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Research Article

In Vitro Evaluation of Antioxidant and Antifungal Properties of Roasted Hazelnut (Corylus avellana) Peel Alcoholic Extracts

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Abstract
Hazelnut (Corylus avellana) processing generates large amounts of by-products, particularly peels, which are rich in phenolic compounds with potential bioactive properties. Their valorization could provide sustainable natural antioxidants and antifungal agents for food, pharmaceutical, and nutraceutical applications. This study aimed to evaluate the antioxidant and antifungal activities of alcoholic extracts from roasted hazelnut peels. Roasted hazelnut peels were extracted with methanol, and the extracts were characterized using FT-IR spectroscopy. Antioxidant activity was assessed by the DPPH radical scavenging assay, while antifungal activity was tested against Aspergillus flavus and Fusarium spp. at concentrations of 0.5 and 1 mg/mL. FT-IR analysis revealed functional groups indicative of phenolic and flavonoid compounds. The extracts demonstrated concentration-dependent antioxidant activity, with maximum radical scavenging observed at 1 mg/mL. In contrast, no antifungal activity was detected against either Aspergillus flavus or Fusarium spp. under the tested conditions. Roasted hazelnut peel extracts are a valuable source of natural antioxidants with potential applications in functional foods and health-promoting products. Their lack of antifungal activity suggests the need for alternative extraction strategies, higher concentrations, or synergistic combinations to achieve antimicrobial effects. These findings support the sustainable use of hazelnut by-products as part of circular economy practices while highlighting opportunities for future research to optimize their bioactive potential.

INTRODUCTION

The use of natural products for the treatment of diseases is as old as human civilization. Archaeological and ethnobotanical evidence suggests that plants were employed in prehistoric times for healing purposes, with their medicinal value initially discovered through instinctive use and empirical observation. Over time, cultural transmission preserved and expanded this knowledge, laying the foundation for traditional medicine systems still practiced today[1,2]. Unlike early empirical practices, modern science has increasingly validated many of these plant-based therapies, demonstrating their pharmacological potential through phytochemical and molecular studies[3]. The 20th century saw the rise of synthetic pharmaceuticals, which significantly transformed clinical practice. However, despite the advances in chemistry and pharmacology, a substantial portion of currently used drugs is either directly derived from natural products or structurally inspired by them[4]. In fact, between 1981 and 2019, approximately 64% of small-molecule drugs approved for use in oncology were derived from natural products or their analogues, highlighting the ongoing importance of bioactive natural compounds in modern drug discovery[5].

Today, interest in medicinal plants is resurging, largely due to challenges associated with synthetic drugs, including antimicrobial resistance, side effects, high development costs, and limited accessibility in low- and middle-income countries[6,7]. In this context, natural products offer a complementary and sustainable approach to therapeutic development, with ongoing research uncovering novel applications for plant-derived bioactive molecules[8,9].

The last few decades have witnessed a global health crisis driven by drug resistance and treatment limitations. For example, antimicrobial resistance (AMR) now represents one of the greatest threats to public health, with projections suggesting that AMR-related mortality could surpass 10 million deaths annually by 2050 if left unchecked[10]. The decline in antibiotic discovery pipelines further emphasizes the urgent need for novel therapeutic options[11]. Similarly, resistance to antifungal agents has emerged as a significant concern, especially with pathogenic fungi such as Candida auris, Aspergillus fumigatus, and Fusarium species showing increasing tolerance to existing drugs[12,13].

Natural products provide unique structural diversity and biological specificity that are difficult to replicate synthetically[14]. Plants, in particular, synthesize a wide array of secondary metabolites-including alkaloids, terpenoids, flavonoids, tannins, and phenolic acids-which function as defense compounds against microbial pathogens and oxidative stress[15,16]. These compounds often exhibit synergistic effects, enhancing antimicrobial and antioxidant activity while minimizing toxicity, thus making them promising candidates for pharmaceutical development[17]. Moreover, the increasing consumer preference for natural, safe, and sustainable therapeutics has accelerated research into plant-based medicine and functional foods[18]. This trend aligns with the goals of the World Health Organization (WHO), which emphasizes the integration of traditional and complementary medicine into modern healthcare systems, especially in regions where conventional drugs are inaccessible or unaffordable[19]. Against this backdrop, the valorization of agro-industrial by-products represents an innovative strategy to source natural bioactives. Nut by-products, particularly hazelnut (Corylus avellana) peels and skins, are gaining attention for their richness in phenolic compounds with antioxidant and antimicrobial properties[20]. Utilizing such residues not only contributes to drug discovery efforts but also addresses environmental challenges associated with agricultural waste disposal.

