Rice straw as a valuable source of cellulose and polyphenols: applications in the food industry

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Abstract.

Background: Rice plants generate a large amount of straw after harvesting, which is currently managed mainly by incineration or used as animal bedding, animal fodder or wrapping of materials during transport. Other technological uses, such as the production of energy and biofuels, pulp and paper production or construction materials have also been described. However, due to the current European Union (EU) restrictions, alternatives for waste management must be sought. Valorisation of rice straw is aligned with the Sustainable Development Goals agenda set by the EU, since interesting biocompounds have been described in its composition and, after a successful extraction and purification, they can be used in various sectors.

Scope and Approach: This review gathers the most relevant works related to the valorisation of rice straw. It focuses on polyphenolic extracts and cellulose derivatives obtained by different extraction techniques, either conventional or innovative. In addition, the different applications that these compounds have in the field of food and nutrition sciences are summarized.

Key Findings and Conclusions: Polyphenols and cellulose fractions have shown their viability to be extracted from rice straw, showing great potential as antioxidants in the food sector or as nutritional components in the development of new food or packaging materials, respectively. In conclusion, the valorisation of rice straw as a rich source of valuable compounds has been demonstrated, which currently generates serious environmental and human problems due to difficulties in its management and incineration, adding value to these underutilized residues and contributing to the circular bioeconomy concept.

Keywords: *rice straw by-products, polyphenols, cellulose, valorisation, food applications, nutrition.*

1. Introduction

Rice (*Oryza Sativa*) is the most consumed cereal in the world, providing a major component of diet for more than half of the population, especially in developing countries. According to the Food and Agriculture Organisation of the United Nations (FAO), around 760 million tonnes of rice are produced per year on a global area of 164 million hectares spread over many countries in the world (FAO. Retrieved April 4, 2022). Asia is the world's leading rice producer, with total production amounts of 90%, followed by Latin America and Africa. In Europe, only the Mediterranean countries grow this cereal crop. Around two-thirds of the rice consumed in Europe is grown in the European Union (EU), and particularly in Spain with around 783,000 tonnes of rice per year (Volume of grain paddy rice produced in the different Spanish autonomous communities in 2020. Retrieved April 8, 2022). Concerning these numbers and due to this extensive global consumption, the processing of rice crops results in a unique combination of lignocellulosic waste streams broadly available at the field as rice straw (RS) or the milling site as rice husk.

Rice is the second most produced food grain worldwide, after wheat and generates some 972 Tg of waste per year (Gupte, Basaglia, Casella, & Favaro, 2022). In particular, RS is considered as a low value-added material that causes huge environmental problems in its management. Approximately 6 tonnes of RS per hectare are produced each harvesting season (Ribó, Albiach, Pomares, & Canet, 2017; Torregrosa, Miguel Giner, & Velázquez-Martí, 2021). In total, between 370-520 million tonnes of RS are produced each year, making it the most abundant agricultural waste worldwide (Van Hung et al., 2020).

Due to the presence of high contents of fibre in its composition, its biodegradability is very low, resulting in its accumulation on the fields. Burning has been traditional solution for disposal, an easy and cheap practice with high environmental impact (Fig. 1). This method is an affordable procedure and has some positive effects such as eliminating weed seeds and reducing the presence of other pathogens. But this method does not consider major environmental and social problems. For example, the smoke produced in the combustion of this crop waste, combined with weather conditions, represents a significant risk of developing acute respiratory diseases for the population living near the rice fields. Furthermore, these emissions are a source of highly polluting atmospheric particles and volatile organic compounds which can affect the climate, the hydrological cycle, and the visibility in the area (Phuong et al., 2021; Singh, Gupta, Chaurasiya, Sharma, & Pimenov, 2021).

As a result, the EU common agricultural policy (CAP) issued in 2018 proposed a progressive reduction of this practice until it would be eradicated with the new CAP due to be implemented from 1st January 2023 (CAP transitional regulation, Retrieved April 26, 2022). This legislative requirement has forced farmers to remove thousands of tonnes of RS lying in the fields after each harvesting season, and they should face with a lack of resources to properly manage this waste.

