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Potential applications of hazelnut industry waste based on material properties

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ABSTRACT

The agricultural industry generates tons of biomass worldwide each year which are denominated as agro-waste and can be considered one of the cheapest and easily renewable resources on the planet. Hazelnut shell and skin are among these agro-waste and their current uses are limited to boiler fuel, mulch or compost. This study is focused on the search for industrial applications that add value to hazelnut shells and skins, which enables its use it as a higher quality eco-material. For this purpose, physical and chemical characterization of the hazelnut by-products was done. Mechanical characterization was not possible due to the nature of the material itself. Once all the characteristics of the hazelnut skin and shell were collected, other materials with similar characteristics were identified through scientific literature. The identification of applications was made in two ways. On the one hand, thanks to the material characterization, applications based on material properties were identified. On the other hand, thanks to the identification of similar materials, applications based on applications of similar materials were found. The results obtained in this research demonstrate that the utilization of the proposed methodology is successful for the identification of potential applications or products to valorize the hazelnut shell and skin. The complete characterization and the research of applications allow a better understanding of the material and, consequently, a greater capacity to develop high-value applications.

1. Introduction

Hazelnuts are one of the world's leading nuts, according to FAOSTAT (2023) this nut is one of the most produced after almonds, cashews, walnuts, and chestnuts. Corylus avellana L. is the European hazelnut and it grows in many countries of Europe and Asia (Pérez-Armada et al., 2019). Turkey is the world's major producer, with 63 % of the total production. Other important contributions are made by Italy (8 % of production and 11 % of exports), United States (7 % of production and 8 % of exports), and Azerbaijan (6 % of production and 6 % of exports) (FAOSTAT, 2023; Renna et al., 2020).

Among the producing countries, Italy has the highest hazelnut consumption rate with 0.52 kg kernel/person. Hazelnuts can be consumed as such (Caccamo et al., 2019), but 90 % are intended for processing in chocolate, confectionery, pastry, as well as in the preparation of numerous liqueurs and foods. In-shell hazelnuts must be opened in order to be incorporated into the industrial food chain Puliga et al. (2022). One of the main downsides associated with hazelnut process is the generation of by-products originated from the hazelnut industry during the harvesting, shelling, and transformation processes. The hazelnut shell, the residual woody biomass resulting from the cracking process, represents approximately 50–55 % of the total nut weight (Fuso et al., 2021) and the hazelnut skin is the perisperm of the hazelnut kernel obtained from the roasting phase during the industrial processing, which corresponds to approximately 2.5 % of the kernel weight. The economic valorization of these by-products is attractive to the industry; however, only the hazelnut shells have direct commercial value as boiler fuel and mulch presently (Renna et al., 2020). High-added value ingredients can be obtained from the hazelnut shell, which are potentially very abundant, valuable, and cheap by-product (Fuso et al., 2021).

In recent decades, awareness and concern about environmental issues have increased (Puliga et al., 2022). The continuous development of modern society and technology, coupled with the rapid population growth (Chojnacka et al., 2020) have produced several environmental problems like the contamination of urban and industrial wastewater (Cimino et al., 2000), the destruction of ecosystems, climate change or

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the scarcity of natural resources (Barczewski et al., 2019; Caccamo et al., 2019). For this reason, interest in topics such as environmental sustainability and waste limitations has increased significantly (Fuso et al., 2021). The agricultural industry generates tons of biomass worldwide each year which are denominated as agro-waste (Gupta et al., 2022). More efficient usage of agricultural residues is very appealing to guarantee sustainable and cleaner production processes that are economically feasible, environmentally friendly, and socially advantageous (Santana-Méridas et al., 2012). Researchers are continuously striving to find new methods and strategies for valorizing agro-waste, because its use brings double benefits, on the one hand, it provides low-cost biodegradable raw materials, creates income, and generates employment and, on the other hand, avoids the damaging effects of untreated agricultural residues (Gupta et al., 2022). In the past few years, scientific investigation has largely centered on studying different forms of exploiting agricultural biomass, which includes hazelnut shell and skin. There have been used several techniques to handle agro-waste, like burning, biomass, unplanned disposal or composting. The inconvenient of these applications is that they do not generate high-value products and often entail problems of environmental impact and waste management. There are studies that offers data on the different parts of the hazelnut such as the husk to biomass and medium-density-fiberboards (MDF) production (Çöpür et al., 2008; Guney, 2013), the leaves to animal feed (Renna et al., 2020), the kernel to cosmetics and oils or the complete hazelnut for valuable resources (Guiné & Correia, 2020). Hazelnut shells have been characterized in several studies; however, this has rarely been done in a detailed manner. The skin, on the other hand, has been scarcely studied, so there is little data available on this material.