Hazelnut (Corylus avellana L.), belonging to the Betulaceae family, is one of the most economically significant nut crops globally. Its production is concentrated in Turkey, which accounts for nearly 70% of the world's supply, followed by Italy, Spain, and the United States[21,22]. According to the Food and Agriculture Organization (FAO), global hazelnut production exceeded 1.1 million tons in 2021, reflecting its growing demand in the food and confectionery industries[23]. Hazelnuts are consumed both raw and roasted, and are a primary ingredient in a variety of processed products, including chocolates, spreads, bakery items, and dairy-based desserts[24]. Beyond their culinary uses, hazelnuts are recognized as a nutrient-dense food, providing healthy fats, proteins, vitamins (particularly vitamin E), and minerals such as magnesium, potassium, and phosphorus[25]. Numerous clinical and epidemiological studies have demonstrated the beneficial health effects of hazelnut consumption. Daily intake of hazelnuts has been associated with improvements in lipid profiles, reduced low-density lipoprotein (LDL) cholesterol, and enhanced high-density lipoprotein (HDL) cholesterol, contributing to cardiovascular health[26,27]. A meta-analysis of randomized controlled trials confirmed that nut consumption, including hazelnuts, significantly reduces total cholesterol and triglyceride levels, thereby lowering the risk of atherosclerosis[28]. Hazelnuts are also rich in bioactive phytochemicals, particularly phenolic compounds such as gallic acid, catechin, epicatechin, and

procyanidins, which exhibit potent antioxidant and anti-inflammatory effects[29,30]. These compounds play critical roles in mitigating oxidative stress, a key driver of chronic diseases such as cancer, diabetes, and neurodegenerative disorders[31]. In vitro and in vivo studies further indicate that hazelnut extracts exert antiproliferative effects against cancer cell lines, suggesting potential chemopreventive applications[32,33]. In addition to cardiovascular and anticancer benefits, hazelnut consumption has been linked to improved cognitive function, bone health, and immune modulation (35). Their high monounsaturated fatty acid content contributes to neurological protection, while mineral-rich profiles support musculoskeletal development. Despite their nutritional value, hazelnut processing generates substantial quantities of by-products, including shells, skins, and peels, which account for nearly 50% of the nut's total weight[36]. Traditionally, these residues have been treated as waste, often discarded or burned, leading to environmental concerns[37]. However, recent research highlights that hazelnut by-products are particularly rich in polyphenols, flavonoids, and tannins, surpassing even the edible kernel in antioxidant capacity[38]. Hazelnut skins, for instance, contain high concentrations of catechin, gallic acid, and polymeric procyanidins, which contribute significantly to free radical scavenging and metal chelation activities[39]. Roasted hazelnut peels, in particular, have been reported to exhibit notable antimicrobial and antifungal activity, making them promising candidates for functional food and pharmaceutical applications[40,41]. Efforts to valorize hazelnut by-products align with the principles of the circular economy, where waste streams are converted into high-value products. This approach not only enhances the sustainability of the hazelnut industry but also provides new opportunities for developing natural preservatives, nutraceuticals, and therapeutic agents (42,43). The phytochemical composition of hazelnuts and their by-products has been extensively studied in the past decade, with a focus on the phenolic profile and associated biological activities. Hazelnut kernels themselves are rich in monounsaturated fatty acids, tocopherols, and phytosterols, while the skins and peels contain significantly higher concentrations of polyphenolic compounds[44,45]. Hazelnut by-products, particularly skins, contain abundant phenolic compounds, including gallic acid, protocatechuic acid, catechin, epicatechin, and procyanidins[46]. Studies have shown that these compounds possess strong radical-scavenging capacity and contribute to reducing lipid peroxidation in vitro[47]. The flavonoid content is especially high in roasted hazelnut peels, which undergo structural changes during thermal processing that enhance the bioavailability of certain phenolics[48]. In addition, tannins present in hazelnut skins have demonstrated antimicrobial and antioxidant properties through multiple mechanisms, including protein precipitation, enzyme inhibition, and disruption of microbial cell membranes[49]. Such complex interactions make hazelnut by-products an attractive source of multifunctional bioactive molecules. Beyond polyphenols, hazelnut by-products contain tocopherols, particularly a-tocopherol, which is a potent lipid-soluble antioxidant[50]. This compound not only protects polyunsaturated fatty acids from oxidation but also plays a critical role in maintaining human cardiovascular and neurological health[51]. Studies indicate that tocopherols and phytosterols in hazelnuts contribute synergistically with phenolics to their overall antioxidant activity[52].