One of the alternatives to burn straw is its direct incorporation as a soil amendment, but this practice generates a lot of controversy among the scientific community (Singh et al., 2021). According to Fu et al. (2021), this practice brings benefits to the soil in the form of organic material. On the contrary, other studies reported that this practice could be detrimental for groundwater, climate and biodiversity in the crop areas if the incorporation of RS into the soil does not take place correctly, with a previous treatment and in particular times during the harvesting season (Gummert, Hung, Chivenge, & Douthwaite, 2020). According to Torregrosa et al. (2021), these current strategies for RS removal from the fields are not profitable processes for farmers since this by-product has not a market value to cover management costs, such as processing and transport. In other rice-producing areas, such as California, the competent administrations have subsidised packaging and transportation of RS as an alternative to burning in terms of sustainability.

Other alternative practice is the efficient removal of RS from the fields with multiple uses, such as energy and biofuels (S. Kumar et al., 2021; Logeswaran, Shamsuddin, Silitonga, & Mahlia, 2020), pulp and paper (Lai et al., 2022), construction materials (Quintana-Gallardo, Romero Clausell, Guillén-Guillamón, & Mendiguchia, 2021), compost (Ghasemzadeh et al., 2022), livestock (Abo-Donia, Ahmed El-Shora, Abd-Elaziz Riad, Basuony Elgamal, & Abdel-Menaem El-Hamady, 2022) and mulch to prevent soil erosion and to reduce water losses (Parhizkar et al., 2021).

Due to these costs and the new EU regulations, finding new outlets for RS becomes necessary. Further applications of this waste and the use of extraction technologies looking for target compounds, such as lignocellulosic fractions, open a potential field to obtain high added value compounds from an agri-food waste and, consequently, it can be considered a clear example of circular economy strategies.

RS can become a source of high added-value products such as polysaccharides or sugars, amino acids, polyphenols, fatty acids, etc., since they can be successfully recovered thinking in an overall economic process (Gummert et al., 2020; Gupte et al., 2022) (Fig. 1). Some research has focused on the extraction of cellulose or lignin from RS (Torregrosa et al., 2021). However, other bioactive compounds, such as phenolics, show also high potential applicability in food, nutrition, cosmetics and pharmaceutical sectors (Capanoglu, Nemli, & Tomas-Barberan, 2022).

This manuscript is specifically devoted to researchers with expertise and interests in biotechnology, as well as to agronomists, nutritionists, scientists with a focus on food, cosmetics of pharmaceutical science and industries seeking potential and more promising valorisation routes of RS.

Fig. 1.

2. Composition and properties of rice straw

RS is composed of the stalk and leaves of the rice plant. The stem is cylindrical in shape, with a length between 60-120 cm, with alternating nodes and internodes, while leaves show an elongated and flat shape and are located alternately through the stem (Fig. 1). These plant fibres have a complex matrix composed mainly of cellulose, lignin and hemicelluloses, among other bioactive compounds. The main function of these compounds is to form the structural network of plant cells, where the hemicelluloses bind to the celluloses through hydrogen bonds, supporting the lignins which in turn act as a natural adhesive.

Depending on the constituent sugars of the polysaccharides, we can differentiate between cellulose, whose structural unit is glucose, and hemicelluloses, which are formed by different monosaccharides. Cellulose is an abundant, renewable, non-toxic, and relatively cheap biopolymer found in Nature; but it is also produced as waste in different industrial sectors. Depending on its source, this linear biopolymer is composed of hundreds to thousands of repeated units of β-glucose molecules linked in the (1-4) position. High molecular-weight cellulose has the ability to form crystalline fibres (Nur Amirah Mamat Razali et al., 2022). Depending on the configuration of the carbon structure and hydrogen bonds, cellulose can be sorted out as primary (I), secondary (II), tertiary (III) and quaternary (IV) according to its biological source, such as trees (I), plants (I, II, III), agro-food waste (III), and algae, some marine organisms and bacteria (IV) . Separation of cellulose from plant structures is quite difficult since it is usually trapped between hemicellulose and lignin. In addition, cellulose is insoluble in common solvents by its complex structure of hydrogen bonds between molecules (Nur Amirah Mamat Razali et al., 2022).

