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Review

Recent Innovations on the Reuse of Almond and Hazelnut By-Products: A Review

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Abstract: Nuts consumption has increased significantly in the last 10 years, especially driven by the stimulated awareness of their possible beneficial health effects. Increased nuts consumption is linked to an obvious accumulation of by-products and waste. With the view of the circular economy, the aim of this review is to analyse the recent and innovative approaches able to valorise the by-products derived from almonds and hazelnuts, two important nut products of the Italian scene, with historical and traditional importance. The most important solutions are concerned with reuse of almond hull, shell, skin, oil cake, and hazelnut shell; skin and oil cake are often considered waste or by-products. Many interesting implications in the feed and food sectors have been detected in the last ten years, aimed at designing innovative materials developed from by-products and extraction of bioactive molecules for different purposes. The perspective chosen to discuss the topic is related to the sustainability of these processes, in terms of both the environment and economy. The circular economy supports a zero-waste approach, which should not also be meant as a zero-cost process in terms of the level of technology that has been partially developed.

Keywords: circular economy; almond; hazelnut; by-products; reuse; waste management; sustainability

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1. Introduction

The concept of the circular economy is gaining momentum in various sectors. This approach consists of considering the products' lifecycle as not linear but circular, that is to say removing, as long as possible, the disposal phase and, on the contrary, introducing a recovery process for the waste. Moreover, a further implementation would be considering the flowchart as infinite, meaning that the product or part of it, even if changing its shape, is kept in circulation [1]. In this way, it becomes possible to create further value by reusing materials several times.

Unfortunately, the design phase is critical to define whether waste or a by-product is recyclable or not because, during the creation phase, it is supposed to be thrown away. It is the case regarding the large number of packages made of composite materials, where it is also difficult and not always possible to undertake classification and separation of the single components [2]. The crucial aspect of this issue is the design phase: the recycling possibility is strictly connected with how the product was projected [3].

The European Parliament reports that, every year, 2.2 billion tons of waste are produced by the entire European Union [3]. This number refers to every kind of waste produced at every level (households and all economic activities) and underlines the fact that our way of life is not sustainable in the light of the limited number of resources available on our planet and the devastating climatic situation that is developing. For these reasons, the European Union is projecting a series of actions to reach climatic neutrality by

2050, enhancing the circular economy. These interventions demand each actor of the value chain to undertake efforts to reach the final objective of a functional circular economy. The food industry is among the main sectors interested in sustainable change [3].

Of the large quantity of waste produced every year, Eurostat reports that 58 million tons are food waste, corresponding to 131 kg per inhabitant. It is even more worrying if considering that over half is direct food waste produced at home. The remaining part is composed of waste coming from primary production, from the manufacturing phase, from distribution flows, and from restaurants and food services [4]. This means that waste from the food sector is produced at every step of the chain. Of the 58 million tons already cited, over 8 million are produced in Italy, where household waste increases to 6 million [4]. The objective of a circular economy approach is to reduce the disposal phases, changing the input management to impact the environment less, designing processes and products made to last, and making reuse and recycling part of the process itself. This point of view aims to reduce the impact of the food systems on climate change and, at the same time, improve the model to face the challenges created by climate change. It becomes clear to understand that different food matrices and products have different issues to deal with, depending on the raw materials, procedures, storage, distribution, selling necessities, and law specifications [5].

Nuts, dried fruits composed of a seed enclosed in an ovary becoming hard at maturity, are an important fruit product in Italy, accounting for over 291,000 t annually produced [6,7]. ISTAT reports that, in 2021, the sold production of peanuts and shelled nuts resulted in a profit of EUR 199,389,000, over EUR 20,000,000 higher than the revenues from the 2020 production [8]. Typically, nuts are regularly consumed in the Mediterranean diet as important sources of energy due to the high content of unsaturated fatty acids, together with nutrients and micronutrients important for health [9]. It is estimated that Italians consumed 11.48 kg/capita/year in 2021 (31.45 g/capita/day), showing an increase with respect to the consumption in 2018, which was quantified as 8.09 kg/capita/year (22.16 g/capita/day) [10].

These data show how the consumption trend is increasing over the years. Around 30 years ago, nuts consumption was not widely diffused; actually, only vegetarians and vegans used them as protein and fat sources. The mediatic influence and large-scale communication were not so widespread to encourage dried fruit intake. In 2003, the FDA stated that regular consumption of nuts may reduce the risk of cardiovascular diseases [11]. Since then, many research studies have been published showing the health-promoting properties of nuts consumption. These fruits show antioxidant, anti-inflammatory, and cardioprotective characteristics, linked to their content of vitamin E and unsaturated fatty acids. Moreover, positive effects of glucose modulation in relation to reduction in type-2 diabetes mellitus occurrence and consequences of reduction in blood cholesterol, blood pressure, and body weight were highlighted. Also, certain protection against cancer was speculated [12–16]. Reductions in the incidence of chronic diseases and death risk were associated with regular nuts consumption, also associated with the Mediterranean food regime [13,15]. Mandalari et al. [17] described how dried fruits are digested, in relation to their chemical and nutritional composition, and the effect they generate regarding the intestinal microbiome and microbiota. Specific genera of bacteria are actually favoured in the gut. These microbes produce short-chain fatty acids, which are able to interfere with inflammation processes. Other research demonstrated how these fruits reduced the risk of cardiovascular disease and coronary heart disease in patients suffering from diabetes mellitus. Nevertheless, the European Food Safety Authority (EFSA) affirmed that these products are not sufficiently characterised and a cause–effect relationship has not been proven; thus, they cannot benefit from health claims [18]. Especially in the last 10 years, attention towards nuts has increased a great deal, popularising them and driving the design of new products and ways of consumption [6,15]. Second to health concerns, another driver of nuts consumption has been the COVID-19 pandemic. This event led to an increase in snacks consumed during the day, and dried fruits were often chosen for this purpose [19].

In Italy, 12% of the fruit shopping in 2022 was dedicated to nuts [7]. In the first 6 months of 2023, an increase in consumption was underlined by 6.3% growth in purchase volume [7].

Nuts are currently present on the market not only as snacks—shelled, fresh or roasted, and ready to eat—but also in multiple preparations, such as desserts, pastries, spreads, ice creams, and baked products. Furthermore, the fat composition of nuts makes oil extraction possible [6].

It is also important to note that issues may arise from nuts consumption, such as allergies and weight gain. In the first case, allergies are quite a common matter, and incidence has been growing over the years. Nut tree and peanut allergies are usually correlated; it is common to find people with allergies to both foods, developing skin, respiratory, gastrointestinal, or even cardiovascular reactions in more severe cases. Such allergies are common in people with other intolerances and sensitisations and are normally considered to be of lifelong duration. However, in some cases, an allergy can be outgrown, leading to acquired oral tolerance [20,21]. The second issue is weight gain, which may arise considering the composition of nuts as energy-dense foods. The literature highlights the fact that their effect is inverse: it has been reported that the desire to eat is reduced by nuts consumption because they have a high satiating effect, especially if consumed as part of a meal. Moreover, their high fibre content makes nutrients bioavailability less effective. Therefore, the introduction of these dried fruits into the diet may assist weight maintenance [22]. A study specifically based on weight modification due to nuts consumption clarified that, even if high in fat and energy, these fruits are not responsible for weight gain and, as a consequence, for the increase in overweight and obesity disorders in the population. Moreover, a certain improvement in diet quality has been recognised regarding nuts, even without the addition of other health-enhancing habits in the dietary regime [23].

In Italy, two main tree nut cultivations are almond and hazelnut. Almond is commonly grown in the south of the country, mainly in Sicily, where it is the basis of some typical products, such as marzipan and almond pastries. In fact, 60% of the national almond cultivations (53,890 ha) are located in Sicily [24]. The cultivated surface has been decreasing in recent years [24]. At the moment, the Protected Geographical Indication (PGI) quality certification has not been approved yet, but the region is currently working to obtain it. Over the past decade, a consortium composed of offices of the local agriculture department, universities, and growers' associations has built a collective brand called "Mandorla di Sicilia", which has been provided to farmers to certify the local origin of the product, belonging to a well-defined pool of cultivars, also facilitating the adoption of cultivation techniques based on the principles of agroecology.

The second cited cultivation, hazelnut, is common in many regions, but the greatest production is found in Piedmont, in the northwest of Italy, where the cultivated area is 24,701 ha and the average yearly production between 2018 and 2022 was 34,403 t [24]. Here, the Nocciola Piemonte PGI certification makes the product refined and highly appreciated. This certification specifically applies to hazelnuts from cultivar Tonda Gentile Trilobata cultivated in the Langhe, Roero, and Monferrato zones in lower Piedmont. Many traditional products from Piedmont are characterised by the presence of hazelnuts, for example the famous Gianduiotto, a chocolate praline with a really representative flavour, or nougat, mainly consumed at Christmastime [25].

High consumption of dried fruits is clearly linked to greater production of by-products, meaning the shell, the skin, and the hull from the cleaning and processing procedures of these fruits, where the edible part is constituted only by the kernel, which is only a small percentage of the overall nut. In almonds, the edible part is, on average, 24% of the overall fruit; that is to say, 76% is waste. This is highly dependent on varietal type considering that European-type cultivars often have a lower seed yield and, consequently, a higher waste (shell) content. In contrast, the cultivars most popular in California and Australia are of the soft-shell type and can achieve as high as 70–80% shell yields. For hazelnuts, the inedible parts amount to a lower value of 58% [26]. The large amount of non-edible constituents of almond and hazelnut makes even more relevant the issue of finding alternative uses for the by-products. Data from the scientific search engine Web of Science were collected using "almond", "almond by-products", "hazelnut", and "hazelnut by-products" as keywords. The results show that, from 1986 to 2023, the number of publications relative to almonds increased significantly (Figure 1), as well as for hazelnut, even though to a lesser extent (Figure 2). Among these, a considerable increase occurred regarding the topic of by-products, from two publications in 1986 to one-hundred-seventy in 2023 regarding almonds (Figure 1), while reaching seventy-eight works (Figure 2).