Recent investigations have explored different extraction techniques, including ultrasound-assisted, microwave-assisted, and supercritical fluid extraction, to optimize the yield of bioactive compounds from hazelnut by-products[53,54]. These advanced extraction methods not only enhance recovery efficiency but also preserve the structural integrity of heat-sensitive compounds, thereby improving bioactivity[55]. In vitro analyses consistently report strong radical-scavenging, reducing power, and metal-chelating capacities in hazelnut peel extracts, often surpassing synthetic antioxidants such as butylated hydroxytoluene (BHT)[56]. Furthermore, preliminary in vivo studies suggest that hazelnut-derived polyphenols modulate oxidative biomarkers and inflammatory responses, supporting their potential application in nutraceutical formulations[57].

Fungal pathogens such as Aspergillus flavus and Fusarium spp. are of particular concern due to their ability to contaminate crops with mycotoxins. Aflatoxins produced by A. flavus are among the most potent natural carcinogens, linked to hepatocellular carcinoma in humans, while fumonisins from Fusarium species are associated with esophageal cancer and neural tube defects[58,59]. These toxins pose significant risks to food safety, especially in cereals, nuts, and legumes. Current antifungal strategies rely heavily on synthetic fungicides, which are associated with ecological toxicity, carcinogenic potential, and the emergence of resistant fungal strains[60,61]. Plant-derived antifungal agents, including those from nut by-products, offer an eco-friendly and sustainable alternative, with applications ranging from crop protection to food preservation and pharmaceutical formulations[62,63]. The

increasing focus on sustainability in food production has driven interest in valorizing agricultural by-products. In the hazelnut industry, processing generates massive amounts of shells, skins, and peels, which are often discarded or incinerated, contributing to waste management problems and greenhouse gas emissions[64,65]. However, these residues represent an underutilized reservoir of high-value bioactive compounds that can be harnessed for pharmaceutical, nutraceutical, and industrial applications[66].

Valorization of hazelnut by-products aligns with the principles of a circular economy, which seeks to minimize waste and maximize resource efficiency[67]. By transforming agricultural residues into functional products, producers can not only reduce environmental burdens but also generate additional revenue streams. For instance, extracts from hazelnut peels can be used as natural food preservatives, replacing synthetic additives while enhancing product shelf life[68].

Furthermore, the pharmaceutical industry can leverage these bioactives for the development of plant-derived antioxidants and antimicrobials, thereby reducing dependency on synthetic drugs that are costly and environmentally taxing to produce[69]. This dual role-waste reduction and bioactive discovery makes hazelnut by-product valorization a promising model for sustainable innovation.

Recent advances in extraction technologies have made the recovery of bioactive compounds from hazelnut residues more feasible at industrial scale. Techniques such as pressurized liquid extraction, supercritical CO2 extraction, and green solvents have been shown to yield high concentrations of polyphenols with minimal environmental impact[70,71]. These methods are not only efficient but also compatible with the principles of green chemistry, further supporting sustainability goals.

Applications of hazelnut by-product extracts extend beyond pharmaceuticals. In the cosmetic industry, phenolic-rich extracts are incorporated into skincare formulations for their antioxidant and anti-aging properties[72]. In the food industry, they are being explored as natural preservatives and functional additives to improve nutritional quality and extend shelf life[73]. Importantly, their antifungal properties make them particularly attractive for preventing spoilage in bakery and confectionery products[74].

The concept of functional foods-foods that provide health benefits beyond basic nutrition-has gained significant traction in recent years. Hazelnut by-products, with their rich polyphenolic profile, are ideal candidates for incorporation into functional food formulations[75]. Clinical and preclinical studies suggest that supplementation with nut-derived polyphenols can reduce oxidative stress markers, improve endothelial function, and modulate gut microbiota composition[76,77]. These findings reinforce the potential of hazelnut by-products not only as waste-derived bioactives but also as contributors to preventive healthcare.

Oxidative stress, defined as an imbalance between reactive oxygen species (ROS) production and the body's antioxidant defense system, plays a central role in the pathogenesis of numerous chronic diseases, including cardiovascular disorders, cancer, diabetes, and neurodegenerative conditions[78,79]. Excess ROS can damage lipids, proteins, and DNA, thereby accelerating cellular aging and disease progression[80]. Dietary antioxidants, particularly those derived from plants, are critical in neutralizing ROS and restoring redox balance. Phenolic compounds, flavonoids, and tocopherols act through diverse mechanisms such as radical scavenging, metal chelation, and modulation of antioxidant enzyme activity[81,82]. Hazelnut by-products, which are exceptionally rich in phenolic compounds, have demonstrated significant antioxidant capacity in vitro and in vivo, making them attractive candidates for functional foods and nutraceuticals[83]. Recent studies emphasize that antioxidant activity from plant extracts contributes not only to disease prevention but also to improved food preservation, as oxidative processes are the primary cause of spoilage and reduced shelf life in processed products[84]. Consequently, hazelnut peel extracts, with their potent antioxidant properties, could serve dual purposes-protecting human health and improving food quality[85].

