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Polyphenols from rice husk: A review of emerging extraction techniques and potential applications

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ABSTRACT

Rice husk is a valuable agri-food by-product and an underutilized biomass. Moreover, it constitutes a natural source of antioxidant compounds. Thus, this review compiles data on the total polyphenol content (TPC) in rice husk classified according to pigmentation. In particular, purple husks show high TPC levels (2.15 - 21.90 mg GAE/g) compared to straw (0.69–20.18), straw with a brown line (18.66–20.90), and speckled brown husks (1.08–1.72). In addition, this residue presents specific families of polyphenols like phenolic acids (ferulic, coumaric, caffeic, vanillic, and gallic acid) and flavonoids (quercetin, kaempferol, rutin, catechin, epicatechin, and naringenin). Additionally, conventional and emerging extraction techniques are compared based on their efficiency, solvent consumption reduction, and preservation of functional properties. We also highlight several patent claims focused on the development of rice husk-derived polyphenol products that demonstrate health benefits. Therefore, rice husk is a by-product that is rich in antioxidant compounds and serves as a key driver of sustainable innovations. Its use aligns with the principles of a circular economy, which aim to minimize waste and enhance value throughout the food system.

1. Introduction

Rice (*Oryza sativa* L.) is one of the most important commercial crops worldwide as a source of calories and essential nutrients like carbohydrates, proteins, vitamins, and minerals, such as iron and zinc (Gong et al., 2017; Qadir & Wani, 2023). There are many varieties of agricultural importance, including white, black, brown, purple, and red rice (Verma & Srivastav, 2020). China, India, Indonesia, Bangladesh, and Vietnam are the leading producers, responsible for most of the global agricultural output (800 million tons) (FAOSTAT, 2023). Rice production in Latin America is also of significant agricultural importance, although it lags production in Asia. Several countries in the region stand out for their rice production, such as Brazil, Peru, Colombia, and Ecuador (Benedet et al., 2024). This large, widespread production leads to several agroindustrial wastes, including husk/hull, straw, and bran, which have low economic value and pose environmental management challenges (Nunes et al., 2024; Park et al., 2019).

In particular, rice husk (RH) makes up approximately 20 % of the total weight of harvested rice, which is around 155 million tons of rice produced worldwide each year (Peanparkdee & Iwamoto, 2019). Rice husk residues that include many polyphenols are a potential source of natural antioxidants, whose bioactive properties have sparked the interest of the pharmaceutical and food industries (Kaur & Ubeyitogullari, 2023; Wisetkomolmat et al., 2023). Polyphenols are antioxidant compounds synthesized through the secondary metabolism of plants, whose chemical structure presents an aromatic ring with one or more hydroxyl groups attached (Bolat et al., 2024). Their structures range from monomers to polymers with high molecular weight (200 to 3000 Da), which can be classified into various categories and subcategories based on their chemical structure, such as the number of phenol rings, the arrangement of functional groups, or the type of carbon skeleton (Zagoskina et al., 2023).

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Rice husk contains high concentrations of polyphenols (between 10 and 30 mg/g of dry weight) (Wisetkomolmat et al., 2023), including vanillic acid, *p*-coumaric acid, ferulic acid, caffeic acid, syringic acid, and quercetin. This residue contains significant amounts of vanillic and *p*-coumaric acids, contributing to its high in vitro antioxidant capacity (Abraham-Diego et al., 2024; Frosi et al., 2023; Jiamphun & Chaiyana, 2022). These compounds have received significant scientific attention due to their ability to neutralize free radicals, thereby protecting cells from damage and lowering the risk of chronic diseases (Bhuyan & Handique, 2022). Thus, extracting and utilizing these antioxidants can not only reduce waste and environmental pollution but also create value-added products for the food and pharmaceutical industries.

Established techniques, such as Soxhlet extraction, hydrodistillation, maceration, and agitated solvent extraction, have been used to recover polyphenols (Oreopoulou et al., 2019). These techniques utilize significant amounts of solvents like methanol, acetone, and hexane, which are expensive, toxic, and environmentally damaging. Consequently, the extracts obtained cannot be used for food applications. Additionally, extraction times are long (> 4 h), which may lead to the degradation of certain heat-sensitive polyphenols (Osorio-Tobón, 2020). Conversely, emerging extraction techniques such as ultrasound, microwave-assisted extraction, supercritical fluid extraction (SFE), pressurized liquid extraction (PLE), and enzyme-assisted extraction (EAE) utilize food grade solvents like water, ethanol, glycerol, and isopropanol (Sridhar et al., 2021). These emerging techniques can reduce extraction times (< 30 min), solvent consumption, and improve the yield and selectivity of extraction and offer several advantages over established "conventional" techniques (Patra et al., 2022). Nevertheless, the choice of the appropriate extraction method will depend on several factors, including the choice of solvent, which is determined by the solid matrix, the polarity of the target compounds, and the desired purity of the extracts.

This review compiles information on the most abundant polyphenolic compounds found in rice husk (*Oryza sativa* L.) and compares conventional and emerging techniques for their extraction. In addition, the potential applications of these compounds in the food and pharmaceutical industries are discussed.

2. Polyphenols present in rice husk

Polyphenols can be synthesized primarily through two metabolic pathways, termed the shikimate and malonate/acetate pathways, which give rise to a wide diversity of structural forms (Zagoskina et al., 2023). In general, polyphenols present polar (hydroxyl and carboxyl) and non-polar (aromatic) groups in their chemical structure. The presence of polar and non-polar moieties enables interactions with a variety of molecules, including sugars, organic acids, and plant amines, and leads to the formation of complex conjugates (Zagoskina et al., 2023). Polyphenols are classified into different groups that vary in phenolic content and chemical structure, including flavonoids, phenolic acids, lignans, tannins, and stilbenes, each exhibiting distinct chemical properties and biological activity (Lang et al., 2024).

