin E

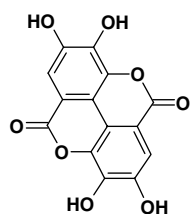
 γ -Tocopherol

C. PHYTOCHEMICALS IN OTHER TISSUES

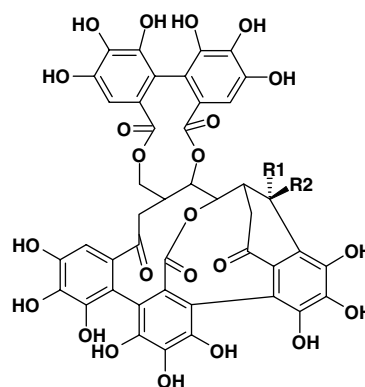
Gallic acid



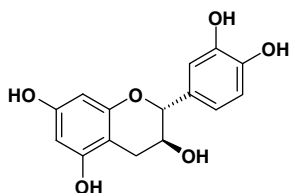
Ellagic acid



Castalagin (R1 = OH, R2 = H) and vescalagin (R1 = H, R2 = OH)



(+) -Catechin



(–) -Epicatechin

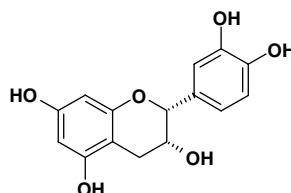
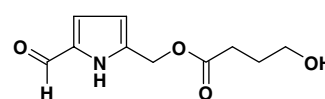
Methyl-(5-formyl-1*H*-pyrrole-2-yl)-4-hydroxybutyrateFigure 1. Phytochemicals and vitamins from various tissues of *Castanea sativa* Mill.

Table 2. Proximate analyses previously reported for chestnut fruits

Dry matter (g 100 g ⁻¹ FW)	Total ash (g 100 g ⁻¹ DM)	Crude fat (g 100 g ⁻¹ DM)	Crude protein ^a (g 100 g ⁻¹ DM)	Crude energy (kcal 100 g ⁻¹ DM)	References
40.1–50.9	7.2–8.0	1.0–1.7	5.6–10.9	–	99
35.6–47.3	2.2–2.9	0.9–1.7	5.4–9.5	–	6
49.3–46.4	2.3–2.5	–	–	–	100
39.9–59.7	1.8–3.2	1.7–4.0	4.5–9.6	–	41
48.7–54.6	1.8–2.3	1.6–2.6	3.9–5.2	–	52
46.7–53.6	1.5–2.2	1.7–3.1	4.9–7.4	–	50
–	–	1.9–4.4	–	410–428	14
45.4–48.1	1.5–1.9	1.6–1.8	5.0–6.5	401–402	49
Fibre (g 100 g ⁻¹ DM)					
Total starch (g 100 g ⁻¹ DM)					References
	NDF	ADF	ADL	Cellulose	
49.7–58.7	23.2–28.9	2.9–3.6	0.4–1.2	2.0–2.9	99
54.9–64.9	20.2–27.2	2.8–3.4	0.6–1.3	2.0–2.4	6
55.3–67.2	–	–	–	–	100
42.2–66.5	9.4–28.5	2.3–4.5	–	–	41
57.5–64.9	12.7–17.5	2.5–3.5	0.2–0.4	2.3–3.1	52
38.6–47.9	13.8–24.4	1.9–3.2	–	–	50
–	12.7–19.9	2.8–4.1	0.4–0.6	2.4–3.6	14
–	2.7–3.8	0.5–0.6	0.02	0.5–0.6	49
Free sugars (g 100 g ⁻¹ DM)					
	Glucose	Fructose	Maltose		References
22.3–29.7	1.1–2.3	1.0–2.3	0.6–1.8		39
6.6–19.5	0–0.3	0.04–0.3	0		38
8.8–14.9	0.04–0.6	0.1–0.8	0.1–1.4		16
Fatty acids (g 100 g ⁻¹ total lipids)					
SFA	C18:1	MUFA	C18:2	PUFA	References
22.8–27.7	17.4–31.5	17.9–31.9	39.1–48.3	43.0–55.9	55
14.1–18.6	20.7–37.6	22.5–39.3	37.6–50.9	42.0–60.1	46
16.2–19.4	29.6–37.4	30.9–38.7	37.9–45.5	42.0–51.9	49
19.9	35.9	37.3	38.2	42.8	29

^a N total × 5.3.