Global consciousness of environmental issues has led to the appearance of environmentally friendly and sustainable green materials based on recyclable, biodegradable, and renewable resources (Demirer et al., 2018). In 1991, the concept of eco-material was established to denote materials designed to diminish environmental impacts by considering their entire life cycle. The eco-material proposal included that each material should be manufactured with a lower environmental load and easily circulated (Manríquez-Altamirano et al., 2021). Recently, interest in eco-materials has increased due to the expansion of the sustainable product design strategy (Sierra Pérez, 2016), which seeks to replace non-renewable materials with natural or renewable ones. Eco-materials need to be studied and further developed, which would help to identify potential applications and design other products based on their properties. This approach aims to reduce the environmental impact of products (Sierra Pérez, 2016). New-age innovations allow this biomass to be used as a source of raw materials for numerous value-added products that feed the Circular Economy (CE) concept (Gupta et al., 2022). The CE is a model based on production and consumption, which encompasses sharing, renewing, repairing, reusing, and recycling existing products as much as possible (Gupta et al., 2022). As part of recycling, upcycling is one of the CE approaches to improve the quality, functionality or aesthetic value of a product or material (Manríquez-Altamirano et al., 2021). This strategy decreases waste and offers a sustainable alternative to current waste management practices (Gupta et al., 2022) and aims to promote changes in the functioning of the entire economic system, moving from linear to circular flows (Korhonen et al., 2018; Manríquez-Altamirano et al., 2021).

Hazelnut by-products have great potential for valorization, but the lack of data on the properties of this material hinders its use in innovative applications or even prevents it from being considered for the development of many others. For this reason, this study is focused on the search for industrial applications for hazelnut shells and skins, which are wastes generated during the cracking and processing of the product. Other objectives of this study are:

- Proper characterization of the material. This enables the full exploration of its maximum potential through a deeper understanding of its properties which permits to consider the most suitable option for its use.
- Identification of materials with similar characteristics. Thanks to material characterization, similar materials can be identified through scientific literature, which is a useful aid in discovering and analyzing the possible applications of hazelnut shell and skin.

2. Materials and methods

An adaptation of the methodology presented by Sierra-Pérez et al. (2016) and Manríquez-Altamirano et al. (2021) was used (Fig. 1). This methodology consists of three main steps. The first step consists of compiling information about the shell and the skin, for which a literature review is carried out and some experimental tests are performed. The second step is the material characterization, where a physical and chemical characterization of both the hazelnut skin and shell is conducted. Thanks to this characterization, an identification of materials with similar properties is also made. Finally, the last step consists of the identification of applications. On the one hand, based on the material properties, and on the other hand, based on similar materials applications.

The hazelnuts used in this research have been grown in the village of Ayerbe (Huesca, Spain) and are hand-picked hazelnuts from a local farmer, grown naturally without fertilizers or pesticides. The shells were obtained by splitting the hazelnuts and the skins were collected after boiling the kernels for three minutes in water to separate them.

2.1. Information compiling

For this study, a review of the body of knowledge of scientific literature was conducted to characterize the material and find applications. In order to gather a wide variety of literature related to the topic of interest, the following initial research questions were formulated to guide the exploration:

- What are the characteristics of hazelnut residues?
- What are the applications of hazelnut residues?
- Which materials are similar to hazelnut residues?

For the search of studies and reviews suitable for solving the questions posed, three online catalogs were used, such as Web of Science, Scopus and Google Scholar. The terms utilized as keywords were “hazelnut shell”, “hazelnut skin” or “hazelnut”. To answer the first question, the terms that were used to refine the search were “physical properties”, “chemical properties”, “mechanical properties”, “characterization”, “CHNS analysis”, “elemental analysis”, “immediate analysis". The terms employed to refine the search for applications started in a general way and became more detailed according to the results found in previous papers. Thus, some of the keywords that were applied were “applications”, “valorization”, “products”, “fiberboards”, “composite”, “animal feed”, “removal of dyes”, “removal of toxic”, “construction”, “energy”, “biofuel”, “substrate” or “fertilizer”. Finally, to find similar materials and other applications of these materials or other hazelnut by-products, terms like “hazelnut waste”, “agricultural biomass”, “hazelnut by-products”, “nut residues”, “walnut shell”, “almond shell” or “biomass applications” were used. Afterward, the citations referenced in the articles were revised to identify relevant information to this investigation. The review of scientific literature was completed over four months.

Using the keywords described, around 120 valid articles were identified. Other articles were examined, but after reading their abstracts or searching for specific properties of hazelnut shell and skin, they were discarded due to be irrelevant to the investigation.

In this way, a lot of data on the properties and applications of hazelnut residues were collected in a clear and orderly manner. Thanks to this exhaustive search, most of the similar materials appeared almost alone during the review. Lastly, for the search of applications of the