Aspergillus flavus is a ubiquitous soil-borne fungus that infects a wide range of crops, particularly cereals and nuts. Although infection itself does not always reduce yield, contamination with aflatoxins poses serious health risks[86]. Aflatoxin B1, the most toxic variant, is classified as a Group 1 carcinogen by the International Agency for Research on Cancer (IARC), with strong links to hepatocellular carcinoma[87]. Chronic exposure also contributes to immunosuppression and childhood stunting in low-resource settings[88]. Efforts to control aflatoxin contamination have relied on fungicides and postharvest interventions; however, resistance development, environmental persistence, and toxic residues remain major challenges[89]. This highlights the urgent need for alternative antifungal agents, particularly natural products with safe toxicological profiles[90]. Fusarium species are widely distributed plant pathogens

that cause significant agricultural losses and produce harmful mycotoxins, including fumonisins, deoxynivalenol (DON), and zearalenone[91]. These toxins have been associated with a spectrum of human and animal health disorders, ranging from gastrointestinal irritation to carcinogenesis and endocrine disruption[92]. Moreover, Fusarium infections are not limited to plants; immunocompromised individuals are increasingly susceptible to opportunistic fusariosis, which is difficult to treat due to resistance to standard antifungals[93].

Given the dual threat to agriculture and human health, research into novel antifungal compounds targeting Fusarium is of high priority. Plant-derived extracts, including those from hazelnut peels, have demonstrated inhibitory activity against Fusarium spp., suggesting their potential role in mitigating both crop contamination and opportunistic human infections [94,95].

Despite growing evidence of the antioxidant and antimicrobial properties of hazelnut by-products, their potential remains underexplored, particularly in the context of antifungal applications. Most current research has focused on the nutritional value of hazelnuts or the characterization of bioactive compounds in the kernels, with limited emphasis on by-products such as roasted peels[96]. Moreover, few studies have systematically investigated their activity against high-priority fungal pathogens like Aspergillus flavus and Fusarium spp., which are responsible for significant food safety concerns and clinical infections[97]. Another critical gap lies in the translation of in vitro findings into practical applications. While hazelnut peel extracts have demonstrated promising antioxidant and antimicrobial activity under laboratory conditions, further evaluation is necessary to validate their efficacy in real-world contexts, including food preservation and therapeutic use[98].

Therefore, the present study seeks to investigate the antifungal and antioxidant activities of alcoholic extracts from roasted hazelnut (Corylus avellana) peels. By focusing on agro-industrial by-products, this research aims to contribute to the sustainable utilization of hazelnut residues in line with circular economy principles, identify novel natural agents with potential applications in food preservation, pharmaceuticals, and nutraceuticals, and address the urgent need for safer and more effective antifungal alternatives against pathogens of agricultural and clinical relevance.

MATERIALS AND METHODS

Materials and Sample Preparation: Fresh hazelnuts (Corylus avellana) were obtained from local suppliers and roasted at 160°C for 15 minutes in a convection oven. The roasted hazelnuts were cooled to room temperature, and the peels were manually separated from the kernels. The collected peels were ground to a fine powder using a mechanical grinder and stored at -20°C until extraction.

Preparation of Hazelnut Peel Extracts: The extraction of bioactive compounds from hazelnut (Corylus avellana L.) peels was performed following a modified protocol adapted from Harborne. Dried hazelnut peel samples, obtained from roasted and unroasted peels as described in Section 2.1, were ground into a fine powder using a laboratory grinder and sieved through a 0.5 mm mesh to ensure uniform particle size. For each sample, 20 g of powdered peel was weighed and transferred into a 500 mL conical flask. The powder was then mixed with 200 mL of 99% methanol (analytical grade, Sigma-Aldrich) to achieve a solid-to-solvent ratio of 1:10 (w/v). The mixture was agitated on an orbital shaker at 150 rpm for 48 hours at room temperature (25 ± 2°C) in the dark to prevent the degradation of light-sensitive compounds. Following extraction, the mixture was filtered through Whatman No. 1 filter paper under vacuum to separate the liquid extract from the solid plant residue. The filtration process was repeated twice to ensure complete recovery of the extract. The resulting filtrate was concentrated under reduced pressure at 40°C using a rotary evaporator (Büchi Rotavapor R-100) to remove the methanol solvent. The concentrated extract was then dried to constant weight in a vacuum oven at 35°C to eliminate residual solvent, yielding a dry extract. The dried extracts were weighed to determine the extraction yield, expressed as a percentage of the initial dry weight of the peel powder. The extraction process is illustrated in Figures 1 and 2.