FW, fresh weight; DM, dry matter; NDF, neutral detergent fibre; ADF, acid detergent fibre; ADL, acid detergent lignin; SFA, saturated fatty acids; MUFA, monounsaturated fatty acids; PUFA, polyunsaturated fatty acids.

(Table 2).⁴⁶ Chestnut fruit dietary contributions to total fat and polyunsaturated fatty acids (PUFA) are relatively low. Chestnut fat contains significant levels of monounsaturated fatty acids (MUFA) and PUFA, which are known for their anticancer effects and their association with a decreased risk of sudden death related to cardiovascular diseases and neurological function disorders.^{47,48}

The energetic value (crude energy) of chestnuts, as in any other food source, comes from the oxidative degradation of carbohydrates, proteins and lipids. Not all of the released crude energy (CE) is available to the organism because a part of this energy leaves the body through the faeces, urine and as gases (mainly methane). The other part corresponds to the energy that is available to the metabolic mechanisms that allow maintenance and thermoregulation of the organism. Few analyses of the crude energy in chestnut kernels have been done, but they reveal significant values showing that chestnuts can be used as an important source of dietary energy (Table 2).^{14,49} From the data presented in Table 2 the mean energy 100 g⁻¹ fresh chestnut

fruits was estimated to be 198 kcal. This represents, depending on the body mass index (BMI), approximately 9.0–9.8% of the RDI for females and 7.7–8.8% of the RDI for males.

Crude protein and free amino acids

The protein content of food is an important factor in achieving a healthy and nutritionally balanced diet (Table 2). From the data presented in Table 2 the mean of crude protein 100 g⁻¹ fresh chestnut fruits was estimated to be 3.5 g. This represents approximately 9.2% of the RDI for females and 7.6% of the RDI for males. The amino acids that constitute the proteins in the diet are of high importance. Amino acids are biologically active and have multiple functions in the body: as sources of energy and as precursors of proteins and various important molecules. Amino acids are divided into essential (those that the human body does not synthesize in sufficient quantities, so they are necessary in the diet) and non-essential (the human body is able to synthesize them in adequate concentrations).

Table 3. Contents of free amino acids previously reported in chestnut fruits

Free amino acids (mg 100 g ⁻¹ FW)	References	
	52	15
Essential		
Arg	4.5–48.2	0.5–1.7
Ile	4.4–14.8	0.3–1.4
Leu	0.8–5.8	0.3–1.0
Phe	1.3–9.6	0.5–1.8
Thr	–	3.6–10.0
Trp	–	0.3–2.2
Val	4.9–11.5	0.8–2.7
Non-essential		
Ala	10.1–45.6	3.3–10.0
Asn	62.0–149.5	14.9–36.4
Asp	22.1–76.4	2.3–11.3
Gln	6.9–16.5	2.2–7.3
Glu	27.4–109.8	4.6–14.7
Gly	–	–
Ser	2.7–7.1	1.4–3.8
Tyr	0–1.4	0.4–1.1

Total amino acids (including free and protein-derived), from acid hydrolysis studies of chestnut fruits, have been analysed for European (Portuguese and Italian; *Castanea sativa*), American (*Castanea dentata*) and Chinese (*Castanea mollissima*) chestnuts; the common predominant protein-derived amino acids were aspartic acid and glutamic acid. Besides proteins, plant tissues also contain free amino acids.^{50,51} There are some reports of measurements for free amino acids in *Castanea sativa* fruits (Table 3).^{52,53} The predominant free amino acids in a recent study were aspartic acid, asparagine and glutamic acid.¹⁵