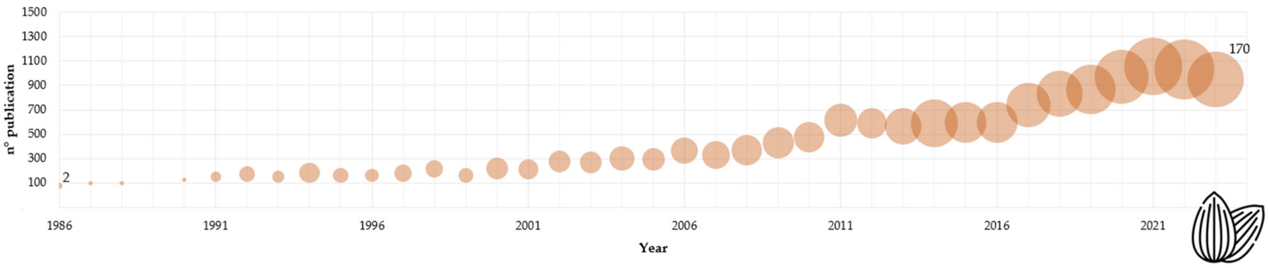

Figure 1. Almond publications trend from 1986 to 2023. The dimensions of the bubbles are related to the number of publications about almond by-products. The first and last bubbles also show the number of publications to which their dimensions are related. Data obtained from Web of Science search engine using "almond" and "almond by-products" keywords and edited by the authors.

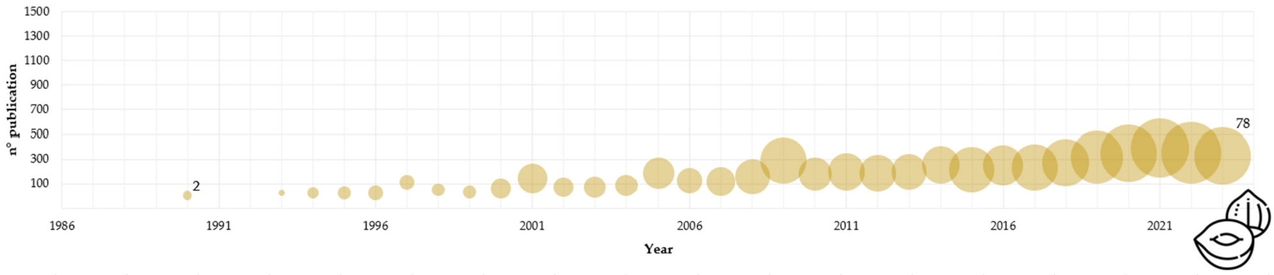

Figure 2. Hazelnut publications trend from 1986 to 2023. The dimensions of the bubbles are related to the number of publications about hazelnut by-products. The first and last bubbles also show the number of publications to which their dimensions are related. Data obtained from Web of Science search engine using "hazelnut" and "hazelnut by-products" keywords and edited by the authors.

The aim of this review is to analyse the available literature regarding innovative reuse and recycling of by-products specifically for almond and hazelnut, with particular attention focused on the possibility to put into practice a sustainable reuse process in terms of both economic and environmental sustainability. Among the many research studies available relative to almond and hazelnut by-products, the focus of this study is on the most recent and original application methods.

2. Research Method and Approach

To provide a complete overview and to describe the range of innovations available in the literature, it is important to define what the authors consider as "traditional" and "innovative" in relation to waste management and circular economy approaches for almond and hazelnut by-products. "Traditional" includes customary and usual methods that have been put into practice since the mid to late 20th century for residue and by-product disposal rather than considering reuse and recycling possibilities. "Innovative" approaches are considered to be more recent, involving new technologies, evaluating a green, sustainable perspective of further waste valorisation. The authors considered the environmental sustainability of innovations alongside their economic impact. Scientific papers were retrieved through the Web of Science database. To discuss the innovations brought about in the sector of almond and hazelnut wastes, studies were chosen preferably dating back to the last 10 years (2013–2023). The selected papers were organised for the discussion according to the matrix and the by-products they concern so that the topic becomes fluid and accessible.

The main results from the research studies were reported, paying particular attention to the steps towards practical application.

3. Almond

The geographical origin of almonds is the Middle East, where the regions share a Mediterranean climate suitable for the growth of *Prunus dulcis*. Prehistoric sources suggest the presence of wild almonds in Israel during the Pleistocene [27]. Further, almonds were exported to North Africa after the Arab conquest of those territories. Eventually, the fruits were transported to Spain and Portugal. Spanish Franciscan Friars brought almond cultivation to America, in particular to California, in the 18th century, where the climatic conditions were favourable for the production. Nowadays, California is one of the main almond producers in the world [28], followed by Australia, Turkey, and then Mediterranean countries.

In Italy, the almond production is mainly centred in Sicily and Apulia, southern regions directly facing the Mediterranean Sea. Here, *P. dulcis* growth was a major cultivation in the 18th–19th centuries because it was able to valorise areas previously dedicated to pasture or covered in bushes and, at the same time, it could grow without particular interventions and in the absence of water. All these reasons make almond cultivation highly regarded, usually found in both orchards/gardens and on hills, with a certain importance also from the landscape point of view [29]. Still today, almond cultivation is a peculiarity in the landscape of Sicily [30]. Over the years, critical issues arose and the traditional management turned out to be no longer suitable to satisfy the expanded interest towards almonds [30,31]. The negative trend experienced in the 1980s is substantially due to traditional management of orchards, with a lack of cultivar renovation, following the ancient traditional management of plants, where almond trees grow mixed with olive trees. Appropriate pruning operations were also neglected [29]. In more recent years, interest was reignited regarding almond cultivation, with growing interest towards breeding and genetic studies, agronomic techniques, and cultivation management; this also led to the definition of modern and more competitive cultivation in Sicily [31]. A productive and remunerative orchard derives from good genotype selection, aimed to overcome limiting characteristics. Newly selected hybrids, innovated from the genetical point of view, should guarantee health characteristics and thus higher resistance to pathogens and stresses, thereby also ensuring high-quality production. Quality and productivity are the main drivers leading to the replacement of traditional cultivars with recently developed genotypes. Early bud break, high presence of twin fruit, and susceptibility to diseases are some of the characteristics making the majority of the traditional varieties not conform to industrial production [29]. The typical Sicilian varieties are Pizzuta d'Avola, Fascionello, Romana, Vinci a tutti, and Cavalera, while more recent cultivars found in the region include Tuono, Genco, Supernova, Ferragnés, Filippo Ceo, and Vario [31].

Introducing and improving automation may have an effect on the economic competitiveness of the final product, for example, with the adoption of a mechanical harvesting method. However, it is important not to damage the seed in order to guarantee product quality. Altuntas et al. [32] carried out a research study to evaluate the resistance of some almond cultivars to rupture force, the specific deformation, the absorbed energy, and the power of cracking. They defined the geometric characteristics and the mechanical properties of the tested varieties and stated that not only does the cultivar influence the result but also the axis on which force was applied.

Differently from other drupe fruits, where the fleshy mesocarp is eaten and the endocarp, called pit, is discarded, almond is the inner part of the stone inside the fruit. The commonly known and eaten almonds are the kernel of the entire fruit. This kernel is covered by a thin brown skin, enveloped by a wooden shell and positioned inside the hull that opens when the almond is mature [33,34]. Skin, shell, and hull are the by-products derived from almond separation and are, respectively, 4–8% of the shelled almond weight, and 20–30% and 40–60% of the overall almond by-products [35]. These seeds can be directly eaten or further processed, depending on the destination. The majority of almonds are sold for direct consumption, already shelled and, in most cases, peeled from the skin layer, traditionally considered easier to be milled and used by confectionary and bakery industries. The skin removal requires a process called blanching, consisting of a rapid treatment with hot water; this leads to the production of an additional waste (water) and conditions the composition of residual skins and waters [35–37]. Another important product derived from almonds is oil as the fruits are rich in fatty acids. It is obtained from the dried seeds and characterised by a nutty taste, a clear amber colour, and a delicate smell. This product is recognised as potentially good for health, showing anti-inflammatory and anti-hepatotoxicity properties, effects against irritable bowel syndrome symptoms, cardiovascular benefits, and reduction in cancer incidence. Moreover, positive effects on skin and emollient properties are recognised; for the listed reasons, the oil is commonly used in cosmetics and pharmacology [38,39]. The residues obtained subsequent to oil extraction, called "cakes", are partially defatted but remain sources of other nutrients [40].

Waste products available from dehulling, shelling, and skin-removing procedures are normally incinerated [41]. This method does not valorise the by-product, which may be employed differently. Research carried out in less recent times focused on the use of waste for combustion and pyrolysis as soil fertiliser or growing substrates and, in some cases, as feed. As the shell, the covering of the kernel, is ligneous, it is the fraction that is most likely to be used as a burning substrate.

The final objective of combustion and pyrolysis is energy and heat production. Biomass combustion has been a very common solution before 1900, when access to carbon fuels improved. This was the most common method to get rid of agricultural waste, from pruning to the shells' by-products [42]. The domestic use of grinded almond shells in biomass boilers and stoves remains widely diffused today, where the by-product is available because of the similar characteristics to commercialised wood pellets and the reduced cost [43]. A feasibility study was conducted in Italy regarding hull combustion. The aim was to exploit the thermal energy derived from the process to dry out almonds. The study demonstrates that the calorific value of hulls is quite comparable to that of shells, corresponding to 88%, thus making them possible to be burnt to produce energy [44].