FT-IR Spectra: Spectra of the isolated compounds were recorded with FT-IR to determine functional groups of compounds and were recorded with an FTIR—Fourier transform infrared spectrophotometer at the Central Laboratory/Faculty of Pharmacy/University of Kufa.

Screening for Antifungal Activity: The antifungal activity assay was performed following the procedure described by Alizadeh[99]. Sabouraud Dextrose Agar (SDA) medium was prepared and sterilized using an autoclave. Once the medium had cooled but before solidification, predetermined concentrations of the plant extract (500 and 1000 µg/ml) were added to sterile flasks containing the medium. The flasks were shaken thoroughly to ensure even distribution of the extract, and the media were then poured into sterile 9 cm Petri dishes, prepared in triplicate for each concentration. Control plates were

Fig. 1: Grinding of Corylus avellana L. Roasted Hazelnut Fruits

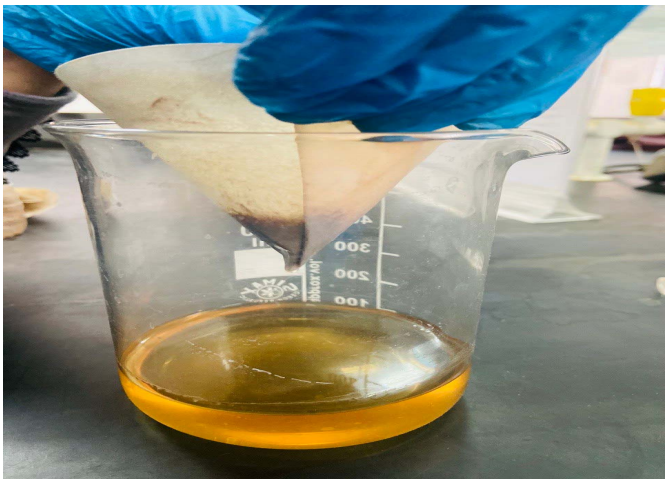

Fig. 2: The plant extract preparation (filtration)

prepared in the same manner but without the addition of plant extract.

After solidification, the plates were inoculated by streaking with a sterile swab containing mycelial fragments obtained from 7-day-old fungal cultures. The inoculated plates were incubated at 25 °C until the fungal colonies in the control group (untreated plates) reached the edge of the Petri dish.

Fungal growth was assessed by measuring colony diameter along two perpendicular diagonals intersecting at the center of each colony, and the average value was recorded. The percentage of growth inhibition was calculated using the following formula:

$$Rr = \frac{R1 - R2}{R1} * 100$$

Where:

R1 = mean colony diameter in control (untreated) plates

R2 = mean colony diameter in extract-treated plates

R_r = percentage of fungal growth inhibition

In Vitro Antioxidant Activity (DPPH Radical Scavenging Assay): The antioxidant activity of the plant extract and its fractions was evaluated using the 1,1-diphenyl-2-picrylhydrazyl (DPPH) radical scavenging method, as described by Masullo *et al.*[100] with slight modifications. DPPH is commonly used as a stable free radical reagent, exhibiting a deep violet color in methanolic solution, which decreases upon reduction by an antioxidant compound.

Dried plant samples were dissolved in dimethyl sulfoxide (DMSO) and prepared at four different concentrations (0.12, 0.25, 0.5, and 1.0 mg/mL). Aliquots of each concentration were placed in test tubes in triplicate. A methanolic DPPH solution was then added to each tube, while distilled water served as the negative control. The tubes were gently mixed and incubated in the dark at 37°C for 20 minutes. The absorbance of the resulting solutions was measured at

517 nm using a UV–visible spectrophotometer. The percentage of radical scavenging activity was calculated according to the following equation:

Inhibition % = [(control absorbance – sample absorbance) / control absorbance] x 100%

Where:

- **A_control =** absorbance of the control (DPPH solution without sample)
- **A_sample =** absorbance of the DPPH solution with the test sample

The inhibition percentages were plotted against the different concentrations of the plant extract to determine the antioxidant potential.