Chestnut fruits (*Castanea sativa*) also contain significant amounts of γ -aminobutyric acid (GABA, derived from arginine: 50–236 mg 100 g⁻¹ DM), which is an important neurotransmitter in the central nervous system.⁵⁴ L-Glutamic acid decarboxylase, located in the cerebrum and hypothalamus, with pyridoxine (vitamin B₆) as its coenzyme, converts L-Glu to GABA. One of the most common consequences of the absence of vitamin B₆, and the associated poor synthesis of GABA, is convulsions in children.⁵⁵ This compound acts by decreasing neuronal activity, calming the body, and in combination with niacinamide and inositol prevents anxiety-related impulses from reaching the motor centres of the brain by filling the receptor site.²⁹

Antioxidant and other vitamins

Vitamins are also essential in a balanced diet for various health related effects (Table 1). An essential compound for human health, which humans cannot synthesize, is vitamin C (ascorbic acid). The biochemical and molecular role of vitamin C (Fig. 1) in the human body is mainly as an antioxidant, as part of a redox cycle with dehydroascorbic acid; two well-known consequences of vitamin C deficiency are the diseases scurvy and anaemia.^{56,57} Previous analyses also report that vitamin C functions as an important antioxidant in the mitochondria of human colon cells.⁵⁸ The major lipid-soluble antioxidant in the cell is vitamin E (Fig. 1), which is exclusively obtained from the diet. This vitamin has a direct antioxidant effect for PUFA, low-density lipoprotein and other cell

membranes components, protecting them from oxidation by free radicals. Vitamin E has been associated with reducing the risk of cancer and cardiovascular diseases.

The compositional analysis of these vitamins in chestnut fruits has been reported previously (Table 4).^{16,59,60} From the data presented in Table 4 the mean vitamin E 100 g⁻¹ fresh chestnut fruits was 1.9 mg, representing 12.7% of the RDI for both females and males. From the data presented in Table 4 the mean vitamin C 100 g⁻¹ fresh chestnut fruits was 15.6 mg, representing 20.8% of the RDI for females and 17.3% for males. This means that chestnuts are a good dietary source of both vitamins E and C. Other vitamins previously reported in raw chestnut kernels are: vitamin A (1 μ g 100 g⁻¹ FW; greater than RDI), which is important for the visual system, growth, epithelial cellular integrity, immune function and reproduction; thiamine (B₁; 0.14 mg 100 g⁻¹ FW; 12.7% of RDI for females and 11.7% for males), which is a coenzyme in carbohydrate and branched-chain amino acid metabolism; riboflavin (B₂; 0.02 mg 100 g⁻¹ FW; 1.8% of RDI for females and 1.5% for males), which is a coenzyme in redox reactions; niacin (B₃; 1.10 mg 100 g⁻¹ FW; 7.9% of RDI for females and 6.9% for males), which is a precursor of important cofactors of enzymes and proteins in the electron transport chain, i.e. NAD⁺/NADH and NADP⁺/NADPH; pantothenic acid (B₅; 0.48 mg 100 g⁻¹ FW; 9.6% of RDI for females and males), which is a constituent of coenzyme A and involved in fatty acid metabolism; pyridoxine (B₆; 0.35 mg 100 g⁻¹ FW; 26.9% of RDI for females and males), which is a coenzyme in amino acid, glycogen and sphingolipid metabolism; folate (58 μ g 100 g⁻¹ FW; 14.5% of RDI for females and males), which is an important cofactor of enzymes involved in various metabolic pathways, in the formation of red blood cells, in DNA synthesis and repair, and may also be important in various neurological functions.^{29,56}