Pyrolysis is a chemical process that involves the thermal decomposition of materials at elevated temperatures in the absence of oxygen or with limited oxygen access. During pyrolysis, the material undergoes breakdown into simpler compounds without combustion, producing products such as gas, oil, char, and ash. This process is typically used in waste management and biomass conversion. This process has been exploited to manage almond shells' waste because the decomposition of their lignocellulosic content, 37% cellulose, 32% hemicellulose, and 27% lignin, mainly results in solid and gaseous compounds with energetic value [45,46]. The gaseous production derived from almonds shells' pyrolysis is influenced by pre-treatments applied on the waste: an acidic pre-treatment results in higher gas production to the detriment of solids; the opposite situation is encountered with basic treatment application [46]. Pyrolysis products are also dependent on the applied temperatures [46,47].

The alternative use of shell as a pure growing substrate for soilless cultures has been studied as a replacement of perlite [48] or rockwool [41]. The physical and chemical properties of the tested substrate were found to be similar to the commercial rockwool in melon and tomato cultivation. The differences highlighted may derive from the different particle size obtained by grinding [41]. Similar conclusions were drawn in relation to the cultivation of sweet peppers: almond shells were considered an acceptable growing media for pepper as the pH and water-soluble organic carbon were adequate. Furthermore, reduced yield and fruit number were found. The comparison between almond shells and almond hull as growing media showed how the second was not properly suited for the specific cultivation [48]. As a fertiliser, the shells undergo a specific acidification treatment and need to be ground. Their composition in terms of minerals and micronutrients is helpful for soil composition [49].

Another upcycling alternative is exploitation for animal feed. This is the case reported by Grasser et al. [50], explaining that almond hulls represented 27% of the Californian feed in the dairy sector. Almond hulls were also tested as a supplement in lamb diet, resulting in a positive effect on the shelf life duration of the meat due to a delay in lipid oxidation up to 7 days. This behaviour was attributed to the antioxidant activity and phenolic content of almond hulls. Moreover, 40% of the cereals in the lamb diet were replaced with almond hulls. The substitution was supported by the economic reasoning of using a cheaper by-product, with a low protein content and quite high carbohydrate content, excluding fibre [51]. From a legislative point of view, the use of almond (and/or hazelnut) by-products in animal feed is approved by Regulation (UE) 68/2013 [52], last modified in 2022. A European directive already dealing with the topic was signed in 1992 but has been subsequently withdrawn.

These reported applications are the most recurring ones, which have been hypothesised as alternative recycling and reuse methods regarding almond processing waste since the final decades of the 20th century. Currently, the intensifying interest in environmental issues and the possibility of making better use of the available resources and technologies make it possible to think of more innovative ways of reusing by-products. The most innovative research studies considered in the review are outlined in Figure 3.

Figure 3. Almond by-products and innovative applications described in the literature for each fraction. Hull (animal feed [53–55], fortified food [56], molecules extraction [57–60], and materials [61]); shell (molecules extraction [58,62,63] and materials [64–67]); skin (molecules extraction [17,68–70] and fortified food [71–73]); and oil cake (fortified food [74]).

3.1. Almond Hull

The hull is the mesocarp plus the skin of the almond tree fruit. It is the main by-product derived from almond extraction, accounting for around 50% of the entire fruit, depending on the almond cultivar [57]. Over the years, research involving the valorisation of by-products has been mainly centred on use and digestibility as feed for ruminants (sheep and dairy cows) as they are rich in sugar and fibre and thus possess high nutritional value [53,54].

Almond hulls, together with shells, were also exploited as growing substrates for *Hermetia illucens* larvae, commonly referred to as black soldier fly larvae. These insects, in the juvenile stage, are used in the feed sector as sources of fat and protein for animals, especially for poultry and fish. The final residues from the rearing of the larvae are high in nutrients, such as nitrogen, being potentially beneficial if used as soil fertiliser. Even if almond hulls play an important role in larvae quality, the waste is not directly applicable in soil fertilisation because the decomposition does not reach a high level in the short time in which *H. illucens* larvae are reared [55].

Almond hulls were also used in the preparation of bread. This is the case described by Kahlaoui et al. [56]. The recipe was developed by including 4% and 8% by weight of hull. In the control, the same percentages were replaced by wheat bran. The hull was previously separated from the almond, dried in the oven, ground, and sieved to a powder with a size between 100 and 250 µm. The difference between green and mature fruit was also considered. The results showed that the consumer preference oriented to the 4% almond hull powder in relation to green fruit, while 8% was preferred in the case of mature fruit. Moreover, the addition of the hull powder increased the fibre and ash content of the bread, while fats were reduced, which might provide significant health-improving characteristics [56].

The preparation of food products using by-products derived from plants or their parts or from other processes and not prepared for human consumption up to 15 May 1997 are considered novel food, as reported in Regulation 2283/2015 [75]. Thus, their commercialisation should be approved by the EFSA based on a complete evaluation to assess the safety of the product.

More recent studies highlighted the high value of almond hulls in relation to their composition, and new techniques were implemented to find valorised, innovative, and, possibly, less impactful, exploitative solutions. The hull's proximate composition is not a fixed characteristic because it is influenced by variety, climatic conditions, and agronomic management. Nevertheless some ranges are available, and it is reported that the main nutrient categories are sugars (18–30%), proteins (2–9%), fibre (10–15%), cellulose (21–35%), and lignins (8–16%) [58,59].

The possibility to extract active molecules from almond hulls may provide an alternative and more valuable pathway towards common and impactful disposal. The hull is rich in triterpenoids and phenols, which, if extracted, could be used in the pharmaceutical and cosmetic sectors or added in specific food productions as functional ingredients or additives to design high-valued products. A higher antioxidant power compared to tocopherol is recognised in almond hull extracts in specific circumstances, and the natural triterpenoids showed health-promoting and antimicrobial characteristics [57]. The optimisation of phenolics extraction gained high interest from the scientific community: methods including the use of pulsed electric fields (PEF), PEF followed by a second step with supercritical CO_2, and food-compatible and pharma-compatible solvents were used [58–60]. In relation to the PEF extraction method, it is important to consider a possible interference pattern, resulting in increments in the antioxidant power of the extract, with respect to a traditional maceration in ethanol [59]. The results enhancing the antioxidant capacity of the extracts also derive from the additional extraction phase using supercritical fluids.

The extraction process may provide valuable and promising results in terms of functional ingredients; however, further waste is produced. Analysis by Salgado Ramos et al. [59] showed a calorific power around 17 MJ/kg of the spent almond hull biomass from extraction, slightly higher than the reference of palm seed and leaf. For this reason, they suggested its use as a bioenergy source and biofuel. As an alternative, the residual carbohydrates from the spent hulls biomass could be involved in other extraction cycles of levulinic acid, furfural, and 5-hydroxymethylfurfural, bio-based substances used in cosmetics and pharmaceutics [59,60].

The wood shortage makes agricultural waste an important source of lignocellulosic material. Research should examine whether the properties are suitable for the same building, packaging, and furniture purposes [61]. An innovative binderless particleboard was developed using dried green almond hull, crushed and sieved to obtain four different particle sizes (2 to 4 mm, 1 to 2 mm, 0.25 to 1 mm, and <0.25 mm). The self-binding properties derived from the hull's sugars, particularly xylose. The results show that the panels obtained with particle size <0.25 mm and pressed for 30 min have similar characteristics to high-density wood fibre boards used in laminated flooring [61].

3.2. Almond Shell

It can represent the component of greatest abundance among the by-products of almond processing, considering that the percentage of shell in a kg of almonds ranges between a minimum of 30% for Californian-type cultivars and a maximum of 80% for Mediterranean ones [31]. The shell is the endocarp of the almond tree fruit, which is mainly composed of cellulose, hemicellulose, and lignins, responsible of the hardness and the strength of the shell [58]. The high amount of cellulose, reaching 45.9%, makes almond shells a good fibrocellulosic material, which can be exploited for cellulose extraction and subsequent use for biodegradable and eco-friendly material design [67]. As an example, Modica et al. [67] showed how the microcrystalline cellulose (MCC) derived from almond shells is suitable to produce handmade cardboard. Firstly, an alkaline treatment of almond shells was needed to avoid the presence of lignins, followed by bleaching with NaClO solution to obtain the starting fibres. A basic method was used for the production. The results showed a consistent paper, with features adaptable for packaging use.

The almond shells' composition may also be promising for other material development purposes. One possibility is to use MCC as a filler mixed with a polymeric matrix such as PBAT (polybutylene adipate-coterephthalate), which is a completely biodegradable polymer, therefore suitable for agriculture and food packaging. Also, in this case, the ground shells need to undergo alkaline treatment and further washing with NaClO to remove hemicellulose and lignin, purifying the cellulose. The microcrystalline cellulosic structures obtained were used at 10% and 20% and mixed into the melted PBAT matrix. The results show that it is therefore possible to obtain a biodegradable material that valorises agricultural waste and has a higher density, compared to commercial MCC, and with a good level of adhesion between matrix and filler. In particular, the 20% filling shows shear thinning behaviour, and thus solid-state viscoelastic behaviour due to the construction of three-dimensional structures [64].

The same MCCs were employed on the basis of their micrometric dimensions, high mechanical strength, and being biodegradable powder in the preparation of stucco for wooden artifacts [65]. Three different stucco formulations were prepared by adding different binders (Aquazol 500, Klucel-c, and a mixture of both) to a cellulose pulp. The results reveal how the mechanical properties of the stucco were improved by incorporating MCC and how its characteristics changed depending on the binder used (Aquazol 500 proves to be the best for the wood matrix). However, the effects of long-term durability under real conditions, as well as the effectiveness on other materials besides wood, were not investigated [65].

Improvement in mechanical properties by adding almond shells was also investigated for plastic materials as low-cost and sustainable alternatives to traditional reinforcing agents [66]. The tested fillings derived from torrefied almond shells, meaning the exocarp underwent a further thermal process to be utilised for this purpose.