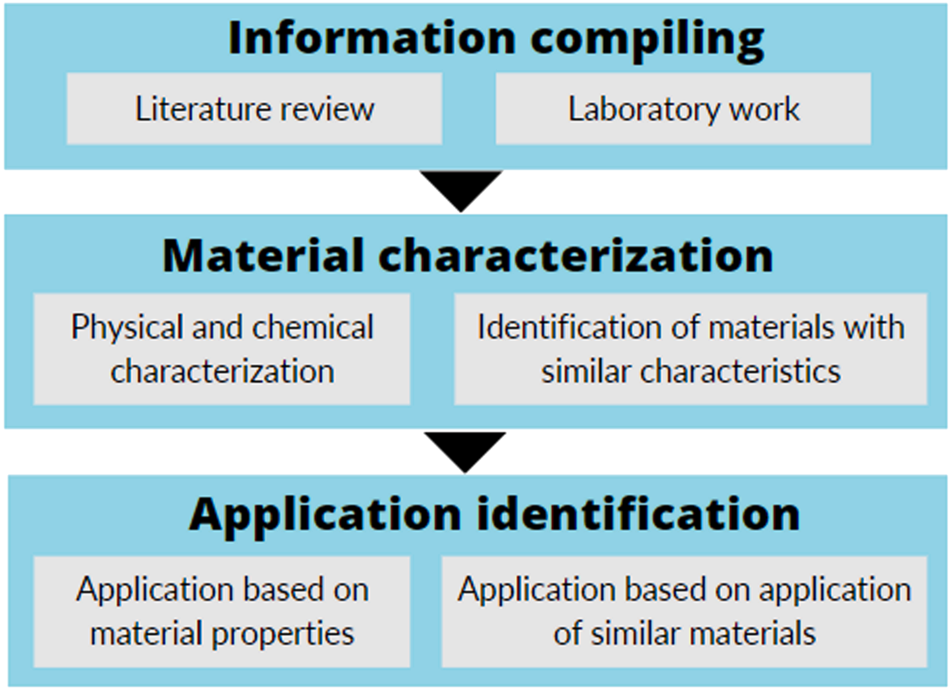


Fig. 1. Methodology followed in this study- adapted from Manríquez-Altamirano et al. (2021); Sierra-Pérez et al. (2016).

similar materials, simpler research was made, with the intention of obtaining a general idea.

2.2. Material characterization

Material characterization was made by literature review and some specific characteristics of hazelnut shells and skins were obtained by experimental tests. For this, the hazelnuts were cracked manually to separate the shell and then, to obtain the skin, the kernels were boiled for three minutes in water and peeled manually.

A physical characterization of hazelnut shell and skin was made by literature and experimental tests. The tests were done for representative samples of hazelnut shell and skin, and for some of the tests, it was necessary to dry the samples in a drying oven.

The degradation in soil tests were performed on fresh and dry samples of hazelnut shell and skin for 9 months. A sample of 10 *g* of fresh hazelnut shells are put and mixed with 81 *g* of universal substrate in a container (3 *g*). The sample of fresh hazelnut skins weighed 0.33 *g* and are put and mixed with 44 *g* of universal substrate in a container (3 *g*). The tests are reviewed to verify the total weight (balance: $e = 0.01$ g $d = 0.001$ g) of each container at interval of 15 days for the first month and after, each month. The same procedure is followed to the dry samples. Sample of dried hazelnut shells (dried at 105 °C for 24 h in an oven) of 6 *g* are put and mixed with 44 *g* of universal substrate in a container (4 *g*). A sample of 0.31 *g* of dried hazelnut skins (dried at 50 °C for 24 h in an oven) are put and mixed with 40 *g* of universal substrate in a container (2.4 *g*). Outdoor degradation test is performed in dry samples of hazelnut shell and skin, which are placed in the exterior, in a shady, south-facing location for 12 months. Sample of dried hazelnut shells (dried at 105 °C for 24 h in an oven) of 8 *g* is placed in a container (10 *g*). A sample of 0.31 *g* of dried hazelnut skins (dried at 50 °C for 24 h in an oven) are placed in a container (10 *g*). They are weighted (balance: $e = 0.01$ g $d = 0.001$ g) and reviewed every month. For more information see *Supplementary Material*.

The skin weight is calculated based on the equation of Renna et al. (2020). The weight of the kernel is calculated by measuring the mass of a representative sample of 20 hazelnut kernels under normal conditions (20 °C and 1 atm) in a balance ($e = 0.01$ g $d = 0.001$ g) and averaging the mass obtained.

$$Mass_{skin} = 2.5\%\ Mass_{kernel}$$

The porosity is calculated according to the equation presented by Selvi et al. (2020).

$$Porosity = 1 - \frac{Density_{bulk}}{Density_{true}} \tag{1}$$

Chemical characterization was performed based on the scientific literature for hazelnut shell, and due to the little information found on literature for the hazelnut skin, an elemental and immediate analysis was conducted. These tests were performed by an external laboratory to obtain elemental composition, moisture, ash, fixed carbon and volatile matter of the hazelnut skin. Moisture content determination was done in an oven with a controlled temperature of 107 °C following UNE-EN ISO 18,134:2016 Standard. The content of ash determination was carried out in a muffle with a controlled temperature ramp-up to final temperature of 550 °C, following the UNE-EN ISO 18,122:2016 Standard. Volatile matter determination was done in a muffle with a controlled temperature of 900 °C following the UNE-EN ISO 18,123:2016 Standard. The determination of the Elemental Analysis (C, H, N, and S) was conducted in the LECO 628 Serie equipment following the UNE-EN ISO 16,948:2015 Standard. The oxygen was determined based on the next equation (Licursi et al., 2017; Solís et al., 2023):

$$O\ [\%] = 100 - (C + H + N + S) \tag{2}$$

Mechanical characterization of hazelnut shell and skin could not be carried out due to the nature of the material since it was not possible to perform the relevant tests. For this reason, in scientific literature it was only found information on the mechanical properties of the whole hazelnut or of the kernel (Bonisoli et al., 2015; Delprete & Sesana, 2014; Selvi et al., 2020).

Identification of similar materials was conducted by literature review and was done in parallel to the material characterization, as many similar materials appeared during the revision of literature for the characterization of hazelnut by-products. In addition, the search for applications based on the properties of hazelnut shell and skin also provided other similar materials.