Minerals

The content of minerals found in chestnut fruits is not only associated with the genotype and weather conditions, but is also related to the mineral composition of the soil where the chestnut trees were cultivated. The mineral content was previously analysed in chestnut fruits, revealing important macro-elements (Ca, P, K, Mg and S), with potassium representing the majority of this group, and also important micro-elements (Fe, Cu, Zn and Mn) (Table 5).^{6,16,41,50} The increasing concern for a healthy nutrient-rich diet has become an important topic of public health and this includes a balanced mineral intake (Table 1). Calcium is associated with essential biological functions such as conferring rigidity to the skeleton. From the data in Table 5 the mean Ca content 100 g⁻¹ fresh chestnut fruits was 23 mg, representing more than the RDI for both females and males. Magnesium is an important cofactor of many enzymes, and is also involved in protein, RNA and DNA synthesis, and maintenance of the electrical potential of nervous tissues and cell membranes. From the data in Table 5 the mean Mg content 100 g⁻¹ fresh chestnut fruits was 35 mg, representing 10.9% of the RDI for females and 8.3% for males. Micro-minerals also play important roles in health; for example, iron is important for the transport of oxygen through red blood cell haemoglobin, and both iron and zinc are essential components of various enzymes that participate in the synthesis and catabolism of many nutrients and xenobiotics.⁵⁶ From the data in Table 5 the mean Fe content 100 g⁻¹ fresh chestnut fruits was 3 mg, representing 16.7% of the RDI for females and 37.5% for males. A recent study stated that daily zinc supplementation (capsules with multivitamins and 7 mg Zn) may positively affect the mood state in young women,

Table 4. Content of the antioxidant vitamins E and C previously reported for chestnut fruits

Vitamin E (μg g ^{−1} FW)					Vitamin C (mg 100 g ^{−1} FW)		References
Tocopherols			Tocotrienols		ASc ^a	DHASc ^a	
α	γ	δ	γ	δ			
–	–	–	–	–	30.8–36.3 ^b		59
–	–	–	–	–	40.2 ^b		29
0.02–0.1	3.8–4.8	0.2–0.3	1.4–3.9	0.01–0.04	–	–	60
–	4.1–27.3	0.2–1.0	–	–	4.2–7.2	3.1–6.8	16
–	–	–	–	–	0.77–1.64 ^{b,c}		101

^a ASc, ascorbic acid (reduced vitamin C); DHASc, dehydroascorbic acid (oxidized vitamin C).

^b Content of total vitamin C (ascorbic acid + dehydroascorbic acid).

^c Data are presented on a DM basis as a range of the values from analyses of raw, roasted, boiled and fried samples.

Table 5. Content of minerals previously reported for chestnut fruits

Minerals (mg 100 g ⁻¹ DM)												References
Ca	P	K	Mg	S	Na	Fe	Cu	Zn	Mn	B	Se	
26.5–44.0	119.2–181.4	631.2–844.1	47.4–75.6	50.7–91.9	24.8–30.9	1.9–9.0	0.4–0.7	0.8–1.2	1.8–5.5	–	–	99
28.1–46.8	129.9–238.4	1016.5–1475.7	55.4–81.3	38.1–132.8	2.28–3.08	2.5–5.3	0.5–0.8	0.9–1.5	2.2–7.8	–	–	6
37.1	181.6	1202.7	67.2	80.2	2.7	3.3	0.7	1.1	4.7	–	–	102
26–72	68–305	789–1130	49–100	–	3.0–26.0	1.4–2.4	0.6–1.0	1.0–1.9	1.7–12.5	–	–	41
40.8–50.6	104–148	473–974	63.3–93.3	–	0.8–3.9	5.3–10.9	1.3–2.7	1.4–3.1	3.1–8.0	–	–	50
30.8–45.8	99.8–156.4	629.2–811.1	49.4–58.7	26.4–50.3	19.9–28.4	3.0–7.1	0.6–0.9	0.6–1.3	1.5–5.1	3.0–3.1	0.4–0.8	16