Alternatively to chemical extraction of cellulose, Valdés et al. [63] proposed an innovative extraction method, a microwave-assisted process, of obtaining cellulose nanocrystals. This method can be considered more sustainable and environmentally friendly since reductions in solvents, time, and energy consumption are experienced, together with reduced manipulation from the operator. Good-quality nanocrystals are obtained, potentially applicable in several industrial procedures. Nevertheless, specific equipment is needed, thus involving costs. Moreover, the extraction conditions need to be reconsidered for each matrix.

Almond shells, as already mentioned, are rich in lignins. A possible exploitation of these compounds after their chemical extraction could be utilisation in the textile industry due to their antioxidant properties instead of synthetic antioxidant products in order to guarantee longer durability of the final product. Additionally, the performance of the extracts was not evaluated practically [62].

Isolating single substances from by-products is always a complex procedure. It is possible in a laboratory environment but difficult to transpose in a practical industrial reality. Surely, extraction is a valorisation route for the by-products rather than a sustainable alternative to disposal. In addition to this, all the extraction protocols analysed in this work led to spent material remaining present, thus not solving the by-products issue.

3.3. Almond Skin

Almond skins are obtained following blanching treatment, which helps in removing the external brown layer protecting the kernel. Blanching is performed to adapt to the high market demand for peeled almonds, not only for direct consumption but also for specific preparations, such as almond beverages. In this case, peeled almonds are soaked and then crushed in water to obtain, after a further filtration step, a vegetal drink with a characteristic flavour, highly consumed by vegan and lactose-intolerant people [76,77]. Blanching is a thermal treatment conducted in water. It has been demonstrated that, while in water, almond skins release part of their phenolic content in it. This makes blanching waters a possible source for extraction of phenolic substances to be used as food ingredients or in pharmaceutics [17,69]. The polyphenolic content of blanching waters was demonstrated to be effective as an antioxidant against lipid peroxidation due to heat or photoinduction [17].

The skin layer is removed from almonds through peeling. It has a highly nutritious composition, rich in fibre and with an interesting protein content, scarce in fats and sugars [69]. Moreover, as already mentioned, skins are rich in phenolic substances, although blanching depletes them of some bioactive compounds, perhaps due to their solubilisation. A further method of separating the peel from the seed is roasting. In this case, the absence of a water bath results in the absence of solubilisation losses and a concentration effect, leading to a 20% increase in polyphenols and between 28% and 32% in proanthocyanins [78]. It is necessary to consider that the high temperatures involved in roasting and the Maillard reaction triggered could transform some compounds, leading to the creation of new products with antioxidant properties. This means that the quantification of phenolics and antioxidants may be higher but not related to the same substances [79].

No antimicrobial effect was detected in the research by Ingegneri et al. [69], differing from the findings of the study by Badalamenti et al. [68]. In this research paper, extract from almond skins was prepared using n-hexane and demonstrated effectiveness against pathogens such as *Escherichia coli*, *Staphylococcus aureus*, *Listeria monocytogenes*, and *Salmonella enteritidis* without affecting the development of technological microorganisms, for example, *Saccharomyces cerevisiae*, the fundamental yeast in fermented foods. These results support the possible introduction of almond skins or almond skin extracts into functional foods or for use as natural antimicrobials following careful investigation of the mechanisms of action and concentrations of use. An example is exploitation of almond skin water extracts as antioxidant preservatives for pork burgers. The extracts were prepared weighing 1 g of skin and then adding 20 g of distilled water. After 60 min at 30 °C in a shaking bath, the samples were cooled, filtered, and centrifuged to easily separate the supernatant to use in the preparation of the patties. Effective results were obtained, and the shelf life of the pork product was extended, probably thanks to the phenolic content and the antioxidant properties of the almond skin extracts. It is important to underline that the water extraction performed was not expensive, thus being appealing from an industrial point of view, combining waste valorisation and sustainability [70].

These data underline the possible employment of almond skin in functional food products. Polyphenol extracts from almond skins may have positive effects on the human body and health: Chen et al. [80], in support of this possibility, showed that intake of these compounds by healthy adults results in improved antioxidant defence mechanisms together with improved resistance of bad cholesterol to oxidation. This occurs because polyphenolic substances possess high antioxidant properties.

Examples of fortified food products using almond skins include the reformulation of a traditional sourdough bread, where semolina was replaced with 5% and 10% almond peel. The functional bread produced showed reduced weight loss during baking and was firmer than the control, which was made using a traditional semolina-based recipe. This may be attributed to the increased fibre content. As expected, the colour of the functional bread crumb was noticeably darker. On the other hand, some safety implications arose regarding the presence of spore-forming bacteria after the baking phase. Spore-forming bacteria could contaminate almond skins, and the bread baking process was demonstrated not to be effective in inactivating the spores. Concerns may be linked to the presence of spoiling *Bacilli*, but also, and more severely, regarding pathogenic bacteria such as *Bacillus cereus* or *Bacillus subtilis*. Contaminations may come from the almond skins and resist the blanching, drying (54 °C), and grinding carried out as preliminary steps to obtain the skin powder to add to the bread [71]. Analogous results for bakery products were obtained by adding almond skins to waffles [73]. Higher content in polyphenols, fibre, and greater antioxidant activity were also measured in functional blackberry jam prepared adding 20% of powdered almond skin with respect to the formulations containing 10% and 15% fortification. These functional features, together with the sensorial one, were not affected by the pasteurisation process [72].

3.4. Almond Oil Cake

Almond seed oil can be extracted and is a high-quality product rich in unsaturated fatty acids and used in cosmetics and pharmaceutics [40]. Virgin almond oil is obtained from the seed through pressing or extraction with supercritical fluids, such as CO_2. In this case, the product does not need to be refined and is suited for human consumption. Higher yield, incidentally, could be obtained from solvent extraction, possibly coupled to ultrasounds, but a refining process is necessary to make the oil edible [81]. The residues of the extraction process consist of partially defatted flour or almond cake (7.9–13.8% fat still present), rich in proteins, fibres, and functional compounds that may be valorised with alternative uses: as an example, being used in the preparation of biscuits. It has been stated that the colour of almond flour is comparable to that of oil cakes, not changing the overall appearance of the biscuits. The possibility of introducing oil cakes as a substitute for almond flour makes almond biscuits an economically sustainable product projected towards the "zero waste" economy [40,74,81]. The innovative studies and results discussed and commented on for each almond fraction are condensed in Table 1.

Table 1. Summary of innovations in almond by-products management.

By-Product	Application	Final Product	Processing and Method Features	Advantages	Downsides and Further Investigations	References
Almond hull	Rearing substrate	*Hermetia illucens* larvae and their residues	The substrate was prepared by grounding the hulls with a hammer mill with a 6.35 mm screen and stored in completely sealed plastic bags until use.	Larvae are able to feed themselves with hull waste. Larvae will be used as protein and fat sources in animal feed.	Residues from larvae rearing are not broken down enough for fertilisation.	[55]
	Functional ingredient	Fortified bread	The hulls were dried in an oven for 24 h at 40 °C. Afterwards, they were ground and sieved (100–250 µm). The powders were stored at 4 °C in vacuum-sealed plastic bags at 4 °C until use.	Better nutritional characteristics found in the fortified product (fibre, ash, and fat)	Maturity stage of the hull influences the characteristics of the final product and its overall liking.	[56]
	Molecules extraction	Functional extract rich in phenolics and triterpenoids	Almond hulls were dried (45 °C) and ground to obtain a powder. The extraction was carried out with a hydroalcoholic solution (ethanol:water 80:20 *v*/*v*) also suitable for food applications.	High recovery rates for the bioactive compounds were found and a promising antimicrobial activity against some pathogens was highlighted.	The almond cultivar influences the composition of the extract. Spent almond hulls are still present.	[57]
		Extract rich in antioxidants	The hulls collected were freeze-dried and then blade-milled (1 mm particles) to obtain a homogeneous dried biomass. Finally, pulsed electric fields (PEF) technology was used for the extraction of antioxidants.	Innovative and sustainable extraction method without employing solvents.	Spent almond hulls biomass still present as a residual waste. Further uses of the extracted compounds were not discussed.	[59]
		Extract rich in lipids, carbo-hydrates, and antioxidants	Double sequential extraction was performed on non-treated hulls. PEF technology was followed by supercritical CO_2 extraction.	Innovative and sustainable extraction method without employing solvents. Higher recovery with respect to the only PEF technology and wider range of molecules extracted (not only phenolics).	Spent almond hulls biomass still present as a residual waste. Further uses of the extracted compounds were not discussed.	[60]

Table 1. *Cont.*

By-Product	Application	Final Product	Processing and Method Features	Advantages	Downsides and Further Investigations	References
Almond hull	Lignocellulosic material replacement	Binderless particleboard development	Green almond hulls were naturally dried for 6 months and then blade-milled to specific particle sizes (2 to 4 mm, 1 to 2 mm, 0.25 to 1 mm, and <0.25 mm).	Alternative to wood materials without binding additives addition.	The physical properties of the new material may make it not suitable for the same uses as wood boards.	[61]
Almond shell	Molecules extraction	Antioxidant lignin extracts	The study did not provide specific information about the management of almond shells. The extraction procedures put into practice used the following chemicals: dioxane–water, HCl, acetic anhydride–pyridine, and ethanol.	Good-quality lignins were isolated and characterised from almond shell by-product.	Impacting chemicals used in the extraction procedures. The possible use in the textile industry was not proven.	[62]
		Microwave-assisted extraction of cellulose nanocrystals (CNC)	The shells were washed with water and allowed to naturally dry for 12 h. After this step, a drying process was carried out (40 °C for 4 h). Small particles (1 mm) were obtained through two grinding steps. The powder was treated with NaOH (7.5% *w*/*w*) at 100 °C coupled to microwave curing. Acetylation (acetic acid and nitric acid) and acid hydrolysis (sulfuric acid) will follow.	Good-quality CNC are obtained with reduced use of solvents, time, and energy.	Chemical substances still needed due to the presence of lignins and hemicelluloses in the matrix. Practical application of CNC was not tested.	[63]
	Microcrystalline cellulose (MCC) exploitation in material design	Packaging cardboard	Dried almond shells were ground to 5 mm particle size and then treated as follows: NaOH solution (7.5% *w*/*w*) for 24 h; distilled water rinsing (pH 7); NaClO (2.5% *w*/*v*) at 60–70 °C for 1 h; and filtering and rinsing with water. Final drying phase before the paper production process.	Resistant and biodegradable cardboard produced from waste.	Impactful chemical procedures still needed for shell pre-treatment to purify MCC.	[67]