RESULTS AND DISCUSSIONS

FT-IR Spectra Results: The Fourier Transform-Infrared (FT-IR) spectroscopy analysis of the alcoholic extract from roasted hazelnut (Corylus avellana L.) peels revealed distinct absorption bands, confirming the presence of various functional groups. As shown in Figure 3, the FT-IR spectrum displayed a prominent absorption band at 3415.93 cm^{-1}, corresponding to the hydroxyl (OH) group. Additionally, absorption bands at 2926.01 cm^{-1} and 2856.58 cm^{-1} were attributed to the C-H stretching vibrations of the phenyl ring. Other notable bands included 1743.65 cm^{-1} (C=O), 1458.18 cm^{-1} (C=N), 1367.53 cm^{-1} (C-O), and 727.16 cm^{-1} (N-H), as summarized in Table 1. These results indicate the presence of phytochemicals such as glycosides, phenols, amino acids, and flavonoids.

Screening for Antifungal Activity: The antifungal potential of Corylus avellana roasted hazelnut peel alcoholic extract was assessed against Aspergillus flavus and Fusarium species at concentrations of 0.5 mg/ml and 1 mg/ml. The results demonstrated that the extract did not exhibit measurable antifungal activity against either fungal strain. In the case of A. flavus (Figure 4), fungal growth was comparable to that of the control plate, with no observable inhibition zones around the treated discs at either concentration. Similarly, for Fusarium spp., both concentrations of the extract failed to produce inhibition zones, and fungal growth appeared unaffected relative to the control.

These findings indicate that the hazelnut peel alcoholic extract lacks significant antifungal properties under the tested conditions.

Antioxidant Activity (DPPH Assay): The antioxidant activity of the C. avellana hazelnut peel alcoholic extract was assessed using the 1,1-diphenyl-2-picrylhydrazyl (DPPH) radical scavenging assay. The extract demonstrated concentration-dependent antioxidant activity, with the highest efficacy observed at 1 mg/mL, followed by 0.5, 0.25, and 0.12 mg/mL, as shown in Figure 5. The degree of yellowing in the DPPH assay, indicative of radical scavenging potential, confirmed the presence of phenolic compounds and flavonoids, which are known to stabilize phenoxy radicals and inhibit free radical formation. The antioxidant activity was not solely dependent on the total quantity of phenols and flavonoids but also on their structural characteristics and quality[101].

This research explored the potential of roasted hazelnut (Corylus avellana L.) peel extracts as a source of natural antioxidants and antifungal agents. The goal was to find a valuable use for this common agro-industrial waste product, potentially opening doors for its application in preserving food, as well as in nutraceutical and pharmaceutical products. Our data reveal a compelling narrative: the extracts show remarkable antioxidant power but, under the conditions of this study, failed to inhibit the growth of key fungal pathogens. This dual outcome enriches the broader scientific conversation on using nut waste as a sustainable, circular economy-compliant resource for bioactive compounds.

Characterization of the extracts via FT-IR spectroscopy provided a chemical foundation for the observed bioactivity. The detected functional groups, hydroxyl (-OH), carbonyl (C=O), and C-H stretches are the molecular fingerprints of valuable phytochemicals like phenols and flavonoids. This aligns perfectly with existing literature that catalogues hazelnut peels as a treasure trove of polyphenolics, including compounds such as gallic acid, catechin, and procyanidins, all renowned for their ability to combat oxidative stress[102,103]. These identified constituents directly explain the clear, concentration-dependent response seen in the DPPH radical scavenging assay. The potent activity at 1 mg/mL reinforces previous work indicating that roasting actually enhances the phenolic content and antioxidant potential of hazelnut by-products compared to the raw kernel, likely by making certain bound compounds more accessible[104,105]. The strength of the antioxidant effect observed here echoes the findings of Locatelli *et al*.[106], who noted that hazelnut skin extracts could outperform synthetic antioxidants like BHT in some assays. This robust activity positions hazelnut peel extracts as a promising, natural alternative to synthetic additives, which are increasingly scrutinized for their environmental and health impacts[107].