Table 6. Content of phenolics and pigments previously reported for fruits and other chestnut tissues

Tissue	Phenolics (mg g^{-1} FW)			Pigments ($\mu\text{g g}^{-1}$ FW)						References
	Total phenolics	Gallic acid	Ellagic acid	Lutein	β -Carotene	Total minor carotenoids	Lutein esters	Total carotenoids	Total chlorophylls	
Wood	–	–	–	0.2	0.7	–	–	–	–	64
Wood	–	–	89	–	–	–	–	–	–	103
Bark	–	–	0.7–21.6 2.8–18.4 ^a	–	–	–	–	–	–	104
Leaves	–	–	–	–	–	–	–	14.7–22.6 ^b	78.2–119.6 ^b	63
Leaves	21.5	–	–	–	–	–	–	–	–	32
Flowers	48.6	–	–	–	–	–	–	–	–	32
Whole shell	26.6–52	–	–	–	–	–	–	–	–	71
Outer shell	25.4	–	–	–	–	–	–	–	–	32
Outer shell	–	–	0.04–0.2 0.7–6.0 ^a	–	–	–	–	–	–	104
Inner shell	102.6	–	–	–	–	–	–	–	–	32
Inner shell	–	–	0.03–0.1 0.5–0.8 ^a	–	–	–	–	–	–	104
Fruit	21.1–36	2.8–9.1	2.7–9.6	–	–	–	–	–	–	52
Fruit	–	–	–	0.1 ^c	0.1	–	–	–	–	62
Fruit	0.7	–	–	–	–	–	–	–	–	32
Fruit	–	–	0.05 0.05 ^a	–	–	–	–	–	–	104
Fruit	6.6–18	6.1–25.6	3.8–47.8	–	–	–	–	–	–	15
Fruit	–	–	–	0.1–0	0.01–0	0.02–0	0.1–0	0.23–1.30	–	16

^a The first values shown are for non-hydrolysed content, the second for acid hydrolysed.

^b Values are presented as mg cm^{-2} .

^c Lutein plus zeaxanthin.

showing a significant reduction in anger and depression with regular Zn intake.⁶¹ From the data in Table 5 the mean Zn content 100 g⁻¹ fresh chestnut fruits was 0.9 mg, representing 11.3% of the RDI for females and 8.2% for males. Chestnuts also contains other important minerals representing the following percentage contributions to the RDI values: P (89 mg 100 g⁻¹ FW; 12.7% of the RDI for females and males); K (465 mg 100 g⁻¹ FW; 9.9% of the RDI for females and males); Na (8 mg 100 g⁻¹ FW; 0.5% RDI for females and males); Cu (0.8 mg 100 g⁻¹ FW; 88.9% of the RDI for females and males); Mn (3.2 mg 100 g⁻¹ FW); and Se (0.3 mg 100 g⁻¹ FW), which are greater than the RDI for females and males.

PIGMENTS AND SECONDARY METABOLITES

Pigments

In a previous study analysing the pigment (carotenoids and chlorophylls) content in chestnut fruits presented in a USDA report, only β -carotene (pro-vitamin A), lutein and zeaxanthin were detected; there were no chlorophylls or related derivatives present in the fruits (Table 6).⁶² However, there are other studies that have analysed pigments in other chestnut tissues. These studies focused on the analyses of carotenoids and chlorophylls in leaves of Portuguese chestnut, showing high levels of these photosynthetic pigments, as well as other data revealing a significant carotenoid content in French chestnut (*Castanea sativa* Mill.) wood (Table 6).^{63,64} The carotenoid content in fruit and leaves could also benefit human health through different mechanisms, such as direct antioxidant effects, redox-sensitive cell signalling and vitamin A signalling pathways.⁶⁵