Polyphenols can also be classified in terms of their water solubility. Some polyphenols are water-soluble, such as conjugated glycosides (flavonoids), and others are insoluble, including many phenolic acids (Gligor et al., 2019). Soluble phenolic compounds are predominantly synthesized in the endoplasmic reticulum of plant cells before being transported and stored in the vacuole. Some insoluble phenolics are bound or covalently linked to macromolecules of the plant cell wall, including pectin, cellulose, hemicellulose, and structural proteins. Additionally, physical associations with these components can involve hydrogen bonding and hydrophobic interactions, although to a lesser extent than covalent bonds (Roasa et al., 2021).

Understanding whether phenolic compounds in rice husk are present in free form or bound to the lignocellulosic matrix is essential, as only a small amount is found in free soluble form, whereas most phenolics acids are localized in the cell-wall matrix in bound forms (Colombo et al., 2024). This distinction determines the extraction severity required, with free phenolics recoverable under mild conditions (conventional techniques) and bound phenolics requiring hydrolytic or matrix-disruptive treatments—such as alkaline, thermal, or enzymatic processes—to break cell-wall linkages and enable their release (Kyriakoudi et al., 2023).

Total polyphenol content (TPC) is commonly expressed as gallic acid equivalent (GAE), a standard compound present in different vegetal matrices. This measurement allows for the assessment of the polyphenol content from rice husks while comparing to other plant sources. Various studies have reported that TPC values vary according to husk pigmentation. For instance, varieties such as straw, straw with a brown line, and speckled brown husks exhibit TPC ranges between (0.69–20.18), (18.66–29.90), and (1.08–1.72) mg GAE/g dry weight, respectively (Butsat et al., 2009; Butsat & Siriamornpun, 2010a, 2010b; Gao et al., 2018; Kaur & Ubeyitogullari, 2023; Smuda et al., 2018; Wisetkomolmat et al., 2023; Xavier et al., 2024). Similarly, purple husks exhibit notable TPC levels, ranging from 2.15 to 21.90 mg GAE/g dw (Butsat & Siriamornpun, 2010b; Nilnumkhum et al., 2017; Wisetkomolmat et al., 2023). Although high phenolic contents have been reported in both pigmented and non-pigmented husks, several studies have found that pigmented rice varieties contain higher levels of phenolic acids.

Conventional extraction techniques are used to obtain rice husk extracts, and the total polyphenol content (TPC) is then measured, whose results can vary due to several extraction parameters, such as solvent, time, agitation speed, and temperature (Table 1). For example, extraction temperatures between 60 and 80 °C maximize the recovery of polyphenols, while higher temperatures can lead to degradation due to the thermal sensitivity of phenolic compounds (Antony & Farid, 2022). Similarly, agitation improves extraction efficiency by increasing TPC, with higher agitation speeds resulting in greater recoveries compared to static extraction conditions (Sakdasukon & Thanachasai, 2022). In this sense, an agitation rate between 180 and 240 rpm is considered optimal to ensure effective mass transfer, whereas higher speeds lead to variability in equilibrium concentration and diffusion coefficient (Sridhar et al., 2021).

In the evaluation of various pigmentation categories of rice husk such as straw, straw with brown line, brown, speckled brown, and purple (Table 1), the highest total polyphenol content (TPC) values were obtained with 95 % ethanol as extraction solvent. While, aqueous methanol yielded comparatively lower TPC values. Ethanol's molecular structure, characterized by a polar hydroxyl group and a non-polar methyl group, facilitates interactions with the hydroxyl and aromatic groups present in polyphenols, thereby enhancing extraction efficiency (Martins et al., 2023).

In addition to solvent effects, variability inherent to the raw material should be considered. Variations in total phenolic content among rice husk samples can arise from factors inherent to each variety as well as from conditions experienced during plant development. In particular, differences in geographic area, climatic conditions, and soil composition influence the chemical composition of the husk, while the genetic makeup of each variety and preharvest environmental factors also contribute to these variations. Moreover, storage conditions and differences in analytical methodologies can affect the measured values, thereby explaining the variability commonly observed among samples (Wisetkomolmat et al., 2023).

2.1. Specific families of free polyphenols from rice husk

Various studies have identified ferulic acid and vanillic acid as the most prevalent phenolic acids in straw rice husk; concentrations can vary between 3.1 to 1360 μg/g dry (Butsat & Siriamornpun, 2010b; Gao et al., 2018; Wisetkomolmat et al., 2023; Xavier et al., 2024) and from 14.4 to 92.6 μg/g dw (Butsat & Siriamornpun, 2010a, 2010b), respectively. Other phenolic acids that have been detected include *p*-coumaric acid, and caffeic acid, with concentrations between 4.84–250 μg/g dry

Table 1
Total polyphenol content (TPC) extracted from pigmented and non-pigmented rice husks by solid–liquid extraction techniques (conventional techniques).