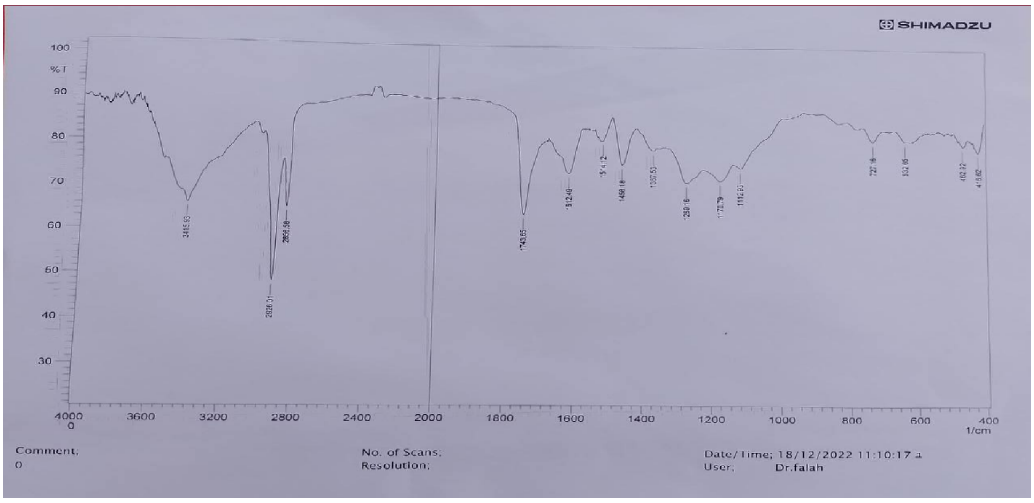

Fig. 3: FT-IR spectrum of Corylus avellana L. roasted hazelnut peel alcoholic extract

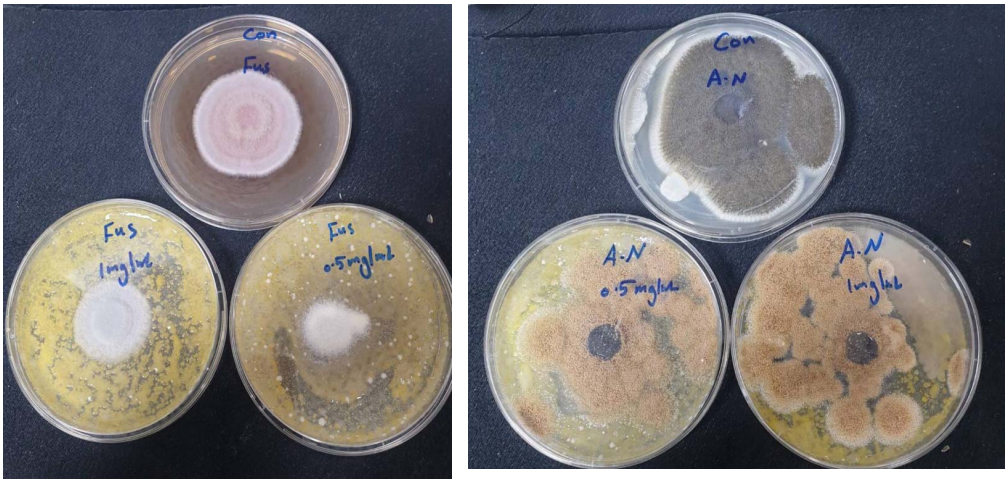

Fig. 4: Antifungal activity of C. avellana hazelnut peel alcoholic extract with concentrations of 500 and 1000 µg/ml on Aspergillus flavus and Fusarium

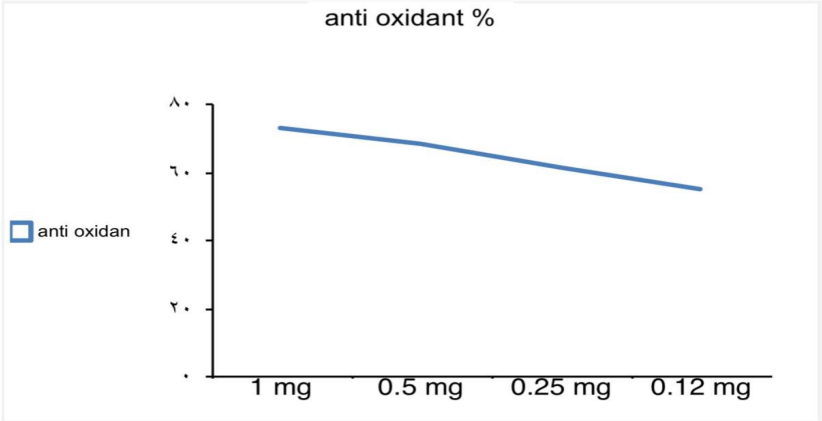

Fig. 5: Inhibition rate of oxidation by DPPH method for C. avellana hazelnut peel alcoholic extract.