In contrast, hemicelluloses are heteropolysaccharides with lower molar weight than cellulose, and therefore easier to hydrolyse under mild conditions to form their constituent sugars. This is due to their amorphous character and short-chain branching, including pentoses, hexoses and uronic acids. Specifically, they form the second most common compound in vegetable fibres and properties include their hygroscopic nature due to the hydroxyl groups present in their structure, which are able to form hydrogen bonds with water (Qaseem, Shaheen, & Wu, 2021). However, they have a degree of polymerisation between 80-200, lower than cellulose, as already reported (Dias et al., 2022). They are classified into four groups depending on their structure: xyloglycans, mannoglycans, xyloglucans and mixed-linkageb-glucans, with different variations in their bonds, chains and ramifications (L. Z. Huang, Ma, Ji, Choi, & Si, 2021).

On the other hand, plant fibres also present non-structural components that constitute a minor fraction in their composition in the form of organic and inorganic matter, mainly water, extracts and ashes. In particular, RS has variable composition (Table 1) in moisture (3.30-10.97%), total solids (TS) (89.03-96.70%), volatile solids (VS) in TS (73.28-95.26%), and ash content (4.78-26.72%) depending on the geographical origin and harvesting conditions (S. Kumar et al., 2021; Logeswaran et al., 2020). Ultimate properties of RS are determined by its carbon hydrogen, nitrogen, sulphur, and oxygen contents, which are comprised between 31.00-47.00%, 4.61-5.40%, 0.28-1.39%, 0.14-0.72%, and 50.46-59.98% respectively (S. Kumar et al., 2021; Logeswaran et al., 2020). In addition, RS is generally composed of 28-45% α-cellulose, 12-32% hemicellulose, 23-28% pentosans and 5-24% lignin, with the major components defining the composition of any lignocellulosic biomass (Kaur, Bhardwaj, & Lohchab, 2017). RS also consists of some components with a minor fraction of soluble and insoluble materials, such as proteins, waxes, pectin, and minerals. The proportion of these components varies with crop variety, growth stage, environmental conditions, soil quality and other related parameters (S. Kumar, Paritosh, Pareek, Chawade, & Vivekanand, 2018).

Table 1. Composition of several RS sources from different geographical origin.

Country of origin	Composition (%)				Reference
	Cellulose	Hemicellulose	Lignin	Others	
India	32.4 ± 1.06	28.3 ± 0.97	19.60 ± 2.02	Extractives: 11.27 ± 1.52 Ash: 8.43 ± 0.70	(Louis, Venkatachalam, & Gupta, 2022)
Malaysia	53.02	22.77	30.98	Holocellulose: 75.79 Ash: 12.00 Extractives: 4.20	(Nur Amirah Mamat Razali et al., 2022)
Indonesia	37.5	35.4	14.5	Ash: 11.3	(Raudhatussyarifah, Sediawan, Azis, & Hartati, 2022)

India	28.5-41.0	15.3-25.9	6.2-12.6	SiO_2: 5.0-8.0	(Bhattacharyya et al., 2020)
Iran	38.4	25.6	21.0	Ash:11.0 Extractives: 4.0	(Dilamian & Noroozi, 2019)
Iran	32.0-38.6	19.7-35.7	13.5-22.3	Ash: 10.0-17.0	(Mirmohamadsadeghi & Karimi, 2020)
China	42.2 ± 2.7	24.2 ± 5.4	20.8 ± 3.7	-	(Y. F. Huang & Lo, 2019)

Polyphenols are other compounds present in RS that are generating a lot of interest due to the benefits that they can offer. Polyphenols are a broad group of natural compounds generated by the secondary metabolism of plants with at least one aromatic ring linked to one or more hydroxyl groups, which can perform different functions by preventing or delaying cellular oxidation in plants through pigmentation mechanisms, as well as by participating in defensive mechanisms against pathogens attack. Polyphenols are soluble in the vacuoles of plant cells and insoluble in plant cell walls (Tapia-Quirós et al., 2022). According to the literature, different polyphenols can be found in RS residues depending on their structure, but they are mainly divided into phenolic acids, stilbenes, and flavonoids (Khosravi & Razavi, 2020). Although these compounds share some characteristics, they differ in their physico-chemical properties due to their different structures, which is a key factor when extracting them.