Total phenolics, specific phenolics and tannins

Various aromatic compounds including simple phenolics and more complex tannins have been detected in chestnut tissues (see Fig. 1 for examples). The chestnut fruit content of phenolics (gallic and ellagic acid) has been previously analysed (Table 6).^{15,52} These acids have been linked with various positive health effects such as antioxidant effects, decreases in the risk of cardiovascular diseases, anticancer mechanisms and anti-inflammatory properties.^{66–68} Many *Castanea* tissues are rich in both simple phenolics and more complex tannins. Low levels (0.01–0.02 mg 100 g⁻¹ edible portion) of monomeric, dimeric and trimeric procyanidins (condensed tannins) have been reported in chestnut fruits.^{69,70} However, other chestnut tissues, e.g. leaves, wood and bark, have much higher levels of these phenolics (Table 6).^{32,71}

Alkaloids

Plants have a high capacity to synthesize a large variety of low-molecular-weight compounds: the secondary metabolites (phytochemicals). The function of these compounds is still not evident but in the past few decades experimental and circumstantial evidence show that they are vital in plant defence mechanisms.⁷²

Alkaloids are an important class of secondary metabolites that are biosynthesized in many plants, but their biosynthesis, regulation and specific roles are not fully understood. The majority of alkaloids are derived from tyrosine, phenylalanine, anthranilic acid, tryptophan/tryptamine, ornithine/arginine, lysine, histidine and nicotinic acid. However, they can also be derived from purines, terpenoids and steroidal alkaloids.⁷³ A new pyrrole alkaloid, methyl-(5-formyl-1H-pyrrole-2-yl)-4-hydroxybutyrate, has been identified in *Castanea sativa* seeds (1 mg 100 g⁻¹ DM) (Fig. 1).⁷⁴

Pyrrole alkaloids have also been found in other plants and marine sponges.^{75–78} Alkaloids of various classes are known to have important medicinal effects in humans.^{79–82} Many important drugs are alkaloids or are derived from alkaloids. There have been no reports on the positive or negative biological effects of the chestnut alkaloid in animals or humans.

Flavour compounds

Flavour is an important organoleptic property of foods and cooking usually leads to positive changes in flavour; this is the case for chestnut fruits. However, the type of cooking determines whether potentially toxic compounds are formed, e.g. the formation of acrylamide during high-temperature cooking. Maillard reactions occur between amino acids and reducing sugars during heating or cooking processes, leading to the development of colour (non-enzymatic browning) and volatile heterocyclic compounds that are involved in flavour.⁸³ This process may also be responsible for the modification of polysaccharides and proteins in chestnut fruits after cooking. Previously identified volatile compounds in roasted chestnuts included γ -butyrolactone (faint, sweet, caramel flavour) and furfural (sweet, woody, almond, fragrant, baked-bread flavours).⁸⁴ Other work has identified considerable amounts of acrylamide in roasted chestnuts that might have negative effects on health, being classified as a probable human carcinogen and also known as a neurotoxin.⁸⁵

HEALTH EFFECTS: ANIMALS

A previous study on chestnut fruits in relation to the fattening of Duroc pigs (non-castrated males) revealed that chestnuts are a good food supplement, contributing to the energy requirements of the pigs and improving the sensorial taste of the meat and ham. However, the percentage of incorporation of chestnut fruits into the pig's diet cannot be more than 30% w/w of the DM, otherwise negative effects on pig performance (growth and fattening), carcass composition and meat quality are observed. The feeding of chestnuts also reduces the nitrogen composition in urine and faeces from pigs and therefore has an additional positive environmental effect, reducing the generation of deleterious nitrogenous substances from pig production.⁶ Chestnut tannin extracts are being evaluated as potential replacements for antibiotics in animal production. Previous studies showed that the addition of hydrolysable tannins extracted from *Castanea sativa* wood to sheep and goat (0.11%), chicken (0.20%) and rabbit (0.45%) diets may improve their health and even increase their life spans. These tannins act by preventing or eliminating the gut colonization by parasites.^{86–88}