The aim of identifying similar materials is to broaden the search for possible applications for hazelnut residues, permitting to consider applications that are not contemplated or not known for hazelnuts.

2.3. Application identification

The application identification has been done through scientific literature by two ways; on the one hand, thanks to the material characterization, applications based on material properties were identified. On the other hand, thanks to the identification of similar materials, other applications based on applications of similar materials were found. This strategy allows to identify a large number of high-quality and very varied applications, having a clear understanding of the main characteristics required of the eco-material and other possible materials suitable for those applications.

3. Results

3.1. Material characterization

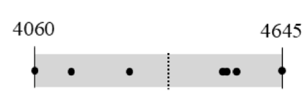
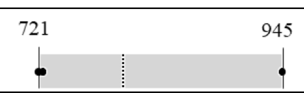
Tables 1–4 show the average results obtained for the physical and chemical characterization of hazelnut shell and skin by scientific literature review and experimental tests. The graphical representation shows the distribution of all the values taken, indicating with a cross our own results. In addition, the mean is indicated by the dashed line.

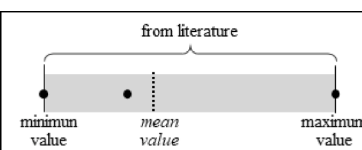
3.1.1. Physical characterization

The average results gathered from literature and experimental tests

Table 1

Results of the physical characterization of the hazelnut shell. (References (Demirbas, 1999; Dogru et al., 2002; Bonisoli et al., 2015; Delprete & Sesana, 2014; Demirbas, 1999; Dogru et al., 2002; Selvi et al., 2020; Aydinli & Caglar, 2012; Demirbas, 1999; Demirkaya et al., 2019; Gozaydin & Yuksel, 2017; Hoşgün & Bozan, 2020; Midilli et al., 2000; Şenol, 2019; Uzuner & Cekmecelioglu, 2014; Yuan et al., 2018; Aydinli & Caglar, 2012; Cimino et al., 2000; Demirbas, 1999; Demirkaya et al., 2019; Dogru et al., 2002; Gozaydin & Yuksel, 2017; Hoşgün et al., 2017; Hoşgün & Bozan, 2020; Karatas et al., 2013; Licursi et al., 2017; Mattonai et al., 2017; Midilli et al., 2000; Pehlivan et al., 2009; Rivas et al., 2020; Surek & Buyukkileci, 2017; Uzuner et al., 2018; Uzuner & Cekmecelioglu, 2014; Wang et al., 2018; Yuan et al., 2018; Aydinli & Caglar, 2012; Demirbas, 1999; Dogru et al., 2002; Ferrero, 2007; Karatas et al., 2013; Licursi et al., 2017; Midilli et al., 2000; Bonisoli et al., 2015; Delprete & Sesana, 2014; Dogru et al., 2002;) is cited in Table body part).

Physical characterization - Hazelnut shell		
Property	**Value**	**Reference**
Mass [g]	**1.15**	**Obtained value**
Degradation in soil [months]	**8**	**Obtained values**
Outdoor degradation [months]	**11**	**Obtained values**
Bulk density [kg/m^3]	320	(Demirbas, 1999; Dogru et al., 2002)
Porosity	0.599	(Bonisoli et al., 2015; Delprete & Sesana, 2014; Demirbas, 1999; Dogru et al., 2002; Selvi et al., 2020)
Moisture [%]		(Aydinli & Caglar, 2012; Demirbas, 1999; Demirkaya et al., 2019; Gozaydin & Yuksel, 2017; Hoşgün & Bozan, 2020; Midilli et al., 2000; Şenol, 2019; Uzuner & Cekmecelioglu, 2014; Yuan et al., 2018)
Ash [%]		(Aydinli & Caglar, 2012; Cimino et al., 2000; Demirbas, 1999; Demirkaya et al., 2019; Dogru et al., 2002; Gozaydin & Yuksel, 2017; Hoşgün et al., 2017; Hoşgün & Bozan, 2020; Karatas et al., 2013; Licursi et al., 2017; Mattonai et al., 2017; Midilli et al., 2000; Pehlivan et al., 2009; Rivas et al., 2020; Surek & Buyukkileci, 2017; Uzuner et al., 2018; Uzuner & Cekmecelioglu, 2014; Wang et al., 2018; Yuan et al., 2018)
Heat of combustion [kcal/kg]		(Aydinli & Caglar, 2012; Demirbas, 1999; Dogru et al., 2002; Ferrero, 2007; Karatas et al., 2013; Licursi et al., 2017; Midilli et al., 2000)
Absolute density [kg/m^3]		(Bonisoli et al., 2015; Delprete & Sesana, 2014; Dogru et al., 2002)

Legend 

show (Table 1) that the moisture content of the hazelnut shell is around 8.94 %, the ash content 1.79 % and the heat of combustion between 4375 kcal/kg. The weight of the hazelnut shell is 1.15 g, the bulk density has a value of 320 kg/m^3, the average absolute density is around 833 kg/m^3 and the porosity shows a result of 0.599.