Rice husk pigmentation	Treatment conditions	TPC (mg GAE/g dw)	Reference
Straw	– Chilled 80 % acetone, reconstituted in 70 % methanol	1.20	(Gao et al., 2018)
Straw	– 95 % ethanol	10.63–20.18	(Wisetkomolmat et al., 2023)
Straw	– 80 % aqueous methanol – 25 °C – 16 h – 150 rpm	1.2–2.2	(Butsat & Siriamornpun, 2010a)
Straw	– 70 % (v/v) ethanol – 60 °C – 1 h – 200 rpm	1.19	(Xavier et al., 2024)
Straw	– 80 % aqueous methanol – 25 °C – 1 h	0.69–1.06	(Butsat & Siriamornpun, 2010b)
Straw	– Ethanol – 50 °C – 1 h	10.6	(Smuda et al., 2018)
Straw	– 80 % (v/v) methanol solution – 50 °C – 1 h	1.92	(Kaur & Ubeyitogullari, 2023)
Straw with brown line	– 95 % ethanol	18.66–29.90	(Wisetkomolmat et al., 2023)
Brown	– 80 % methanol – 37 °C – 150 rpm	1.1–2.1	(Butsat et al., 2009)
Speckled brown	– 80 % aqueous methanol – 25 °C – 1 h	1.08–1.72	(Butsat & Siriamornpun, 2010b)
Purple	– 95 % ethanol	20.79–21.90	(Wisetkomolmat et al., 2023)
Purple	– 0.1 % hydrochloric acid in absolute methanol – 72 h	2.15	(Nilnumkhum et al., 2017)
Purple	– 80 % aqueous methanol	2.38–2.56	(Butsat & Siriamornpun, 2010b)

TPC= Total polyphenol content.
mg GAE/g dw=mg of gallic acid equivalent (GAE) per gram dry weight (g dw).

(Butsat & Siriamornpun, 2010b, 2010a; Gao et al., 2018; Wisetkomolmat et al., 2023; Xavier et al., 2024), and 3.8–420 g dry (Gao et al., 2018; Wisetkomolmat et al., 2023), respectively.

Although straw rice husk presents phenolic acids as the major compounds, other polyphenols such as flavonols, flavanols, and flavanones have been quantified in this type of residue. For example, flavonols like quercetin (180- 460 μg/g), kaempferol (560–3590 μg/g), and rutin (210–330 μg/g dry) are among the most abundant phenolic compounds in straw rice husk, while catechin (360–2240 μg/g) and naringenin (200–690 μg/g) are the main flavanol and flavanones, respectively (Wisetkomolmat et al., 2023). Although the quantities of specific free polyphenols can vary based on factors such as rice variety and growing conditions, we summarize currently available values in Fig. 1 and include polyphenols identified in both pigmented and non-pigmented rice husks. The identification of these compounds was performed mainly by High-Performance Liquid Chromatography (HPLC) with diode array detection (DAD) or coupled to electrospray ionization quadrupole mass spectrometry (ESI–Q-MS), using C18 reversed-phase columns under gradient elution conditions. Fig. 1 presents the comparative profile of specific polyphenols in non-pigmented and pigmented rice husk.

3. Contrasting total polyphenol content: rice husk versus other agro-industrial residues

Various agro-industrial residues are a natural source of phenolic compounds with potential antioxidant capacity. These by-products represent a promising alternative to obtain bioactive phenolic compounds with diverse applications in food, pharmaceutical, and industrial sectors. However, the total polyphenol content can vary depending on the specific types of husk residue utilized (Fig. 2).

In particular, rice husks present the highest proportions of polyphenols (~30 mg GAE/g dw) compared to other husks such as soybean (~1.5 mg GAE/g dw), sacha inchi (~3.23 mg GAE/g dw), barley (~3.4 mg GAE/g dw), cacao pod (~7 mg GAE/g dw), and coffee (~10 mg GAE/g dw). Rice and almond husks have a similar amount of bioactive compounds (Fig. 2). However, the accessible amount of polyphenols is influenced by husk type, agricultural practices, and the extraction techniques employed to recover these compounds. Thus, comparing the polyphenolic content of one residue to another can be quite complex. Nevertheless, the relative concentrations displayed in Fig. 2 provide a summary of current estimates for available polyphenol content and highlight the potential of various residues as natural sources of antioxidant compounds.

4. Emerging extraction techniques for polyphenols

Although various conventional techniques can extract phenolic compounds, recent developments have focused on advanced and selective techniques that improve efficiency, reduce solvent use, and preserve the bioactivity of these compounds. In the following section, we highlight various emerging techniques for the extraction of phenolic compounds from rice husk. Among the emerging extraction techniques, several have been specifically applied to rice husk for the recovery of polyphenols (Table 2).

4.1. Enzymatic-assisted extraction (EAE)

Enzymatic-assisted extraction employs carbohydrate-hydrolyzing enzymes like cellulases, pectinases, and hemicellulases, which hydrolyze plant cell walls, increasing permeability and enhancing the extraction of bioactive compounds (Fărcaș et al., 2022). The hydrolysis process begins when enzymes break down cellulose into glucose. This environmentally sustainable method uses water as the main solvent and depends on the optimization of key parameters (Sridhar et al., 2021). Factors such as temperature, time, pH, enzyme dose, and substrate particle size critically influence the efficiency and selectivity of polyphenol recovery (Nadar et al., 2018).