HEALTH EFFECTS: HUMANS

Chestnut and allergies

Chestnut pollen can cause type 1 (contact allergy, immediate hypersensitivity reaction) allergies in some humans (pollinosis).^{89–91} A previous study presented the molecular and immunological characterization of the major allergen from the European chestnut: Cas s 1.⁹² However, it is generally considered as having a low to moderate allergy risk, but is related to cross-reactivity with natural rubber latex allergens. Recent studies with chestnut fruits have identified the major allergens, and in Korean test subjects the sensitization rate from ingestion was 3.2%.⁹³ In the same study, IgE-reactive proteins in chestnut were greatly reduced by

simulated gastric digestion. Reduction of IgE-reactive proteins was even more effective when digestion was performed with boiled chestnuts, probably due to protein denaturation during cooking and further denaturation in the stomach.

Beneficial effects of chestnut

Celiac disease is a debilitating polygenic disorder caused by intolerance (autoimmune reactions) to peptides derived from digestion of the cereal protein gluten.⁹⁴ The symptoms of celiac disease include diarrhoea, irritable bowel syndrome, malabsorption syndrome leading to deficiencies in vitamins and minerals (folate, vitamins E, D and K and the mineral Fe), unexplained weight loss and also autoimmune diseases (type 1 diabetes, biliary cirrhosis and Sjögren's syndrome). It has also been associated with Down's and Turner's syndromes and various neurological disorders.⁹⁴ Celiac sufferers have to use gluten-free foods, which limits the type of foods they can consume. Chestnut fruits do not contain gluten and thus there are many new products derived from chestnuts and chestnut flour that have been created to replace wheat/cereal-containing foods. In addition, from the various proximate analyses, it is clear that chestnut fruits are a good source of essential dietary nutrients and minerals. The low crude fat content, in combination with the high polyunsaturated fatty acids in this fat, makes chestnuts a very healthy food. The free sugars and high starch content also make chestnuts an energetically valuable food crop.

Chestnut as a functional food

From the various composition and health studies it is clear that chestnut fruits, and potentially other extracts from chestnut trees, have considerable potential as functional foods or as food ingredients, e.g. chestnut polyphenolic extracts as a natural source of antioxidants and other beneficial compounds such as gallic and ellagic acids and the ellagitannins. It has previously been shown that many ellagitannins, including castalagin and vescalagin, have potent antitumor, antioxidant, antimicrobial and antimalarial properties.^{95–98}

GENERAL COMMENTS: THE FUTURE FOR CHESTNUT

To increase the market value and consumption of chestnut fruits, based on the potential positive health effects measured from compositional and human health studies, it is important to further promote the benefits of these fruits through consumer awareness campaigns and food fairs.

In terms of future research it is clear that there are several specific areas for improving both the production and quality of chestnut-derived materials. One of the major factors affecting the quality of chestnut products is climate stress, e.g. increasing CO₂ and UV, decreasing water availability, and increasing extreme weather events leading to increased pathogen and pest damage. By conserving and developing the genetic resources for *Castanea sativa* Mill. and related species (germplasm banks and wild species) and developing more effective selected breeding programs, it should be possible to improve not only the resistance to various stresses but also to improve nutritional and other economically important traits. Another aspect related to chestnut quality, and specifically for the fruits, is the industrial processing method. It is clear from recent studies that some aspects of processing decrease the nutritional value of the fruits. It is therefore necessary to identify

which stages of processing are causing the biggest deleterious effects and to develop more effective processing methods.

Finally, to further support health claims regarding chestnuts it will be necessary to perform human cell model studies (for basic evaluation of metabolism and gene expression, e.g. associated with the induction of health-related genes and apoptosis of cancer cells) and also human intervention studies to evaluate the pharmacokinetics and health biomarkers associated with fruit consumption.

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