Table 1. *Cont.*

By-Product	Application	Final Product	Processing and Method Features	Advantages	Downsides and Further Investigations	References
Almond shell	MCC as filler	PBAT (polybutylene adipate-coterephthalate) composite material with MCC	Dried almond shells were ground to 5 mm particle size and then treated as follows: NaOH solution (7.5% *w*/*w*) for 24 h; distilled water rinsing (pH 7); NaClO (2.5% *w*/*v*) at 60–70 °C for 1 h; and filtering and rinsing with water. Final drying phase was performed for the final product.	Production of a completely biodegradable polymer.	Impactful chemical procedures still needed for shell pre-treatment to purify MCC.	[64]
	MCC as micrometric reinforcer	Stucco for wooden artifacts	Dried almond shells were ground to 5 mm particle size and then treated as follows: NaOH solution (7.5% *w*/*w*) for 24 h; distilled water rinsing (pH 7); NaClO (2.5% *w*/*v*) at 60–70 °C for 1 h; and filtering and rinsing with water. Cellulose pulp was then mixed with each binder (Aquazol 500, Klucel-c, and a mixture of both).	MCC improved the stucco mechanical properties.	Application on other materials and long-term resistance were not tested.	[65]
	Reinforcing agent	Reinforced plastic material	Almond shells were milled to obtain small pieces and then torrefied.	Low-cost reinforcing agent.	The study did not investigate the physical properties of the final product that could be obtained and its effectiveness.	[66]
Almond skin	Molecules extraction	Antimicrobial activity of almond skin extract	The skins (separated through blanching) were dried at 60 °C and reduced to powder, then freeze-dried. The extraction from almond skin was performed using hexane.	The antimicrobial activity shown against food pathogens (*Listeria monocytogenes*, *Salmonella enteritidis*, *Escherichia coli*, and *Staphylococcus aureus*) without affecting technological microorganisms (i.e., *Saccharomyces cerevisiae*) may be encouraging in the possible use of the extract in the food sector.	The procedure could valorise the by-product, but the hexane extraction is still impactful.	[68]

Table 1. *Cont.*

By-Product	Application	Final Product	Processing and Method Features	Advantages	Downsides and Further Investigations	References
Almond skin	Molecules extraction	Phenolics from almond skins enhancing pork burger shelf life	Almond skins were separated from the seeds through blanching and then dried. They were stored under vacuum at room temperature until use. Extraction was performed using distilled water as solvent in a shaking bath (30 °C for 60 min). Filtration and centrifugation followed to collect the supernatant.	The addition of the extracts to the patties prolonged their shelf life, probably due to the effect of bioactive compounds (phenolics and antioxidants). Moreover, the extract used was only prepared using water.	Further investigation regarding the antimicrobial activity of the extracts would be interesting, as also stated by the authors.	[70]
	Functional ingredient	Fortified semolina bread	The skins were separated after blanching and then dried in oven (54 °C). Then, they were ground and sieved to reach particles of 250 µm. The powder obtained was used in the bread preparation.	Increased fibre content (compared to semolina bread), with possible health-promoting implications.	The colour, texture, and volume of the product was obviously influenced by the almond skins. Safety issues (spore-forming bacteria still present after baking) need to be examined in depth.	[71]
		Fortified waffles	The blanched skins were dried for 10 h at 95–98 °C. The authors did not make explicit reference to the grounding of the skins, but the preparation of waffles is not able to leave this step out of consideration.	Higher content of almond skin resulted in higher fibres, polyphenols, and antioxidant activity; thus, the fortified waffles could have health-promoting implications.	The colour, texture, and sensorial aspects of the product were obviously influenced by the almond skins.	[73]
		Fortified blackberry jam	The skins (separated through blanching) were dried at 60 °C and reduced to powder; 20% *w*/*w* was added to the jam.	The final product was higher in fibre and polyphenols, thus with possible health-promoting implications. The addition of almond skin powder did not negatively affect the sensorial perception of the jam.	It might be possible to implement the study by trying the addition of other percentages of almond skin powder	[72]

Table 1. *Cont.*

By-Product	Application	Final Product	Processing and Method Features	Advantages	Downsides and Further Investigations	References
Almond oil cake	Functional ingredient	Fortified cookies	The oil cake was ground for 20 s to obtain a fine and homogeneous powder. The samples were stored in the dark at −20 °C until use.	The final cookies had a high nutritional profile as lower in fat (no lard) compared to commercial cookies, and higher in proteins, due to the oil cake addition.	As the oil cake still contains fats, an assessment regarding storage stability would add value to the research.	[74]

4. Hazelnut

Hazelnuts (*Corylus* spp.) are native to Europe, Asia, and continental America. The most cultivated species is *Corylus avellana*. The first findings date back to 9000 years ago and are proof of the ancient use and processing of hazelnuts and were mentioned in a Chinese manuscript dating back to 5000 BC, underlining the fact that they were already known and used. Moreover, these nuts were relevant in the Roman Empire, as reported by Virgil and as indicated by evidence found in Pompei [28,82,83]. The expansion of cultivated hazelnuts from the initial core probably occurred locally for Italy and the Balkan area, while it moved from southwestern France to other areas if we consider the results of some genetic analyses intersected with further historical and archaeological data [82]. Nowadays, hazelnut cultivation is mainly widespread in Eurasia and North Africa on the Mediterranean coast, and in Turkey, the world's leading production country (71%), followed by Italy (7%) [82,84].

Piedmont, in the northwest of Italy, is an area particularly suited to hazelnut cultivation. Traditional cultivation is managed through genetic selection in relation to the capability of adapting to the soil and climatic conditions and the use of plant protection products to protect the crop from diseases and insects that could threaten its development. Eventually, nuts respecting the market's requirements in terms of quantity and quality are obtained [85,86]. Nevertheless, besides the traditional production systems, the organic one is developed, characterised by higher education levels of producers, absence of synthetic fertilisers (replaced by manure) and plant protection products, and low input costs but high investments regarding labour and certification [87]. Some studies compared the two approaches to understand their economic performance, potentially identifying strengths and weaknesses to support producers' choices [87,88]. It transpires that, according to general organic agriculture and farming, as well as for hazelnuts, a premium selling price should be considered to cover all the costs that may be incurred during the productive phase [87].

The well-known hazelnut cultivars in Italy are enriched by European quality certifications. In detail, the cultivar Tonda Gentile Trilobata adopted in the Langhe area is renowned throughout the world thanks to the Protected Geographical Indication (PGI) certification of "Nocciola Piemonte". It has unique flavour and taste characteristics. Additionally, the Tonda Gentile Romana cultivar is recognised with Protected Denomination of Origin (PDO) certification and is traditionally grown in Latium. Another PGI cultivar is raised, the Tonda di Giffoni cv. The latter is a high-quality product particularly used in the food industry for its technological traits [85].

Hazelnut plant is a shrub, traditionally managed according to its original multi-stemmed bush shape, even if more recently the cultivation system as a small tree, with a single trunk, is expanding. This technique favours the mechanised management of the crop. Hazelnuts are harvested when mature, in late summer, depending on the cultivar, the weather, and the climate of the cultivation area. Mechanical harvest is possible in large and clean areas with a sort of vacuum machine drawing the hazelnuts that have fallen to the ground. An alternative possibility consists of using specific harvesters combining shaking the tree and vacuuming the nuts on the trees; this technique could cause some damage to the plant. Subsequently, a drying phase helps to achieve optimal quality for the commercialisation of the nuts and to enable long-term preservation [89,90].

Hazelnut fruit is an indehiscent fruit, composed of a hard wooden epicarp, the shell. Inside, the kernel, or seed, which is the main product with the highest value, is found, covered by the skin. Considering the nut at harvest, the husk could also be considered. Hazelnut is rich in phenolic compounds. It is peculiar to underline that the kernel, separated from the skin by a roasting process, is exceptionally abundant in dietary fibres, 11–14%, even compared to other nuts, such as almonds (9.3%) [91,92]. Once hazelnuts have been obtained, their fate is similar to that of almonds: the main uses include direct consumption (of both fresh and roasted seeds), confectionary preparations, and pastry and bakery productions. Furthermore, oil is extracted from hazelnuts, obtaining a refined and valuable product rich in unsaturated fatty acids. Oleic and linoleic acids, a certain level of vitamin E active compounds, and phytosterols are substances from hazelnuts with a reported positive effect on human health [93]. It is worth remembering that roasting is an essential stage of the process as it improves the flavour, the colour, and the texture of the nuts while removing the skin [94]. The majority of the hazelnuts sold and consumed have undergone the roasting process. Temperature, air flow velocity, and time are the most relevant parameters influencing the process and the final physico-chemical modifications taking place, such as Maillard reaction. This results in overall consumer favourability regarding brown, roasted-flavoured, and crunchy hazelnuts [95].

The increased economic importance linked to hazelnuts necessarily determines the need to dwell on the consequential production of waste and by-products. Remembering that the seed constitutes roughly half of the entire fruit, this need becomes even clearer.