The results obtained from literature and experimental tests for the hazelnut skin Table 2 show that the moisture content is 13.88 %, similar to the average results of 10.43 % obtained by scientific literature, and the ash content is 4.08 %, slightly higher than the 2.47 % average reported in the literature. These differences could be due to the different varieties used in the studies. We have utilized Spanish hazelnuts while other authors utilized Turkish or Italian hazelnuts and as a consequence of the difference in the growing environment, the varieties and characteristics of the hazelnut produced in each region are not the same (Zhao et al., 2023). The weight of the skin has a value of 0.028 g.

3.1.2. Chemical characterization

The average results gathered from literature (Table 3) show that cellulose content is 26.96 %, the hemicellulose content is 22.5 % and the lignin content is 43.04 %. The average values of fixed carbon and volatile matter are 23.37 % and 73.85 %, respectively. The average results from the elemental analysis show that carbon content (C) is 49.98 %, hydrogen content (H) is 5.69 %, nitrogen content (N) is 0.6 % and oxygen content (O) is 42.84 %.

The results obtained from literature and experimental tests for the hazelnut skin Table 4 show that the averages contents of cellulose, hemicellulose and lignin are 11.16 %, 3.74 % and 39.34 %, respectively. The proximate analysis show that the fixed carbon content is 24.9 % and the volatile matter 57.2 %. The elemental analysis show that carbon content (C) is 44.57 %, hydrogen content (H) is 6.07 %, nitrogen content (N) is 1.6 %, sulfur content (S) is 0.12 % and oxygen content (O) is 47.64 %, while (Oliva et al., 2021) reported 59.72 % C, 6.38 % H, 0.98 % N, 0.1 % S and 32.82 % O. These differences in the results of the elemental analysis could be due to the difference in the variety of hazelnut utilized (Zhao et al., 2023) and due to small differences in the analysis itself, such as the machine used or the standard followed.

3.1.3. Mechanical characterization

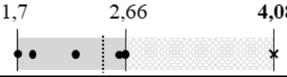
The mechanical characterization of the hazelnut shell and hazelnut skin have not been possible due to the nature of the material since they are bulk materials. For this reason, mechanical tests could not be performed, and the information found in scientific literature it is almost nonexistent. The little information available corresponds to the literature to develop cracking machinery (Bonisoli et al., 2015; Delprete & Sesana, 2014; Güner et al., 2003), where there are some results of mechanical properties of the whole hazelnut and kernel.

3.2. Application identification

Tables 5 *and* 6 show the results of the applications identified by the two pathways. In both cases, hazelnut shell obtained more results of possible applications. Table 5 presents the applications identified based on material properties, alluding to the important characteristics to take into account. The ash content is important for applications like biosorbent, fertilizer, biogas or construction. Moreover, phenolic compounds and chemical composition are relevant for the applications of animal feed, bioactive compounds, fertilizer or composites. The hazelnut shell is a lignocellulosic material, so some related applications to this characteristic appeared, such as fiberboards, substrate or renewable fuels. The high heat of combustion makes this agro-waste suitable for energy production applications, like biogas o different types of renewable fuels (pellets, bio-oil, biochar). One of the properties that should be considered for almost all applications is the moisture content, since in some cases it would be necessary to dry the hazelnut by-products and in others it would be significant for the correct development of the application.

Table 6 shows the applications found based on application of similar materials. Many similar materials appeared during the literature review searching for hazelnut shell and skin properties and in the subsequent search for applications. Similar materials found also correspond to agricultural residues, such as the shells and skins of many nuts, the stone of some fruits, the straw of some cereals or the stalk of some plants like cotton or sugarcane. Some uses of these materials had also been identified for hazelnut by-products; however new potential applications were uncovered, highlighting new ones such as packaging, tableware, insulation or adhesives.

Table 2
Results of the physical characterization of the hazelnut skin. (References (Bonisoli et al., 2015; Delprete & Sesana, 2014; Anil, 2007; Ivanović et al., 2020;Özdemir et al., 2014; Anil, 2007; Ivanović et al., 2020; Oliva et al., 2022b; Özdemir et al., 2014; Tunçil, 2020) is cited in Table body part).

Physical characterization - Hazelnut skin			
Property	**Obtained values**	**Value**	**Reference**
Mass [g]	**0.0285**	0.028	(Bonisoli et al., 2015; Delprete & Sesana, 2014)
Degradation in soil [months]	**6**	N/A	N/A
Outdoor degradation [months]	**7**	N/A	
Moisture [%]		7,4 11,86 **13,88** 	(Anil, 2007; Ivanović et al., 2020; Özdemir et al., 2014)
Ash [%]		1,7 2,66 **4,08** 	(Anil, 2007; Ivanović et al., 2020; Oliva et al., 2022b; Özdemir et al., 2014; Tunçil, 2020)

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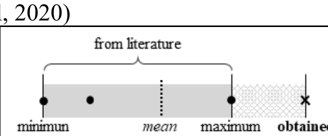
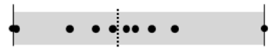
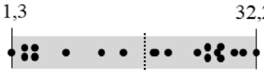
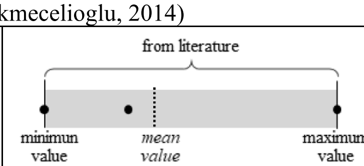