Cellulase-assisted extraction has been employed to recover polyphenolic compounds from glutinous rice husk. For example, Jiamphun and Chaiyana (2022) reported that the use of low cellulase concentrations (0.5 %, w/w), a solid-to-liquid ratio of 1:5 (w/w), employed at a pH of 6.5 and temperature of 50 °C for 24 h, improved the extractability of vanillic and ferulic acids. Interestingly, ferulic acid was detected in EAE extracts and not in conventional ethanolic extraction, which can be attributed to the enzymatic hydrolysis of cell wall polysaccharides, facilitating the release of bound phenolics. Contrary, an increase in the cellulase concentration from 0.5 % to 1.5 % decreases the total polyphenol content by 43 %. According to Edo et al. (2025), excessive enzyme concentrations may release higher amounts of soluble cell wall fragments, which can interact with polyphenols and make them less accessible for extraction.

Park et al. (2016) optimized the extraction of tricin and polyphenols from rice husk by combining enzymatic hydrolysis with high hydrostatic pressure (EAE-HPP). Different food-grade enzyme concentrations (0.5 % v/w) were evaluated, like Celluclast, Pectinex, Rapidase, and Viscozyme; under pH 5.0 at 40 °C for 3 h, followed by HPP at 500 MPa for 6 min (20 °C). These enzyme preparations contain cellulase, as well as

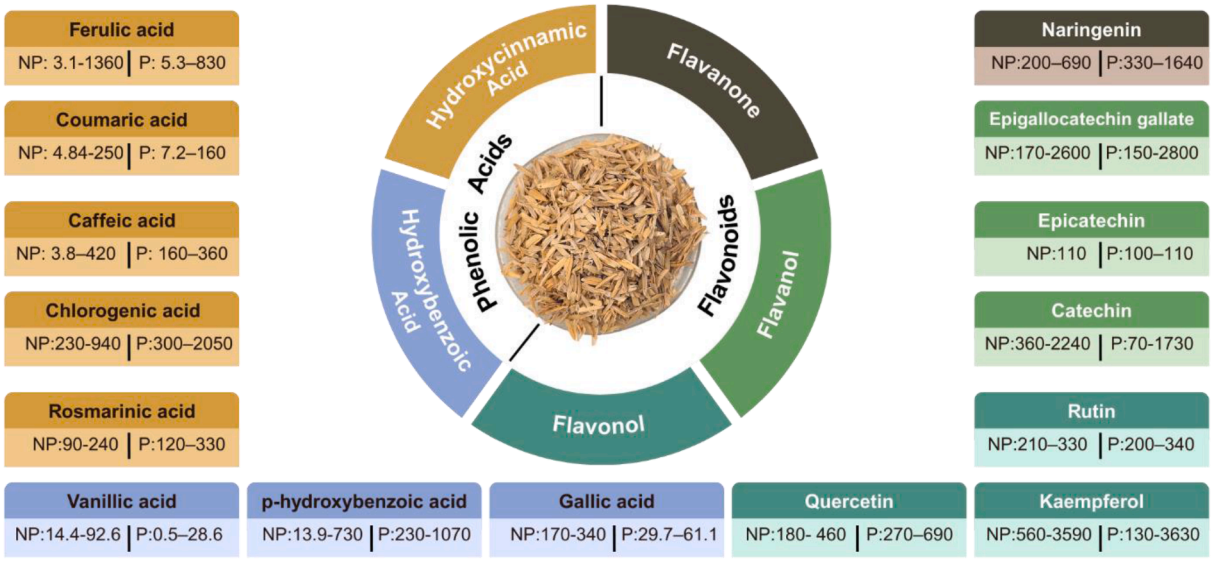


Fig. 1. Specific polyphenols identified in non-pigmented and pigmented rice husk. NP = non-pigmented rice husk; *P* = pigmented rice husk. Values expressed as μg g^{-1} dw.

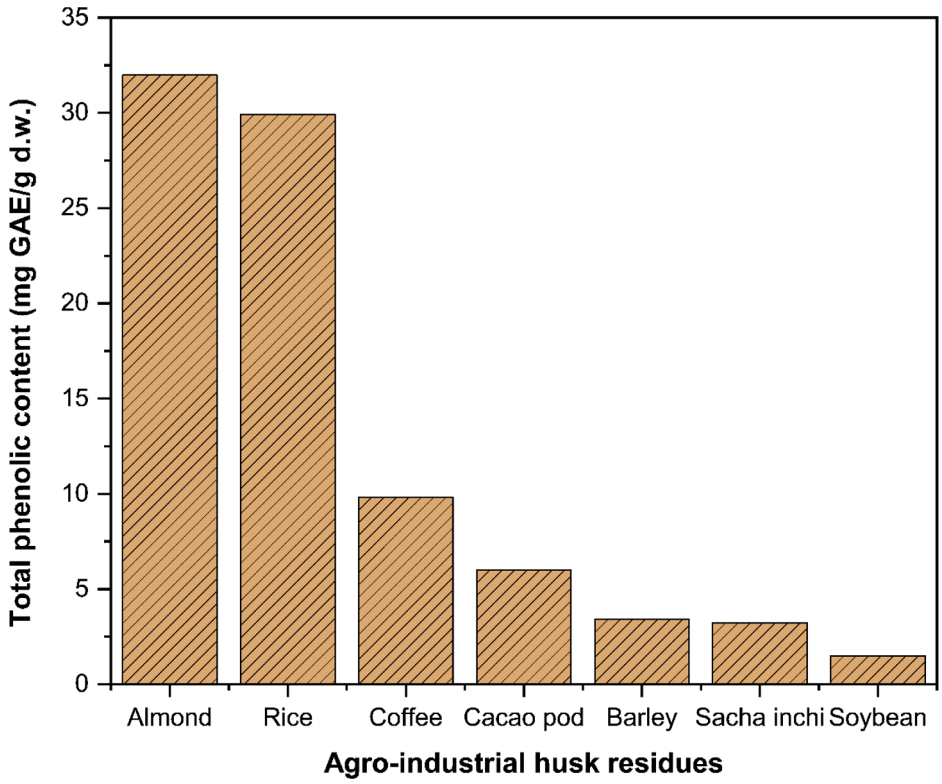


Fig. 2. Comparative Phenolic Content of Agro-Industrial Husk Residues and Rice Husk. Data compiled from previously reported studies (Cabezudo et al., 2021; Cangussu et al., 2021; Kahlaoui et al., 2019; Kittibunchakul et al., 2022; López-Perea et al., 2019; Valadez-Carmona et al., 2017; Wisetkomolmat et al., 2023).