The main waste consists of the shells. They have a lignocellulosic composition, a high calorific power, a quite homogeneous particle size, and low ash production, all reasons encouraging their use as biomass for biofuel. This is a particularly common reality in Italy where hazelnuts' shells are widely spread as a pellet substitute in biomass stoves [96]. The use of hazelnut by-products as biofuel and burning biomass is a diffused practice. Solid biomass pellets have also been produced from peanuts and hazelnut shells, resulting in a cheap way to reuse these matrices [97].

As with almonds, hazelnut waste has also been involved in pyrolysis procedures obtaining solid char together with liquid, aqueous (containing methanol, acetic acid, and acetone) and non-aqueous (a tar high in aromatic compounds), and gaseous fractions [98,99]. Hazelnut shells were also indicated as highly suitable for the production of activated carbons [100].

Another investigated application concerns the cuticle of hazelnuts as a functional feed. It was demonstrated that the replacement of corn with this by-product, in an amount of 150 g/kg of dry matter, influences meat colour and quality. In particular, the colour becomes brighter and more vivid, while the myofibrillar fragmentation index (MFI) (index of meat maturity and tenderness) increases, meaning higher sensory tenderness is reached more rapidly [101,102]. In addition, this dietary regime achieved positive outcomes in terms of delayed lipid oxidation of the meat, possibly due to the antioxidant power of the α-tocopherol present in the meat, in comparison to a control-fed group [103]. An effect on the rumen microbiota was also detected: in particular, the feeding regime enriched with hazelnut diet seemed to valorise the relative abundance of microorganisms positively correlated to vaccenic acid, an intermediate of the isomerisation process of linoleic acid to stearic acid, linked to health benefits for animals. On the other hand, the control diet was related to microorganisms positively correlated to the C18:1 t10 isomer, involved in some issues for animal performance and perhaps human health [104].

Hazelnut skins were also considered for dairy cows' nutrition. No negative effects were experienced regarding animal health. The most remarkable results showed an overall reduction in saturated fatty acids and an increase in monounsaturated fatty acids in milk from cows fed with hay and concentrate partly substituted with hazelnut skin. Also, the tocopherol content in milk was higher when compared to milk from the control group's cows. Moreover, feed efficiency may be improved by the addition of skins to dairy cows' diet [105].

Disposal of hazelnut by-products directly in field by burning them is not uncommon. This practice is environmentally impactful due to the derived air pollution and, at the same time, makes soil less fertile. A possible alternative might involve the direct use of these by-products as soil fertilisers [96]. Husk, derived from hazelnut harvest, may be used as compost or fertiliser. Its chemical composition and its degradation pathway make the product acceptable for the purpose [106]. Hazelnut shells and skin were used for the formulation of a compost too. The objective was to partially replace peat in nursery substrates for hazelnut plants. Research conducted demonstrated the suitability of these by-products for substrate production, with a replacing percentage to be analysed case by case according to the plant to be grown. Specifically, 20% of hazelnut by-product is the maximum amount that could be reached without influencing the plant growth [107].

From the perspective of the circular economy, an approach that places more value on hazelnut by-products would be an option for industry-wide growth towards sustainability. The following results are schematically summarised in Figure 4.

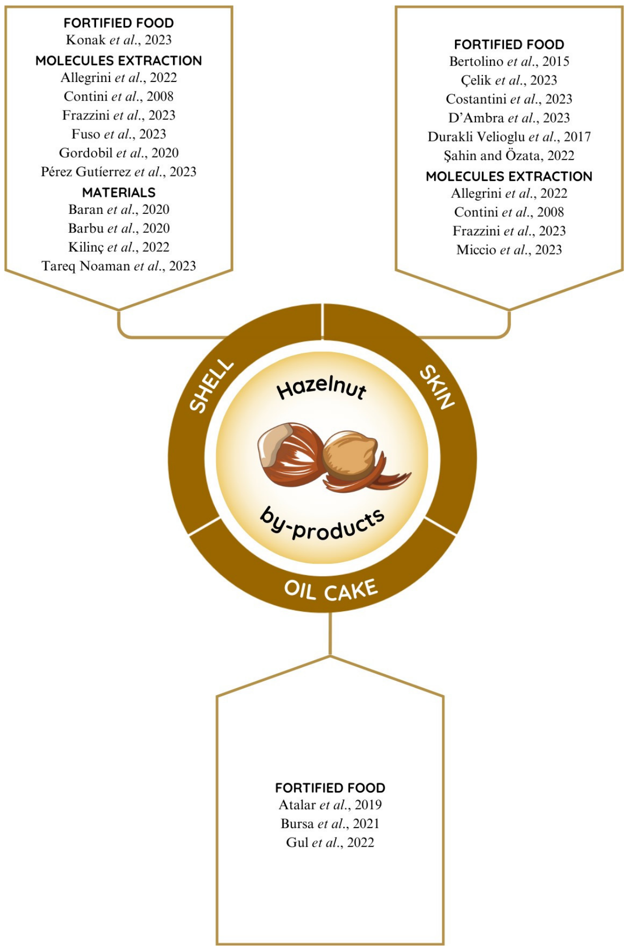

Figure 4. Hazelnut by-products and innovative applications described in the literature for each fraction. Shell (fortified food [108], molecules extraction [96,109–113], and materials [114–117]); skin (fortified food [118–123] and molecules extraction [96,109,110,124]); and oil cake (fortified food [125–127]).

4.1. Hazelnut Shell

As previously presented, hazelnut shells are the external envelope of hazelnut kernels and account for around 50% of the total fruit weight. Being a lignocellulosic material, the shell is mainly constituted by cellulose (15.4%), lignins (25.9%), and hemicellulose (22.4%), making up the majority of the fibre content of the shells. Phenolic compounds are also present in this fraction [96,111]. Phenolics could be exploited as valuable substances for possible effects on human health, including antioxidant, anti-inflammatory, and antimicrobial properties [96,109]. Wooden shells were macerated in three different aqueous solutions of methanol, ethanol, and acetone, respectively. The results showed an extraction rate of just under 3%, without any relation to the solvent used. High antioxidant activity was detected for the polyphenolic phase of the extracts [109]. In relation to fibre content, Fuso et al. [111] tested the use of a hydrothermal treatment performed at various temperatures to implement and optimise the extraction of these components from the shells. The results show that the highest extraction yield was obtained at 150 °C, followed by 175 °C, and it subsequently decreased at 200 °C. Moreover, different extraction temperatures also influenced the extraction profile in terms of monosaccharides, indicating that the highest amount of xylose derived from the 150 °C extraction. The possible utilisation of extracted fibre in the food, nutraceutical, and pharmaceutical industries may induce further experimentation on the topic.

In relation to medical, pharmaceutical, and cosmetic applications, it is worth presenting two innovative and bio-sustainable solutions to valorise hazelnut shells as sources of important bioactive compounds. Pérez Gutíerrez et al. [113] created an extract (ethanol 70%) from hazelnut shells to incorporate into patches favouring wound healing [113]. The action mechanism relies on the fact that antioxidant properties would reduce the pro-inflammatory activity favoured by oxidative stress. The patches were created according to the sustainable idea of exploiting natural ingredients in their preparations. Specifically, they were self-binding curative patches made of chitosan gels, reinforced by green clay. These two ingredients are already guaranteed for use in the pharmaceutical and cosmetics sectors. In addition to this, they are recognised as possessing certain antimicrobial and wound-active effects. The inclusion of hazelnut shells' extract enhanced these features, with significant action against *Staphylococcus aureus*, a bacterium involved in wound infections, and the ability to favour quick wound healing. These properties were experienced with a concentration of extract of 8.45 µg/mL. Antimicrobial activity was also observed for shell and cuticle extract against *Escherichia coli* O137 strain, probably because of their content of tannins and phenols [110].

The possible application of lignin, obtained from hazelnut shells in cosmetics, was investigated. Together with the expected antioxidant activity of the compounds, the lignins showed the capability of reducing the incidence of UVA mainly, combined with the entire UV spectrum, and presented sun protection qualities when mixed with commercially available cream samples. In spite of that, the sun protection factor was quantified as rather low (SPF 6.9) [112].

The literature also reports an example of reusing hazelnut shells in relation to the food industry. In this case, the perspective was to valorise the by-product by obtaining a functional snack. The snack designed contained teff flour, persimmon powder, almond beverage, carob flour, and quince seed mucilage, with the addition of hazelnut shell powder in the innovative formulation. The result was a product with significantly higher content of phenolic compounds and dietary fibre. The latter resulted in significant changes in the physical and sensory characteristics of the product: reduced water holding capacity and water solubility index, due to the insoluble fibre fraction, and decreased hardness in relation to the control recipe. Sensory evaluation of the panel resulted in a preference for the innovative formulation compared to the control snack, strengthening the feasibility of the functional snack [108].

Different studies highlighted the possibility to use hazelnut shells as reinforcing and composing ingredients in some materials [114–117].

One of the investigated applications was related to the possibility of replacing wood raw material in particleboards with nutshells, without affecting the mechanical and physical features. Considering hazelnut shells, the panels obtained showed reduced water adsorption capacity with respect to classic wooden panels. The mechanical properties were influenced by the type of adhesive used to bind the shells together. It is important to underline that the safety of these panels was assessed by the acceptable amount of formaldehyde contained ($\leq$2.5 mg/100 g) [115].

The solid and rigid behaviour of hazelnut shells makes it possible to think about a possible application as abrasive powder. This is the case studied by Kilinç et al. [116], where the granules obtained from hazelnut shells' waste were employed in abrasive blasting, a mechanical technique to remove a paint layer on wooden material. The changes highlighted in the material properties were the function of the blasting parameters, meaning the distance between the nozzle and the treated object, the nozzle diameter, the angle used for treating, the pressure employed, and, of course, according to the abrasive material utilised. Encouraging results concluded the possibility to effectively employ agricultural waste in industrial processes.