Table 3
Results of the chemical characterization of the hazelnut shell. (References (Aydinli & Caglar, 2012; Cimino et al., 2000; Demirbas, 1999; Dogru et al., 2002; Gozaydin & Yuksel, 2017; Karatas et al., 2013; Licursi et al., 2017; Midilli et al., 2000; Solís et al., 2023; Aydinli & Caglar, 2012; Demirbas, 1999; Dogru et al., 2002; Karatas et al., 2013; Midilli et al., 2000; Solís et al., 2023; Arslan et al., 2012; Aydinli & Caglar, 2012; Cimino et al., 2000; Cruz-Lopes et al., 2012; Demirbas, 1999; Demirkaya et al., 2019; Gozaydin & Yuksel, 2017; Hoşgün & Bozan, 2020; Licursi et al., 2017; Mattonai et al., 2017; Midilli et al., 2000; Pehlivan et al., 2009; Pérez-Armada et al., 2019; Rivas et al., 2020; Şenol, 2019; Surek & Buyukkileci, 2017; Uzuner et al., 2018; Uzuner & Cekmecelioglu, 2014) is cited in Table body part).

Chemical characterization - Hazelnut shell		
Property	**Value**	**Reference**
C [%]	46,76 – 55,48 	(Aydinli & Caglar, 2012; Cimino et al., 2000; Demirbas, 1999; Dogru et al., 2002; Gozaydin & Yuksel, 2017; Karatas et al., 2013; Licursi et al., 2017; Midilli et al., 2000; Solís et al., 2023)
H [%]	4,92 – 6,76 	
N [%]	0,2 – 1,4 	
O [%]	36,45 – 45,83 	
Fixed carbon [%]	19,43 – 27,6 	(Aydinli & Caglar, 2012; Demirbas, 1999; Dogru et al., 2002; Karatas et al., 2013; Midilli et al., 2000; Solís et al., 2023)
Volatile matter [%]	62,4 – 79,22 	
Cellulose [%]	16,67 – 42,6 	(Arslan et al., 2012; Aydinli & Caglar, 2012; Cimino et al., 2000; Cruz-Lopes et al., 2012; Demirbas, 1999; Demirkaya et al., 2019; Gozaydin & Yuksel, 2017; Hoşgün & Bozan, 2020; Licursi et al., 2017; Mattonai et al., 2017; Midilli et al., 2000; Pehlivan et al., 2009; Pérez-Armada et al., 2019; Rivas et al., 2020; Şenol, 2019; Surek & Buyukkileci, 2017; Uzuner et al., 2018; Uzuner & Cekmecelioglu, 2014)
Hemicellulose [%]	11,3 – 32,28 	
Lignin [%]	30,2 – 51,3 	

Legend


4. Discussion

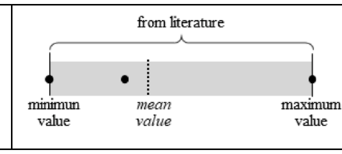
Other studies consider the use of hazelnut residues; however, most focus on low-value applications. It is not yet widely contemplated that hazelnut waste, such as shell and skin, could be used for a variety of value-adding applications.

The main objective of the promotion and valorization of hazelnut shell and skin is to recognize this biomass as natural, biodegradable, and abundant material with numerous potential applications. After the literature review, many possible applications were found but, nowadays, hazelnut shells are only used for energy production, compost or mulch; the skin has an even lower valorization, being only used as an ingredient in other foods or directly discarded. Certain applications, such as packaging or tableware, currently exhibit low economic viability; others, such as insulation or paperboard are still in experimental stages, so their feasibility still needs to be improved and other applications, such as biosorbents or bioactive compounds, need to be more scalable in order to be able to replace their traditional competitors. Nevertheless, different sectors such as construction, water treatment, agribusiness, animal feed, energy production or bio-composites can utilize these agricultural wastes as a high-quality eco-material and add value to these residues. After Turkey, Italy is the next leading producer and one of the major importers of hazelnuts, as it is the world's largest consumer. This is due to its great chocolate industries, which utilize tons of hazelnuts every year, however, they must be cracked and peeled. Hazelnut by-products have the capacity to generate the development of the rural world, improving different steps of the supply chain and encouraging the installation of companies that process the hazelnuts. Applications like the production of fiberboards or building materials require jobs, which leads to the creation of employment in rural areas. The integration of manufacturing factories in these regions allows them to obtain the maximum benefit, since they get income from the products they

Table 4
Results of the chemical characterization of the hazelnut skin. (References (Oliva et al., 2021; Mancini et al., 2018; Oliva et al., 2021; 2022a; 2022b; Tunçil, 2020) is cited in Table body part).

Chemical characterization - Hazelnut skin			
Property	**Obtained values**	**Value**	**Reference**
C [%]	**44.57**	59.72	(Oliva et al., 2021)
H [%]	**6.07**	6.38	
N [%]	**1.6**	0.98	
S [%]	**0.12**	0.1	
O [%]	**47.64**	32.82	
Fixed carbon [%]	**24.9**	N/A	N/A
Volatile matter [%]	**57.2**	N/A	
Cellulose [%]	N/A	10,1 – 13,9	(Mancini et al., 2018; Oliva et al., 2021, 2022a, 2022b; Tunçil, 2020)
Hemicellulose [%]	N/A	2,1 – 5,9	
Lignin [%]	N/A	34,4 – 44,2	

Legend



generate and, in turn, indirectly through the possibility of export-import of the hazelnut itself with other links in the chain.