pectinases, hemicellulases (e.g., xylanases), and esterases. Rapidase yielded the highest total phenolic content (3.550 mg GAE/g), compared to Pectinex (3.364), Celluclast (3.299), and Viscozyme (2.861 mg GAE/g). The use of EAE-HPP increased the extractability of polyphenols by around 2-fold compared with HPP (500 MPa) and conventional ethanol extraction (25 °C for 24 h). Although ethanol improves the solubility of polyphenols, the combined use of enzymatic hydrolysis and HPP significantly enhances the selective release of phenolic compounds. This new approach allows the disruption of the cellulose matrix, improving the release and potential bioavailability of bound phenolic acids.

Despite the substantial potential of EAE-based techniques, industrial applications are limited by the high cost of enzymes and the limited integration of enzymes in industrial-scale processes (Gligor et al., 2019). For instance, commercial preparations such as cellulase, pectinase, and Viscozyme are priced between approximately USD 140 and 170 per 50

mL (Sigma-Aldrich, 2025), highlighting the economic barrier for industrial implementation. Furthermore, factors such as incomplete disruption of the cellular matrix, enzyme instability under processing conditions, limited reusability, and the gradual loss of catalytic activity significantly hinder scalability for commercial applications (Ramalingam et al., 2019).

4.2. Microwave-Assisted extraction (MAE)

Microwave-assisted extraction uses electromagnetic radiation with frequencies between 30 and 300 MHz (Edo et al., 2025). Stimulating molecular motion generates heat and can break down cell walls and polyphenols. This heating occurs both internally and externally in the matrix with minimal thermal gradients and disruption of hydrogen bonds, making the process highly efficient (Osorio-Tobón, 2020). Because microwave radiation is absorbed by polar species, MAE predominantly relies on polar solvents like methanol, ethanol, or water (Gil-Martín et al., 2022). Frosi et al. (2023) found that use of 500 W during the MAE process, combined with 80 % ethanol for 5 min at 90 °C, yielded the highest amounts of polyphenols from rice husks. Simultaneously, reversed-phase high-performance liquid chromatography coupled with diode array detection and electrospray ionization multi-stage mass spectrometry (RP-HPLC-DAD-ESI-MS^n) predominantly identified hydroxycinnamic acids and flavonoids.

MAE is characterized by reduced extraction time, lower energy requirements, and decreased solvent consumption, while providing higher extraction yields (Zhao et al., 2018). Kyriakoudi et al. (2023) applied alkaline hydrolysis combined with MAE at 155 °C for 3.6 minutes using a solvent-to-solid ratio of 50:1 (v/w). Subsequently, ethyl acetate extraction was performed, yielding a high recovery of total polyphenols (2995 mg GAE/100 *g*). High levels of phenolic acids were detected, with *p*-coumaric acid ranging from 711 to 1269 mg/100 g and ferulic acid from 160 to 289 mg/100 g from dry rice hulls.

Industrial scale-up remains challenging, however, and there is limited information on the actual energy savings and environmental impacts associated with microwave use, such that the true sustainability of the process remains unclear (Bouchez et al., 2023).

4.3. Ultrasound-assisted extraction (UAE)

Ultrasound-Assisted Extraction (UAE) induces cavitation, vibration, crushing, and mixing in the extraction medium, which collectively enhance mass transfer and solvent penetration (Wen et al., 2018). The cavitation mechanism unfolds in four consecutive stages. Initially, cavitation bubbles form near the surface of the plant matrix due to ultrasonic wave propagation. These bubbles collapse violently, generating localized zones of high pressure and temperature. The resulting micro-jets impact the plant tissue, disrupting its structure and allowing direct contact between intracellular components and the surrounding solvent (Wen et al., 2018).

UAE has been demonstrated for the extraction of various polyphenols (Mounika et al., 2022), and several studies have demonstrated optimization of UAE conditions for enhanced recovery of phenolic compounds from agro-industrial residues. For example, Irakli et al. (2018) optimized UAE to recover free phenolics and combined UAE with alkaline hydrolysis (AH) to obtain bound phenolics. UAE with 41 % ethanol at 40 °C for 60 min yielded a high amount of free polyphenols (168 mg GAE/100 *g*), while UAE-AH conducted with 2.5 M NaOH at 80 °C for 120 min yielded bound phenolics (696 mg GAE/100 *g*). Ethanol was selected as the extraction solvent due to its low toxicity, biodegradability, and high availability in pure form.