A surprising and significant finding, however, was the complete absence of antifungal action against Aspergillus flavus and Fusarium spp. at the concentrations tested (0.5 and 1 mg/mL). This result stands in contrast to several other studies that documented modest antimicrobial effects from hazelnut shells and skins against a range of microorganisms[108,109]. For example, work by Belviso *et al.*[110] showed that extracts could

Table 1: FT-IR spectrum data (cm^{-1}) of Corylus avellana L. roasted hazelnut peel alcoholic extract. Plant Part

Plants parts	OH	C-H	C=O	C=N	C- O	N– H
Corylus avellana peel	3415.93	2926.01and 2856.58	1743.65	1458.18	1367.53	727.16

inhibit spoilage microbes in baked goods, a effect credited to the combined action of tannins and phenolic acids. The discrepancy in our results may stem from several critical factors. The concentrations selected for this screening might simply have been too low to penetrate the resilient cell walls of Aspergillus and Fusarium species, which are notoriously difficult to combat with plant-based antimicrobials[111]. Furthermore, our chosen extraction method, while excellent for pulling out polar antioxidants, may have been less effective at isolating non-polar or specific antifungal agents (e.g., certain terpenoids), which often require specialized techniques like supercritical CO2 or ultrasound-assisted extraction for optimal yield[112,113]. It is also plausible that the roasting process, while boosting antioxidants, could have degraded more heat-labile compounds responsible for antifungal activity, a phenomenon noted in other studies on thermal processing[114].

This lack of efficacy against such high-priority fungi highlights an important knowledge gap. Aspergillus flavus and Fusarium species are major threats to global food security and public health due to their capacity to produce dangerous mycotoxins like aflatoxins[115,116]. With resistance to conventional fungicides on the rise, the search for new, sustainable antifungal solutions is urgent[117]. Although our extracts showed no direct antifungal activity, their potent antioxidant properties could still offer an indirect preservative benefit. By reducing oxidative rancidity in food matrices, they could help stabilize the environment and potentially slow down processes that favor fungal colonization and mycotoxin synthesis[118]. Subsequent investigations should focus on testing much higher concentrations, employing different extraction solvents, or exploring synergistic blends with other natural antimicrobials to overcome the observed resistance.

Repurposing hazelnut peels dovetails with worldwide initiatives to curb agricultural waste and build more sustainable food systems. The international hazelnut sector produces massive amounts of by-product; the skin and shell alone can account for half of the total nut weight[119]. Converting this low-value residue into high-value ingredients, such as natural preservatives, tackles an environmental issue while simultaneously creating new economic streams[120]. A growing number of reports point to the viability of hazelnut waste in cosmetics, fortified foods, and even pharmaceuticals, capitalizing on its diverse profile of phenolics and tocopherols[121,122]. Our results lend support to this concept, particularly for functional foods where the antioxidant extract could improve nutritional profile and delay spoilage, as successfully trialed in products like yogurt and bread[123,124].

Several limitations of this work must be acknowledged. The exclusive use of in vitro models means our findings cannot be directly translated to complex biological systems or real-world food products without further validation. Although the DPPH assay is a reliable and standard method, it represents a simplified model of antioxidant behavior and cannot capture the intricate dynamics of how these compounds interact within a living organism or a food matrix[125]. The null result on the antifungal front underscores the need for a more detailed chemical analysis to pinpoint exactly which compounds are present and which might be responsible for antimicrobial effects in other contexts. Future work must utilize advanced techniques like LC-MS to fully characterize the extract's phytochemical portfolio[126]. Ultimately, in vivo studies and human clinical trials will be essential to confirm any proposed health benefits.

In summary, alcoholic extracts from roasted hazelnut peels demonstrate powerful antioxidant properties, underpinned by a rich content of phenolic compounds. This makes them strong candidates for use as natural ingredients in health-focused foods and supplements. Their inability to inhibit the growth of Aspergillus flavus and Fusarium spp., however, indicates that realizing their full antimicrobial potential will require refined strategies, such as optimized extraction protocols or combination therapies. These insights add valuable momentum to the effort of transforming hazelnut by-products from waste into worth, fostering innovation in sustainable industry practices.

CONCLUSION

The present study demonstrated that alcoholic extracts from roasted hazelnut (Corylus avellana) peels possess strong antioxidant potential but lack measurable antifungal effects under the tested conditions. FT-IR analysis confirmed the presence of phenolic and flavonoid compounds, which accounted for the concentration-dependent radical scavenging activity observed in the DPPH assay. These findings support the role of hazelnut by-products as promising sources of

natural antioxidants that could be utilized in functional foods, nutraceuticals, and as alternatives to synthetic preservatives.However, the extracts showed no inhibitory activity against Aspergillus flavus and Fusarium spp., indicating that either higher concentrations, alternative extraction methods, or synergistic combinations with other bioactives may be required to unlock potential antifungal properties. This highlights an important gap for future investigations, particularly considering the urgent global need for sustainable and effective antifungal agents. Overall, valorizing hazelnut peels aligns with circular economy principles by transforming agricultural residues into value-added products. While their antioxidant properties are well established in this study, further research is needed to optimize extraction techniques, explore broader antimicrobial applications, and validate the in vitro findings through in vivo and real-world studies.

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