According to the existing body of knowledge, this study follows the methodology proposed for the characterization and valorization of agro-waste, applying and adapting it specifically for hazelnut shell and skin. In contrast to the traditional use of biomass, this study focused on finding applications that add value to agricultural residues which enables its use it as a higher quality eco-material. Thereby, the reduction of untreated biomass is performed and the dependence on certain materials is decreased as well, helping to improve some environmental problems like the scarcity of natural resources or climate change.

In addition, this research provided information on the physical and chemical characterization of the hazelnut shell and skin that could be helpful for other research lines. Mechanical characterization was not possible due to the nature of the material itself, however, some data on stiffness, breaking strength, deformation or elastic modules were found for the kernel or whole hazelnut (Bonisoli et al., 2015; Delprete & Sesana, 2014; Selvi et al., 2020). Some studies offer data on the different parts of the hazelnut such as the husk to biomass and MDF production (Çöpür et al., 2008; Guney, 2013), the leaves to animal feed (Renna et al., 2020), the kernel to cosmetics and oils or the complete hazelnut for valuable resources (Guiné & Correia, 2020). Even though there are studies that provide data in particular of the hazelnut shell and skin, these have different perspectives, for example, the production of animal feed or fertilizer (Chojnacka et al., 2020; Renna et al., 2020), the adsorption of heavy metals and dyes (Cimino et al., 2000; Ferrero, 2007), the production of natural colorant (Özdemir et al., 2014),the development of cracking machinery (Bonisoli et al., 2015), to produce hydrogen, ethanol or renewable fuels (Hoşgün et al., 2017; Midilli et al., 2000; Solís et al., 2023). Some studies focus on the production of phenolic compounds and activated natural ingredients from shell and skin, which are considered renewable additives for biofuels production (Anil, 2007; Contini et al., 2012; Pérez-Armada et al., 2019; Rivas et al., 2020; Zeppa et al., 2015). There are some studies where hazelnut shell is used, mixed with other materials in different proportions, to produce fiberboards and composites (Barczewski et al., 2019; Çöpür et al., 2008).

The agricultural industry generates tons of biomass worldwide each year which can be considered one of the cheapest and easily renewable resources on the planet. More efficient usage of agricultural residues is very appealing to guarantee sustainable and cleaner production processes that are environmentally friendly and economically viable (Santana-Méridas et al., 2012). Researchers are continuously attempting to find new methods and strategies for valorizing agro-waste, because its use brings benefits such as providing low-cost biodegradable raw material, generating employment, or avoiding the harmful effects of untreated agricultural residues.

5. Conclusions

The large amounts of agricultural biomass generated each year can end up being a problem for the environment if they are not managed correctly. Hazelnut shell and skin are one of these agro-waste and currently the only use they are receiving is as boiler fuel, mulch or compost. The material characterization was challenging due to the non-standardization of the experimental test, since these tests only contemplate materials from which normalized samples can be obtained, so this characterization can be helpful for other research lines. Thanks to its physical and chemical characterization, the good properties of hazelnut shell and skin make this raw material suitable for many applications and high-value products. According to its properties, some similar materials and applications were found; and, thanks to that similar materials, other applications were identified.

The principal objective of the valorization of hazelnut shell and skin is the encouragement of the use of agro-waste as natural, biodegradable, abundant and inexpensive material that can be utilized for multiple products and applications. As it has been seen, these hazelnut residues

Table 5
Application based on material properties.

Application	Part	Properties	Reference
Animal feed	Shell and skin	Phenolic compounds, chemical composition, dry matter, ash, lignin	(Caccamo et al., 2019; Campione et al., 2020; Centikaya & Kuleyin, 2016; Renna et al., 2020; Salami et al., 2019)
Fiberboards	Shell	Cellulose, hemicellulose, lignin, ash, moisture	(Çöpür et al., 2008; Cruz-Lopes et al., 2012; Pirayesh et al., 2012)
Composites	Shell and skin	Chemical composition, moisture, density, cellulose, hemicellulose, lignin	(Balart et al., 2018; Barbu et al., 2020; Barczewski et al., 2019; Battegazzore et al., 2014; Demirer et al., 2018; Guiné & Correia, 2020)
Bioactive compounds	Shell and skin	Cellulose, hemicellulose, lignin, ash, moisture, chemical composition	(Anil, 2007; Arslan et al., 2012; Aydinli & Caglar, 2012; Di Michele et al., 2021; Fuso et al., 2021; Gozaydin & Yuksel, 2017; Özdemir et al., 2014; Pérez-Armada et al., 2019; Rivas et al., 2020; Santana-Méridas et al., 2012; Surek & Buyukkileci, 2017)
Biosorbent	Shell and skin	Ash, chemical composition, cellulose, lignin, density, hemicellulose, moisture, pH, porosity, heat of combustion	(Bharathi & Ramesh, 2013; Cimino et al., 2000; Ferrero, 2007; Kazemipour et al., 2008; Pehlivan et al., 2009)
Substrate	Shell	Lignin, hemicellulose, cellulose	(Özçelik & Pekşen, 2007; Puliga et al., 2022)
Fertilizer	Shell and skin	Cellulose, hemicellulose, lignin, ash, moisture, chemical composition	(Chojnacka et al., 2020)
Renewable fuels	Shell	Cellulose, hemicellulose, lignin, ash, moisture, chemical composition, heat of combustion, organic matter, fixed carbon	(Ceylan & Topçu, 2014; Chojnacka et al., 2020; Demirbas, 1999; Demirkaya et al., 2019; Figen Antmen, 2019; Guney, 2013; Hoşgün et al., 2017; Licursi et al., 2017; López et al., 2020; Montenegro Camacho et al., 2016; Solís et al., 2023; Uzuner & Cekmecelioglu, 2014)
Biogas	Shell	Ash, volatile matter, fixed carbon, pH, moisture, density, chemical composition, heat of combustion, cellulose, lignin, hemicellulose	(Chojnacka et al., 2020; Dogru et al., 2002; Karatas et al., 2013; Midilli et al., 2000; Montenegro Camacho et al., 2016; Ş enol, 2019)
Construction	Shell	Density, water absorption, chemical composition, mechanical properties, conductivity, ash	(Baran et al., 2020; Jannat et al., 2021; Sathiparan & De Zoysa, 2018)