Jha et al. (2017) combined UAE and MAE to recover phenolics from black rice husks. UAE used a sonication bath at 35 kHz, while MAE operated at 2450 MHz. Optimized conditions yielded 1.72 mg GAE/g after 10.02 min sonication time at 49.46 °C, using a 1:40.79 (w/v) solute-to-solvent ratio, 67.34 % ethanol concentration for UAE, and 31.11 s microwave time for the MAE process. Although this combined approach significantly reduces extraction time, optimization is necessary to minimize the degradation of phenolics caused by free radicals generated during ultrasonic cavitation (Campos-Lozada et al., 2022). The synergy between ultrasound and microwave irradiation enhances mass transfer through cavitation-induced cell disruption and rapid dielectric heating, which facilitates the efficient polyphenol release from the plant matrix. The effectiveness of the UAE is strongly influenced by factors such as ultrasonic frequency, acoustic energy, and amplitude. Frequencies between 20 and 50 kHz are generally considered optimal for maximizing cavitation effects and improving mass transfer (Lavilla & Bendicho, 2017; Medina-Torres et al., 2017). Although UAE is easy to operate and is cost-effective, reproducibility can be challenging due to the attenuation of ultrasonic energy by the solvent and the experimental setup that can reduce the acoustic intensity reaching the sample (Wen et al., 2018). Consequently, while ultrasonic baths are suitable for preliminary screening or small-scale extractions, their application in processes requiring consistent energy delivery may be limited.

4.4. Hydrothermal process (HP)

Hydrothermal processes operate at high temperatures (> 150 °C) and pressure up to 25,000 kPa (Park & Jo, 2019). Hydrothermal extraction is straightforward and safe and relies on self-generated pressure with often purified water as the solvent. Considered environmentally friendly, it is effective for extracting bioactive compounds; however, heat-sensitive phenolic compounds are vulnerable to degradation under these conditions (Brites et al., 2024).

For example, Brites et al. (2024) subjected rice husk to hydrothermal treatment for the extraction of phenolic compounds. Samples were autoclaved at 180 °C, 200 °C, and 220 °C, as well as through a sequential temperature protocol. The sequential extraction culminating at 220 °C yielded the highest total phenolic content, reaching 0.43 mg GAE/g. These results indicate that progressive heating enhances the release of phenolic compounds, likely due to a greater disruption of the plant matrix.

Although this process offers shorter processing times, reduced solvent use, it also allows the recovery of both polar and less polar compounds, making it an environmentally friendly and versatile technique. However, the resulting water extract requires additional steps such as evaporation, precipitation, or dehydration to remove excess solvents. Moreover, under subcritical conditions, water becomes more reactive and corrosive than at room temperature, thereby requiring more demanding maintenance and cleaning of the equipment (Žagar et al., 2024). In addition, subcritical water exhibits increased acidity, promoting hydrolytic degradation of polysaccharides, proteins, and polyphenolic compounds (Sarker et al., 2021).

4.5. SC—CO_2 extraction

Supercritical fluid extraction is an eco-friendly technique that operates under relatively mild critical conditions (31.1 °C, 7.4 MPa) (Kaur & Ubeyitogullari, 2023). Carbon dioxide, the most commonly used supercritical solvent, is chemically stable, non-toxic, and enables extraction at moderate temperatures and pressures, which promotes the preservation of heat-sensitive compounds (Da Porto & Natolino, 2017).

Although this technique provides a clean and selective approach, limitations in recovering bound phenolics highlight the need for complementary treatments when targeting the full phenolic profile. Accordingly, techniques that combine cell wall disruption strategies (e.g., high-pressure processing, microwave treatment, ultrasound-assisted extraction) with green solvents achieve higher phenolic recovery from rice husk than conventional techniques. For example, Kaur and Ubeyitogullari (2023) optimized supercritical CO_2 extraction using ethanol-water mixtures as cosolvents. The most effective conditions for phenolic recovery were established with 30 MPa, 60 °C, and a

water-ethanol mixture of 50 % (v/v), yielding 1.26 mg GAE/g. They evaluated the influence of solvent composition on yield and found that the extraction primarily recovered free phenolic acids, whereas the yield of bound phenolics was markedly lower. Thus, alkaline hydrolysis was required to release these bound compounds, indicating that supercritical CO_2 alone is not efficient for extraction. These approaches improve the release of bound compounds and enhance extraction selectivity, but their application at an industrial scale is still limited by cost, reproducibility, compound stability, and scalability. Thus, combined techniques represent the most promising pathway for sustainable large-scale production, although further optimization and techno-economic validation are still required.

Table 2
Emerging techniques for polyphenol extraction.

Extraction method	Optimal conditions	Extraction yield	Specific polyphenols	Reference
EAE	– 0.5 % w/w cellulase – pH 6.5 50 °C – 24 h	180.0 mg GAE/g extract	Vanillic acid (10,900 μg/g extract) Ferulic acid (3200 μg/g extract)	(Jiamphun & Chaiyana, 2022)
EAE +HPP	– EAE – 0.5 % v/w – pH 5.0 – 40 °C – 3 h – HPP – 100–500 MPa – 6 min – 20 °C	3.55 mg GAE/ g dw	Tricin (22.20 μg/g rice husk)	(Park et al., 2016)
UAE	– 40 °C – 60 min – 41 % ethanol	1.68 mg GAE/ g dw	*p*-coumaric acid (142.0 μg/g), ferulic acid (52.0 μg/g), vanillic acid (12.0 μg/g rice husk)	(Irakli et al., 2018)
MAE	– 500 W – 90 °C – 80 % ethanol – 5 min		C-glycosilated apigenin, hydroxycinnamic and hydroxybenzoic acid derivatives, and flavonols	(Frosi et al., 2023)
UAE+MAE	– UAE – 10.02 min – 49.46 C – 67.34 % ethanol – MAE – 31.11s – 2450 MHz	1.72 mg GAE/g dw	Gallic acid (2.98 μg/g), p-coumaric acid (31.19 μg/g), ferulic acid (20.45 μg/g), quercetin (46.84 μg/g), salicylic acid (17.95 μg/g), quinic acid (2682.37 μg/g), apigenin (1.34 μg/g), syringic acid (65.34 μg/g), chlorogenic acid (123.65 μg/g), and catechin hydrate (1.72 μg/g dry extract)	(Jha et al., 2017)
HP	– Heating rate of 5 °C/min – 1 h – 220 °C	0.43 mg GAE/g dw	——	(Brites et al., 2024)
SC-CO_2	– 30 MPa – 60 °C – 25 % ethanol	1.29 mg GAE/g dw	*p*-Coumaric, ferulic, and syringic acids	(Kaur & Ubeyitogullari, 2023)