Hazelnut shells as reinforcing agents, as already observed for almond shells, were tested mixed together with cement. The obtained cement composite exhibited improved properties, in particular considering the compressive strength and hardness when added proportionally to the amount of ground shells used, probably due to interactions occurring among the particles (maximum enhancement at 2.5% of shells addition in weight) [117]. The same objective of strengthening cement by creating a mixture was considered using ash obtained from the traditional burning of hazelnut shells. Contrary to what was described by Tareq Noaman et al. [117], the different composition of the ash affected the compressive strength of the material in an inversely proportional manner: increasing the ash content over 5% in weight led to a decrease in the strength of the material. Cement blended with ash reduced the pose time significantly up to 96% of the time [114].

4.2. Hazelnut Skin

Skin or cuticle is the brown perisperm enveloping the seed, which becomes evident when the shell is broken. It is tightly attached to the hazelnut kernel and, as already discussed, requires roasting treatment to obtain the naked seed [96].

Thus, roasted cuticles are a by-product from hazelnut processing. Every year in Italy, approximately 3000 tons of this by-product are produced [121]. Possible valorisation could derive from the content of functional and bioactive compounds they contain [96,109,124]. Phenolic compounds can be extracted with an interesting yield exploiting water as a solvent and thus valorising the waste used as raw material [124]. Hazelnut cuticle extracts were also demonstrated to be effective against a specific *E. coli* strain [110].

Many literature studies exploited the functional role of hazelnut skin as a possible ingredient in food products, enriched via their active features (antioxidant activity, high content of unsaturated fatty acids, and high fibre content) and obtaining textural and flavour improvements and healthier products without negatively affecting the sensorial perceptions of the consumer. In this sense, the right proportion between hazelnut skin and other ingredients should be found to obtain the best mouth sensation [118,120–123].

Among the examples of functional food preparation, it is interesting to report the case of the production of pork burgers with the addition of 2.5% roasted hazelnut skin, reduced to a powder by grinding it to a size <500 μm. The addition of the novel ingredient led to a brown colour significantly darker than the usual pork products, a reduction in lipid oxidation, and overall appreciation by the panellists. Some negative effects were observed in terms of reduced tenderness due to the addition of a matrix rich in fibre, and slightly higher bitterness and astringent sensations, possibly linked to the increased tannin content.

Nonetheless, the product was highly appreciated, also thanks to observed improvement regarding odour and colour features [121].

Another instance of a functional product obtained with hazelnut skin regards the bakery sector. The objective pursued was to obtain products (bread, cookie, or cake) with high fibre content. The research study considered the production of fortified bakery products as achievable: the increase in hazelnut skin powder was proportional to the phenolic content of the products. Considering the overall aspect of the foods, the main difference was highlighted in the dark brown colour, a result that was also achieved regarding cookies by Costantini et al. In the case of the cookies, the fatty acids profile also changed, favouring the monounsaturated fraction as the butter amount was lowered thanks to the skins' fat content. Trans-fatty acids were detected, probably deriving from the hazelnut roasting process; this could be an issue that requires attention [120]. Cookies and cake did not experienced changes in appearance, while bread, as expected, showed a lower specific volume when increasing the hazelnut skin content and lowering the flour amount. From a sensorial point of view, the smell and taste were preferred for the novel products [122].

An opposite sensorial evaluation derived from the addition of roasted hazelnut skin powder (3% and 6%) to yoghurt. In this case, the increased dietary fibre amount was associated with less creamy and consistent products, thus impacting the overall acceptability. Considering the feasibility of the functional yoghurt, the addition of hazelnut skin results in an interesting increase in antioxidants and fibre content [118].

Chocolate spreads are another food category in which hazelnut skins were considered for partial replacement of cocoa. The results demonstrate the possibility to produce a chocolate spread cream with a reduced amount of cocoa powder replaced by hazelnut skin powder (15%, 30%, and 45%) and a higher quantity of phenolic substances. In this preparation, the fatty acid profile was highly dependent on the main fat employed rather than the presence of hazelnut by-product [123].

Hazelnut oil is a valuable product, aromatic and flavourful, obtained from both natural and roasted hazelnuts. In the latter case, the oil has higher stability. Hazelnut skin is a by-product abundant in fat, even more than the hazelnut kernel itself. For this reason, the possibility to transform it into raw material for oil extraction is an entirely interesting and reasonable idea. The fatty acid composition of the oil obtained from hazelnut cuticles approximately matches the composition of oils extracted from the seed, whether roasted or untreated, with some differences in ratios: the main fatty acids detected are oleic acid (40.13%), linoleic acid (20.64%), and palmitic acid (16.87%). Hazelnut skin oil is characterised by high antioxidant activity, linked to higher oxidative stability, also due to the low entropy value determined. These properties, if compared to hazelnut oils extracted from the seed, exhibit even higher rates, directing attention to the product [119].

4.3. Hazelnut Oil Cake

Analogously to what concerns almonds, the residue obtained from pressing hazelnuts to obtain oil is a defatted material with an interesting polyphenolic content for further use [40]. Generally, once hazelnuts have been pressed, the cakes are used for feed purposes. Nevertheless, attempts have been made to find more valorising uses to exploit the high phenolic content, thus achieving benefits for human health and economic advantages [126]. Financially favourable hazelnut products could partially replace sugar and milk in chocolate with a recovery matrix, with a view to sustainability and "zero waste", but also for a functional food with added values. The results from [126] defined the possibility to prepare a composite chocolate exploiting hazelnut oil cake. The sensory analysis conducted clarified that high levels of replacement cause some negative effects regarding taste, meaning reduced sweetness as masked by the bitterness of hazelnut cake, reduced odour, stronger foreign taste, and persistent sandy texture.

Another purpose to take advantage of spent hazelnut cake is the production of beverages [125,127]. Gul et al. [127] developed a yoghurt-like product starting from different percentages of hazelnut beverage obtained from hazelnut cake mixed with cow's milk. The product obtained has high nutritional value due to the phenolic compounds and the antioxidants from hazelnut. The novel food designed had higher viscosity compared to classic cow's milk yoghurt due to the higher water holding capacity. The best ratio tested was the one replacing 25% of cow's milk with hazelnut beverage according to the sensorial panel.

The innovative studies and results discussed and commented on for each hazelnut fraction are condensed in Table 2.

Table 2. Summary of innovations in hazelnut by-products management.

By-Product	Application	Final Product	Processing and Method Features	Advantages	Downsides and Further Investigations	References
Hazelnut shell	Functional ingredient	Functional snack	The hazelnut shells were reduced to powder through grinding and sieved (0.15 mm)	The final snack was rich in phenolic compounds and fibre compared to control prepared without hazelnut shell powder.	The snack formulation was very specific and particular. The incorporation of hazelnut shell powder in food should be considered also in other formulations.	[108]
	Molecules extraction	Antioxidant phenolic extracts from hazelnut shell and skin	Both shells and skins were milled and subsequently defatted using hexane. Long maceration (aqueous methanol, ethanol, and acetone) at room temperature (overnight and in the dark) was used for the extraction.	Valorisation of two by-products from hazelnut processing.	Pre-treatment with hexane is needed. The extraction still produces residuals. Further exploitation of the extracts was not suggested.	[109]
		Antioxidant extract from hazelnut shell and skin	The extraction was carried out through maceration in (aqueous acetone and ethanol) in an ultrasound bath and then centrifuged. No previous treatment of the waste was described.	The extract resulted in effectiveness against *E. coli* 137 strain; thus, it might help in overcoming antibiotic resistance issue.	The extraction still produces residuals, and the use of chemicals (acetone) is still needed.	[110]
		Hydrothermal treatment from fibre extraction	The hazelnut shells were ground and sieved. The powder obtained was added to water to perform the hydrothermal treatment in a reactor at different temperatures (125, 150, 175, and 200 °C).	The extraction using only water makes the product suitable and safe for further use.	High temperatures needed for the extraction, thus high energy consumption. Residuals are still produced after the extraction.	[111]

Table 2. *Cont.*

By-Product	Application	Final Product	Processing and Method Features	Advantages	Downsides and Further Investigations	References
Hazelnut shell	Molecules extraction	Lignins extraction	The shells were dried and milled (0.25–0.40 mm particles). The extraction was performed using aqueous ethanol treatment. An acidification step was carried out for the lignin precipitation. Filtration was needed to collect the lignins. Finally, they were rinsed until neutrality was reached and dried (50 °C).	The use of extracted lignins in cosmetics was investigated as sun screening agents.	The extraction still produces residuals, and the use of chemicals is still needed.	[112]
		Bioactive compounds extracts	Hazelnut shells were ground (particle size 500–1000 µm) and macerated in aqueous ethanol. Filtration with cellulose filter followed to collect the suspension enriched with bioactive molecules.	The addition of bioactive extracts in medical patches resulted in efficiency regarding favouring wound healing and inhibiting the growth of Staphylococcus aureus.	The preparation is complex, and residual waste from extraction is still present.	[113]
	Cement composites	Cement reinforced with hazelnut shell ash waste	Hazelnut shell ash waste (<0.150 mm) was added to cement in different percentages (5, 10, 15, 20, 25, and 30%) without any pre-treatment.	The addition of hazelnut shell ash has a positive effect in reducing the overall setting time of the cement.	The addition of ash lowers the resistance to compressive strength. Moreover, the use of ash means that the hazelnut shells were already burnt.	[114]
		Cement reinforced with shells	A fine powder was obtained via crushing, grinding, and ball milling the hazelnut shells.	The addition of shells improved the compressive strength and the hardness of the cement up to 2.5% addition.		[117]