3. Strategies for recovering biocompounds from RS

Different extraction methods can be used to valorise RS with the aim to obtain cellulose, hemicellulose, polyphenols, total fibre, fatty acids, and other valuable compounds. The selection of the most suitable extraction method is based on the physical and chemical characteristics of the bioactive compounds to be extracted. However, this review is mainly focused on chemical, mechanical processes, their hybridization, and other sustainable methods to obtain cellulose and polyphenols, which are important fractions with multiple potential applications (Gummert et al., 2020). Fig. 2 summarizes the main advantages and limitations of some techniques used to obtain a valuable fraction based on cellulose or polyphenols from RS.

Fig. 2

3.1 Traditional extraction processes

Traditional extraction techniques based on chemical or mechanical processes have been highly popular by their simplicity. The most common methods are based on conventional solid-liquid extraction using organic or aqueous solvents, with alkaline or acid reagents, at high temperatures and specific time intervals (Dilamian & Noroozi, 2019). Solvent can penetrate the solid matrix, disrupt it, and dissolve the essential compounds, with further diffusion out of the solid matrix and collection of the extracted solutes.

Sometimes, due to the sample nature, a pre-treatment is necessary to remove fractions that could difficult the overall extraction process and reduce yields. In the case of cellulose extraction, a previous removal of the lignin and hemicellulose fractions is necessary.

Oxidation with hydrogen peroxide or sodium hypochlorite is often used as the most adequate pre-treatment in these extraction processes. Thakur et al. (2020) removed lignin and hemicellulose fractions by treating RS first with 12 wt% NaOH at 121 °C for 1 hour and then with 5 wt% acidified sodium chlorite at 75 ºC for 90 min. Then, cellulose nanocrystals (CNC) were obtained from RS-extracted cellulose by acid hydrolysis with sulphuric acid. Dilamian and Noroozi (2019) extracted cellulose from RS using conventional organic solvents, such as a mixture of toluene and ethanol 2:1 (v/v). In their process, they used a 1.25 wt% acidified $NaClO_2$ solution at a liquid-to-solid ratio of 15 mL/g and 75 °C for 1 hour to remove lignin after chemical pre-treatment to subsequently obtain cellulose nanofibers by a mechanical processes, including compression techniques and steam explosion, among others (Dilamian & Noroozi, 2019). These techniques produce a transversal rupture along the longitudinal axis of the cell fibres, causing an increase in the extraction yield. In the case of cellulose, this can be performed in several steps and smaller and more uniform crystals are obtained, but with a lower percentage of crystallinity, reducing the overall extraction yield of these nanoparticles. Razali et al. (2022) carried out a comparative study between chemo-mechanical extraction of cellulose and pulping techniques in RS. Alkaline pulping resulted in a high percentage of extracted cellulose (84.9%), while in the chemo-mechanical process, lower rates were obtained (75.9%).

In the case of polyphenols, these are usually linked by covalent bonding to insoluble polymers, as in RS structures. Therefore, it is necessary to use an extraction method capable of an efficient release of these compounds without degradation (Menzel, González-Martínez, Vilaplana, Diretto, & Chiralt, 2020). Organic solvents are commonly used in these processes as well as water or hexane when non-polar solvents are required. The most adequate solvent is selected by considering the polarity of the active compounds to be extracted. Karimi et al. (2014), extracted phenolic and flavonoid compounds from RS in different crop varieties using solid-liquid extraction methods with 80% (v/v) methanolic solution under reflux for 2 hours at 90 °C, obtaining extracts with high antioxidant activity. Other authors extracted phenolic compounds using a stirring method resulting in a total content of polyphenols of 256 mg of gallic acid equivalents (GAE)·per 100 g RS (Freitas, González-Martínez, & Chiralt, 2020). The properties of the extraction solvent, such as diffusivity and solubility, solvent-solid ratio, particle size, extraction time, and temperature, can influence the extraction efficiency. In general terms, these chemical extraction methods require large volumes of organic solvents and long extraction times (Fig 2).

3.2. Current trends to improve sustainability in extraction, innovative methods.

Based on the current trends to improve sustainability in extraction, innovative methods, such as extraction assisted by microwaves (MAE), ultrasounds (UAE), or hybrid techniques, i.e. either both techniques simultaneously or alternatively during the same extraction process, were used to recover polysaccharides and phenolic compounds from RS.