5. Technological applications of phenolic compounds found in rice husk

Polyphenols exhibit a broad spectrum of biological activities, including antioxidant, anti-inflammatory, anticancer, antimicrobial, antidiabetic, antihypertensive, anti-obesity, and antiatherosclerotic effects (Zhang et al., 2022). These beneficial actions are associated with several mechanisms. They can scavenge reactive species and mitigate oxidative DNA damage, modulate cytokine production and secretion, induce apoptosis in abnormal cells, and inhibit digestive enzymes such as α-amylase and α-glucosidase. Additionally, polyphenols contribute to improved endothelial function and enhanced vasodilation. Due to these diverse properties, polyphenols are extensively investigated as active compounds in functional foods and health-related products aimed at preventing chronic diseases such as diabetes, cardiovascular disorders, and cancer.

Polyphenols derived from rice husk exhibit diverse biological activities, which are closely linked to their chemical structure. Especially, the number and position of hydroxyl groups on the aromatic ring are crucial. These groups facilitate hydrogen atom transfer, which enables the scavenging of free radicals and reactive oxygen species. This process significantly contributes to the prevention of oxidative stress and the protection of essential biomolecules such as lipids, proteins, and DNA (Bešlo et al., 2023; Rudrapal et al., 2022). Furthermore, these structural features are also associated with anti-aging activity.

In this regard, phenolic acids such as vanillic acid and ferulic acid have demonstrated the ability to inhibit collagenase and hyaluronidase. These two enzymes are responsible for degrading key extracellular matrix components like collagen and hyaluronic acid. This enzymatic inhibition is considered a fundamental mechanism in the prevention of skin aging (Jiamphun & Chaiyana, 2022).

Beyond these mechanisms, caffeic, vanillic, ferulic, chlorogenic, and p-coumaric acids have been reported to inhibit early glycation reactions. They achieve this by forming hydrogen bonds with amino acid residues, thereby reducing fructosamine formation and preventing protein crosslinking. These phenolic compounds also act as "trapping" agents for reactive carbonyl species, such as methylglyoxal, and preserve free lysine residues, thus establishing a direct relationship between their antiglycative and antioxidant mechanisms (Frosi et al., 2023). Vanillic acid isolated from purple rice husk further demonstrates significant antimutagenic activity by effectively reducing aflatoxin B1-induced micronucleus formation in rat liver. This effect is attributed to the induction of hepatic glutathione S-transferase, an enzyme that enhances the detoxification and elimination of genotoxic metabolites, thereby contributing to DNA protection (Nilnumkhum et al., 2017).

Polyphenols also exhibit potent antimicrobial activity by altering the structure of bacterial membranes. This leads to increased membrane permeability and the leakage of essential intracellular components, including potassium, ATP, nucleic acids, and proteins, compromising cellular integrity and function. Membrane depolarization and changes in fluidity have also been reported in association with polyphenol activity (Chen et al., 2024). The antimicrobial effectiveness of these compounds is closely linked to their degree of hydroxylation, which dictates their interaction with microbial membranes. For instance, caffeic acid demonstrates higher antimicrobial activity than p-coumaric acid due to the presence of an additional hydroxyl group on the aromatic ring (Panda & Duarte-Sierra, 2022).

In technological applications, polyphenols have been incorporated into chitosan-based films used in active packaging. Their inclusion significantly increases the antioxidant capacity of these films, enhances their overall functionality, and supports their applicability in food packaging (Brites et al., 2024). Within lipid-based systems, phenolic acids such as ferulic, p-coumaric, and vanillic acids effectively reduce lipid oxidation and improve the oxidative stability of both bulk oils and oil-in-water emulsions under moderate thermal conditions (Park et al., 2019).

In summary, various high-value applications of phenolic compounds derived from rice husk have been reported. These include integration into active packaging materials, stabilization of lipid matrices, and use as antioxidant, antiglycative, and chemopreventive agents. The primary applications and associated techniques reported in the literature are summarized in Table 3.

5.1. Patent literature focused on health-related products containing polyphenols from rice husk

Multiple patent claims focus on extraction techniques and purification of valuable polyphenols from waste rice husks, as well as applications of polyphenols. The generation of intellectual property encourages commercialization by providing legal protection, which promotes private investment in obtaining beneficial compounds and developing innovative products from materials that would otherwise be discarded.

Several patent applications involve the use of rice husk polyphenols in the development of therapeutic formulations. These formulations are intended for the treatment and prevention of diseases such as lung and breast cancer, as well as depressive disorders and metabolic conditions. Furthermore, these formulations have been reported to exhibit histamine receptor antagonism and to support the innovation of beverages with potential health benefits (Table 4).