Table 2. *Cont.*

By-Product	Application	Final Product	Processing and Method Features	Advantages	Downsides and Further Investigations	References
Hazelnut shell	Particleboards production	Hazelnut shells as lignocellulosic materials in particleboards	The shells were cleaned and shredded (8 mm). Then, they were dried. The particles were sieved to select those suitable for the process (middle size 3–6 mm and fine <3 mm). Melamine urea formaldehyde and polyurethane were used as binders to obtain the panels.	Better physical properties were highlighted for the particleboards with respect to classic wooden boards.	Further investigations may be necessary to test other adhesives and resins used.	[115]
	Abrasive powder	Abrasive blasting media for paint removal	Hazelnut shells selected as abrasive blasting media had a particle size between 200 µm and 400 µm.	A good paint removal effect from the aged wooden specimen was obtained.	Further research should focus on application of naturally aged samples as the specimens used in the study were specifically prepared in the laboratory.	[116]
Hazelnut skin	Functional ingredient	Fortified yoghurt	Hazelnut skin was milled and sieved to obtain 0.5 mm particles. The powder was stored at 4 °C until use.	Increased phenolics, antioxidants, and dietary fibre in the fortified yoghurt compared to control (without hazelnut skins).	Sensory profile was negatively affected.	[118]
		Fortified cookies	The skins were ground before being added in the cookie dough.	Higher unsaturated fatty acids compared to control (no hazelnut skin).	Presence of trans-fatty acids due to skin roasting. As also stated by the author, analyses regarding fibre and antioxidant content are lacking.	[120]

Table 2. *Cont.*

By-Product	Application	Final Product	Processing and Method Features	Advantages	Downsides and Further Investigations	References
Hazelnut skin	Functional ingredient	Fortified pork burgers	The skins were ground to 500 µm particles.	Higher fibre and polyunsaturated fatty acids compared to control. Reduced lipid oxidation was also verified	Bitterness, astringency, and lower tenderness were experienced from the sensory analysis.	[121]
		Fortified bread, cookies, and cake	Hazelnut skins came from roasting process. The authors did not make explicit reference to the grounding of the skins, but the preparation of bakery products is not able to leave this step out of consideration.	Cookies and cake fortified with hazelnut skins improved their sensory characteristics.	The colour, texture, and volume of the bread was obviously influenced by the hazelnut skins.	[122]
		Fortified cocoa hazelnut spread	Hazelnut skins were reduced to powder. Cocoa powder was partially replaced in the recipe with the hazelnut skin powder obtained (15%, 30%, and 45%).	The fortified product sensory profile was preferred by the panellists compared to control (0% hazelnut skin), and a higher amount of phenolics was verified.	The impact of the hazelnut skin addition on the fatty acid profile was not relevant.	[123]
	Food product	Oil extracted from hazelnut skin	Hazelnut skins were ground to obtain a powder. Extraction was performed using hexane as solvent.	High-quality oil with good fatty acid profile. Antioxidant activity and oxidative stability higher compared to oil extracted from hazelnut seed.	Extraction was performed using laboratory techniques and using impactful solvent (hexane).	[119]
	Molecules extraction	Bioactive compounds extracts	The hazelnut skin was collected already dried and no further processing. A Soxhlet extractor was used.	The solvents used in the research (water, ethanol, and limonene) study are considered "green".	The study is only focused on the laboratory scale.	[124]

Table 2. *Cont.*

By-Product	Application	Final Product	Processing and Method Features	Advantages	Downsides and Further Investigations	References
Hazelnut oil cake	Food product	Hazelnut beverage	Hazelnut oil cakes were ground to obtain a homogeneous powder. The preparation of the beverage started from the powder added with water. Thermosonication process was compared to the simple sterilisation thermal treatment.	Thermosonication provided better results in terms of structure compared to the simple heating process.		[125]
		Yoghurt-like product from hazelnut beverage	Hazelnut oil cakes were ground to obtain a homogeneous powder. The preparation of the beverage started from the powder added with water. After obtaining the beverage, the yoghurt was prepared (partially) replacing cow milk (1:0, 3:1, 2:1, 1:1, and 0:1 milk/hazelnut beverage ratios).	The product obtained has a high nutritional level thanks to the addition of hazelnut beverage (phenolics and antioxidants).	High level of cow milk substitution determines a negative sensory evaluation.	[127]
	Functional ingredient	Compound chocolate	Hazelnut cake was double ground to reach 200 µm particles so that it is not perceived in the final product.	Product with higher nutritional quality, with partial replacement of milk and sugar.	The sensory panel highlighted negative sensation in mouth and reduced sweetness and foreign taste in chocolate with high substitution levels. A sandy texture was also perceived.	[126]

5. Discussion and Conclusions

The sustainability of the processes, production, and materials listed in this review, regarding both almond and hazelnut by-products, must be considered in a comprehensive and integrated manner. This means that environmental and economic impact aspects must both be considered to create an overall balance regarding the circular economy approach. What clearly emerges in the literature analysed in this review is a strong positive view and dedication in the research activity towards the circular economy, enabling waste reduction and lowering consumption of natural resources that are becoming scarce, thus favouring the environment [128].

Environmental sustainability, reuse, and recycling perspectives need to be compared with the more traditional methods of waste disposal and its true cost effectiveness. In many cases, production processes require extensive use of energy, water, and chemical reagents in order to obtain materials suitable for end use. The best instrument that would enable these deductions to occur is life cycle assessment (LCA) [31,129]. This method helps in determining the environmental sustainability of a process or an entire production chain, considering the impact produced by every single stage. Boundaries for the system should be established, and the results will be valid only for the system referred to [129,130].

The same reasoning must be applied for economic management: the reagents and energy used for new production have costs that must be considered, in addition to the fact that new investments may be required in terms of the supply chain, logistics, facilities, and machinery. In this regard, it may be worth discussing local management, also to enhance the local economy and a short supply chain [131].

Combining the two points of view, it is good to establish how much actual economic benefit is derived from the new production and, at the same time, the actual environmental benefits. A circular economy approach promotes a zero-waste model in which residues and by-products are profitably re-introduced into the flow to obtain the output. This ideally fruitful concept needs to be adapted in practical cases, also meaning introducing specific manipulations or intermediate phases to adapt the former waste. Nevertheless, zero-cost product enhancement is certainly not possible from any perspective. The important theme is to establish, case by case, the convenience of applying a certain reuse or recycling protocol for the by-products in relation to their characteristics and their possible exploitation. In this context, it seems relevant today to assess the level of technological maturity (Technology Readiness Level or TRL) that reuse processes with the application of circular economy principles have reached after multiple experimental efforts [132]. Indeed, while it is possible to speak of high TRLs for some established processes (especially in the areas of energy and infrastructure), any other use related to the potential expressed in the food sector, particularly in terms of nutraceutical reinforcement, is not yet so widespread and developed on an industrial scale.

The possibility of reusing a by-product instead of managing its disposal can favour the producer and, at the same time, can support buyers who can employ the raw material as a cheap ingredient or component. Moreover, as thoroughly discussed, almond and hazelnut by-products can be exploited for multiple purposes, for their mechanical characteristics, thus as fillers or abrasives in strengthened materials, or as functional ingredients in food, feed, cosmetics, or pharmaceutics as they are still rich in bioactive compounds.

The possibility to obtain extracts rich in bioactive substances (phenolics, antioxidants, and lignins) is feasible if considering the research field but really complex to implement out of a laboratory: many chemicals and instruments are needed, thus affecting both economic and environmental sustainability, and waste is still produced. The processes involved require time and energy; it is important, even today, to consider that the valorisation of processing waste based on the extraction of bioactive substances is a process that can be credited to TRL 4 since it requires the adoption of tools and protocols that are only available in relation to specific in-laboratory scientific research activities. A significant step forward could be achieved precisely by increasing the TRL value with a shift to a higher level of maturity (TRL 5 or 6) regarding industrial interest and thus to wider validation on a production scale with broader benefits in terms of reuse or recovery.

Discussion may arise considering the feasibility of the process from both practical and economic points of view: cost reduction related to the reuse of a raw material already in the company's possession can be completely cancelled out by the further processing required, thus being incompatible in the light of a sustainable system. All these aspects lead to the conclusion that the highest priority for a sustainability-oriented system is reducing the overall impact of a product, also in accordance with the Sustainable Development Goals (SDGs) outlined and promoted by the United Nations [133].

It should be noted, finally, that this analysis still presents a limitation arising from the need to also consider the circular economy from a more specifically social perspective. Recent studies have highlighted the importance of the social component of sustainability in the systemic framework of circularity, especially in the field of agri-food products and the waste generated from their post-harvest production and processing. While on one hand circular economy approaches are often simplified by principles related to reducing resource use, reuse, and recycling, with a reduction in the use of often non-renewable resources, on the other hand, the use and recycling of resources raise a series of reflections on social equity concerning participation and inclusion regarding the benefits derived from circularity [134]. The transition towards a circular vision of reuse in the agri-food sector, including in the almond and hazelnut industries, has significant implications for the lives of farmers, processing workers, and consumers, and the possibility of achieving adequate sharing of commitments and benefits among all the stakeholders appears to be a further aspect worthy of in-depth exploration.

Specific focus should be directed towards the food sector, in which almond and hazelnut by-products are important. Fruits and vegetables are the main contributors to the total amount of food waste generated globally. A sustainable food chain should first be focused on a transdisciplinary approach to avoid producing waste and by-products, for example, introducing innovations to extend the shelf life of products (active and intelligent packaging and storage systems) and policies to stimulate companies towards a greener attitude [135]. When by-products cannot be avoided through careful process design, their valorisation could be put into practice. It is worth remembering that, if the reuse remains within the food industry, the production and commercialisation of a food product can in no way be separated from an adequate safety guarantee that it can be consumed without causing issues. Considering the topic of this review, nut allergies are among the main obstacles that can arise since childhood and cause severe issues, due as well to cross-reactions with other foods or allergens. Meanwhile, some problems can already arise during the field stages, such as development of aflatoxigenic fungi; the possible presence of harmful substances in the various fractions may also be the result of the treatments they undergo, such as acrylamide and polycyclic aromatic hydrocarbons in the roasted hazelnut cuticle [136–138].

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