These methods have been proposed to reduce the limitations shown by conventional extraction, since they offer shorter extraction times, less energy requirements and solvent amounts. Besides, these "green" extraction techniques are in line with sustainable development strategies (Fig. 2) (Picot-Allain, Mahomoodally, Ak, & Zengin, 2021).

MAE is a "green" extraction method based on the direct impact of microwaves energy, in the frequency range of 300 MHz–300 GHz on polar compounds. Electromagnetic is transferred to heat following ionic conduction and vibration/oscillation of the polar molecules, causing interand intra-molecular friction (Mirzadeh, Arianejad, & Khedmat, 2020). Intracellular heating ultimately leads to pressurization effects that induce the breakdown of cell walls and membranes, as well as electroporation effects (Picot-Allain et al., 2021). On the other hand, UAE is typically used for the disruption of cell walls and membranes by creating compression and decompression through sound waves at frequencies higher than 20 kHz. This extraction method is also improved by the acoustic cavitation that facilitates the solvent penetration into cells and, the release of the intracellular compounds to the bulk solvent (Gordalina, Pinheiro, Mateus, da Fonseca, & Cesário, 2021).

UAE with output power 500 W and irradiation time 40 min was used to obtain cellulose nanofibers (CNF) from previously extracted cellulose (Dilamian & Noroozi, 2019). Freitas et al. (2022) compared the extraction of phenolic compounds from RS by UAE and stirring, obtaining higher total polyphenol content in fractions obtained by UAE. Putra et al. (2022) carried out a comparative study between different polyphenol extraction methods: maceration, Soxhlet and UAE, obtaining higher yields for the latter. Louis et al. (2022) extracted CNF from RS using a combination of MAE and UAE, obtaining extraction yields of 84.51 ± 1.21% of cellulose with 93.37 ± 2.43% purity.

In summary, these novel and sustainable extraction techniques (MAE and UAE) have proved to be more economical and environmentally-friendly than conventional extraction techniques for RS. Moreover, with these new technologies, multiple quantitative extractions can be simultaneously achieved with controlled temperature and high reproducibility.

In addition, promoting the use of green solvents is one of the strategies used to get more efficient and sustainable methods for extraction (Torres-Valenzuela, Ballesteros-Gómez, & Rubio, 2020). Moreover, the use of green solvents supports the production of chemical-free compounds recognized as safe and preferred by consumer (Garcia-Vaquero, Rajauria, & Tiwari, 2020). Some authors have proposed the use of supercritical fluids and bio-based and supramolecular neoteric solvents to replace conventional organic solvents (Fernández, Boiteux, Espino, Gomez, & Silva, 2018; A. K. Kumar, Parikh, & Pravakar, 2016). Asim et al. (2021) produced delignification from

RS using an ionic liquid based on food-grade cholinium hydroxide and lysine to obtain food-grade glucose from hydrolysed cellulose pulp

In this context, a new concept of green solvents is called "natural deep eutectic solvent" (NADES). These have gained considerable attention for the extraction of bioactive compounds due to their unique physical and chemical characteristics and their biodegradable and lower toxicity and lower cost than ionic liquids (Tang, An, & Row, 2021). The applications of NADESs in the extraction of rice by-products are beginning to emerge because NADES are considered suitable solvents in extraction and separation processes (Guti, Palos-hern, Burrieza, Luis, & Gonz, 2022; Santos et al., 2022).

4. Rice straw as a source of valuable extracts: cellulose and polyphenols

4.1. Morphological form of cellulosic particles

Rice straw can be considered a significant source of cellulose, and several authors have been recently working in its isolation and processing with application in different sectors (Binyaseen et al., 2022; Saini, Kardam, Kadam, Kumar, & Gaikwad, 2022). Table 2 summarizes the main studies works obtaining different morphological forms of cellulose particles from RS with applications in the pharmaceutical, cosmetic, biomedical, and food sectors (He et al., 2021). The efficient extraction and isolation of cellulose from RS represent a major challenge, but research in this field is continuously increasing since this compound, together with lignin and hemicelluloses, are potential sources of functionalised materials, such as nanocelluloses, microcrystalline cellulose (MC), and nanolignins (Louis et al., 2022; Perumal, Nambiar, Moses, & Anandharamakrishnan, 2022; Singh et al., 2021).