have a great potential for diverse sectors, such as energy production, bio-composites, water treatment, construction, biochar production for removal or simply, as an ingredient for the preparation of different animal and human foodstuffs.

The results obtained in this study demonstrate that the proposed methodology is successful for the identification of potential applications to valorize the hazelnut shell and skin. The complete characterization of the material could be helpful for other research lines and the applications found add value to these agricultural residues which allows to use it as a higher quality eco-material. Consequently, the better understanding of the hazelnut shell and skin provides a greater capacity to develop high-value products if future research.

Table 6
Application based on application of similar materials.

Application	Part	Similar material	Reference
Composites	Shell and skin	Rice husk, cotton stalk, sugarcane, walnut shell, peanut shell, sunflower stalk, coconut shell, almond shell and skin, pistachio shell, chestnut shell	(Alsaadi et al., 2018; B. Zhou et al., 2020; Barczewski et al., 2019; Essabir et al., 2013; Kaymakci & Ayrilmis, 2014; Loh et al., 2013; Sarki et al., 2011; Yang et al., 2003; Zaaba & Ismail, 2019)
Packaging	Shell	Rice husk, coconut shell, chestnut shell	(Arun et al., 2022; Elhussieny et al., 2020; Esposito et al., 2020)
Natural colorant	Skin and shell	Almond shell, cashew shell	(Erdem Işmal et al., 2014; Sharma et al., 2020)
Insulation	Shell	Cotton stalk, sunflower stalk, date pit, apricot stone	(Al Marri et al., 2021; Binici et al., 2013; Gadea Borrell et al., 2020; X. yan Zhou et al., 2010)
Building material (bricks, cement,)	Shell and skin	Sawdust, cotton stalk, sugarcane, peanut shell, coconut shell, wheat straw, pistachio shell, date pit, rice husk	(Agwa et al., 2020; Ajiwe et al., 1998; Aouba et al., 2016; Bahurudeen et al., 2015; Gunasekaran et al., 2011; Limami et al., 2021; Tekin et al., 2021)
Compost	Shell and skin	Pistachio shell, date pit	(Hossain et al., 2014; Xue & Farrell, 2020)
Paper-paperboard	Shell and skin	Rice husk, sugarcane, wheat straw, corn stalk	(Daud et al., 2016; Evelyn et al., 2019; Jeetah et al., 2015; Singh et al., 2011)
Adhesive	Shell	Chestnut shell, cashew shell	(Santos et al., 2017; Sharma et al., 2020)
Mushroom cultivation	Shell	Coconut shell, almond shell	(Barshteyn & Krupodorova, 2016; Díaz & Díaz-Godínez, 2022)
Tableware	Shell and skin	Rice husk, sugarcane	(Deepthi et al., 2023; Liu et al., 2020)
Cat litter	Shell	Walnut shell, corn stalk, wheat straw	(Naturally Fresh, 2023; Nature's Miracle, 2023; sWheat Scoop, 2023)

Finally, in order to valorize these wastes, it would be interesting to expand the research; for this purpose, it is proposed a more exhaustive comparison with materials of similar properties and from there, identify the applications of these materials and determine if the hazelnut by-products are suitable for such applications. Then, it is suggested to carry out an ideation process together with experts from different fields (materials, environment, design, manufacturing, processes, etc.) to generate new product ideas and evaluate their feasibility according to a variety of criteria.

Declarations

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Ethical statement – studies in humans and animals

The research presented in the manuscript *"Potential applications of hazelnut industry waste based on material properties"* by **Laura Aguado González, Jorge Sierra-Pérez, Simone Blanc, and Samuel Moles** did not involve experiments with human participants or animals. Therefore, no ethical approval was required for this study.

CRediT authorship contribution statement

Laura Aguado-González: Writing – original draft, Methodology, Investigation, Conceptualization. **Jorge Sierra-Pérez:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Simone Blanc:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization. **Samuel Moles:** Writing – review & editing, Methodology, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The datasets generated during the current study are available in the Supplementary Material.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.afres.2025.101060.

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