6. Future perspectives

Although multiple techniques have been proposed for the extraction of polyphenols from rice husks, progress in efficiency and sustainability remains warranted. The exploration of other green solvents like glycerol, isopropanol, and natural deep eutectic solvents (NADES) has the potential to move the field forward. Pressurized liquid extraction is a promising approach, as it allows for the optimization of solvent composition and operational parameters to enhance the recovery of target compounds. This technique has been successfully applied to other agricultural residues, although the potential for rice husk has not been systematically studied.

Furthermore, most current studies do not consider the localization of bioactive compounds within the rice husk structure, which is critical for selecting appropriate extraction strategies. The application of advanced imaging and microstructural characterization techniques could provide valuable information on the spatial distribution of these compounds. Applying such approaches to rice could further advance our description of the spatial distribution and local environment of bioactive compounds.

As highlighted by Rongpipi et al. (2019), the comprehensive characterization of plant cell wall architecture and cellulose structure requires an integrated approach using techniques such as atomic force microscopy (AFM), solid-state nuclear magnetic resonance (ssNMR), and X-ray diffraction (XRD). These techniques provide information on surface topography, polymer interactions, and crystallinity, and have been applied successfully to study the spatial organization and mechanical properties of cellulose. Their application to rice husk could facilitate a more detailed understanding of the structural matrix in which polyphenols are embedded, thereby guiding the optimization of extraction techniques. Additionally, preserving the integrity of the cellulose fraction after polyphenol removal would enhance recovery and functional applications.

Rice husk polyphenols demonstrate significant potential for incorporation into active packaging systems due to their antioxidant and antimicrobial properties. Moreover, following polyphenol extraction, the remaining biomass could be further valorized through the recovery of cellulose, contributing to an integrated and sustainable use of this agro-industrial by-product.

7. Conclusions

The high content of polyphenolic compounds in rice husk highlights the potential of this agricultural residue as a valuable source of bioactive molecules. Among these constituents, ferulic, *p*-coumaric, caffeic, vanillic and chlorogenic acids stand out for their specific functional properties. These compounds exhibit promising functional properties, including antioxidant activity, antimicrobial, antiaging and chemopreventive effects, which support their use across food, cosmetic, pharmaceutical, and packaging industries. Moreover, recent developments in extraction techniques have improved the recovery of these compounds, opening the door for incorporation into bioplastics, functional foods, cosmeceuticals, and health-promoting formulations on a commercial scale. Further work may advance and establish rice husk as a sustainable raw material, in particular if the interaction between polyphenol structure and functional behavior in different applications can be accurately described. The high potential for innovation in fields where natural antioxidants and multifunctional ingredients are in growing demand may lead to substantial societal advances in the near future.

CRediT authorship contribution statement

Milagros Sofia Bustamante-Bernedo: Writing – review & editing, Writing – original draft, Project administration, Investigation, Funding acquisition, Conceptualization. **Enrique D. Gomez:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization. **Nils Leander Huamán-Castilla:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization.

Table 3
Functional applications of rice husk-derived phenolics.

Component	Technique (Description)	Application	Reference
Phenolic compounds	Chitosan-based films with rice husks water extract.	Bioplastics for active food packaging	(Brites et al., 2024)
Hydroxycinnamic acids and flavonoids.	A microwave assisted extraction to recover rice husk polyphenols.	Antiglycative and antioxidant ingredient	(Frosi et al., 2023)
p-coumaric acid, vanillic acid, and ferulic acid.	In vitro antioxidant properties of extracts of rice hulls.	Enhanced oxidative stability in bulk and oil-in-water emulsion	(Park et al., 2019)
Vanillic and ferulic acid.	Antioxidant and anti-aging activity assays applied to rice husk extracts, including radical scavenging and collagenase inhibition tests.	Development of natural antioxidants and anti-aging agents for cosmeceutical and anti-wrinkle products	(Jiamphun & Chaiyana, 2022)
Vanillic acid	Mutagenicity and antimutagenicity assays applied to purple rice husk extracts, including the Salmonella mutation assay and rat liver micronucleus test.	Natural antimutagenic agents for cancer chemoprevention	(Nilnumkhum et al., 2017)
Anthocyanins (malvidin-3-glucoside, peonidin-3-glucoside, cyanidin-3-glucoside) and vanillic acid	In vivo assays evaluating the chemopreventive effects of purple rice husk extract in chemically induced hepatocarcinogenesis in rats.	Chemoprevention of early-stage liver cancer through detoxification enzyme modulation and apoptosis induction	(Punvittayagul et al., 2021)

Table 4
Patents on rice husk polyphenol-based products and their claimed health benefits.

Application	Main composition	Pharmacological properties	Patent number	Publication year	
Health product	Rice husk polyphenols extract	Anti-lung cancer activity	CN107158161A	2017	Rejected
Health product	Rice hull flavonoids extract	Anti-breast cancer function	CN107156842A	2017	Rejected
Health-care product	Rice hull flavonoids extract	Antidepressant activity	CN107184834A	2017	Rejected
Pharmaceutical composition	Germinated rice hull extract	Preventing or treating diabetic or diabetic complications	KR101854960B1	2018	Granted
Pharmaceutical/Health product	Rice hull extract	Improving sleep disorders, anxiety, and depression Histamine receptor antagonist	US2015320823A1	2015	Abandoned
Processed product	Rice husk extract	Development of beverages with potential health benefits	KR20190059579A	2019	Rejected

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.

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Data availability

Data will be made available on request.

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