4.1.1. Cellulose fibres from RS

Cellulose fibres were obtained from RS residues using an alkaline treatment with NaOH 2 M for 2 h at 90 ºC (Dinh Vu, Thi Tran, & Duy Nguyen, 2018). These authors found that, after this treatment, lignin and other compounds remained on the fibres surface, showing a yellowish colour, which were further treated to limit the moisture adsorption. The alkaline treatment converted the hydrophilic -OH groups into hydrophobic -ONa groups, reducing their affinity for water. Other authors obtained cellulose from RS with reduced crystallinity (from 64.5% to 50.1%) due to a silanisation process, which was carried out to improve the mechanical properties and, therefore, the final applicability of the obtained cellulose fractions (Nur Amirah Mamat Razali et al., 2022). Cellulose fibres have been also used to improve foods' physical and textural properties. For example, the incorporation of these fibres into yoghurt can modify whey separation, water holding capacity, viscosity, firmness, adhesiveness, cohesion, elasticity, gumminess, and chewiness (Güler-Akın et al., 2018).

4.1.2. Microcrystalline cellulose from RS

Cellulose has been also extracted from RS in the form of MC or nanocellulose. Some authors proposed the extraction and isolation of MC by enzymatic processes or by acid hydrolysis, with a wide range of applications in the pharmaceutical, food, and cosmetic fields (Nsor-Atindana et al., 2017; Xu, Zhang, Cao, Wang, & Xiao, 2016). Raudhatussyarifah et al. (2022) carried out two acid hydrolyses to obtain MC from RS in order to release this fraction from the amorphous part of the cellulose structure. These authors reported extraction yields of 54.77 % and 57.62 % for the hydrolysis carried out by using sulphuric acid or 1.5 M hydrochloric acid, respectively. However, these treatments have to be optimised since MC crystallinity depends on the plant source, and it can be evidenced by the FTIR characteristic bands observed in the 2918-2851 cm^{-1} and 3800-3000 cm^{-1}, regions, as well as other characteristic peaks observed for lignin and hemicellulose fractions. Luo et al. (2019) obtained a yield of 93.2% for MC extracted from RS using organosolv fractionation for 6 h followed by bleaching for 10 h.

4.1.3 Carboxymethyl cellulose from RS

Alternatively, carboxymethyl cellulose (CMC) can be also obtained from RS. This hydrophilic colloid is considered a safe and non-toxic product as well as a binding ingredient to provide uniform textures in many matrices. CMC can increase viscosity and limit foods and materials hydration with wide applications in food, cosmetics, textiles, and pharmaceutical sectors (Rodsamran & Sothornvit, 2020). The final properties of CMC will depend on the degree of substitution achieved in the -OH groups of the cellulose, in C_2, C_3, and C_6 positions, which are substituted by the sodium carboxymethyl group (Masrullita et al., 2021).

4.1.4 Nanocelluloses from RS

Cellulose-derived nanomaterials have received much attention for their excellent properties, such as low density, high tensile strength, low toxicity, and high aspect ratio (Gurudatta, Saquib, Gupta, & Swati, 2022). Cellulose nanofibres (CNF), cellulose nanocrystals (CNC), or cellulose nanospheres (CNS) are examples of nanocelluloses that have been obtained from different materials (Verma, Chhajed, Gupta, Roy, & Maji, 2021), and they can also be used in the food sector (LakshmiBalasubramaniam, Patel, Nayak, Howell, & Skonberg, 2021; Louis et al., 2022). Zhao et al. (2019) obtained CNCs and CNFs from RS using acid hydrolysis. CNCs were rod-shaped with an average diameter of 9.1 nm, and a network with an average diameter of 13.3 nm was achieved for CNFs. Authors also noted that the crystallinity indices and thermal stability of nanocellulose were also dependent on its source. In this work, RS was compared to poplar wood, and it was observed that the arrangement and length of the hydrogen bonds were different in the nanocellulose obtained from each material. As a result, a more regular arrangement and shorter length in poplar wood resulted in higher hydrogen bond energy, higher crystallinity and thermal stability of the nanocellulose. Razali et al. (2021) obtained CNCs from RS of an Indica variety by HCl hydrolysis, reporting a crystallinity value of 56.12% and a production yield of 40.87%. A lower yield (25.6%) was obtained by Oun and Rhim (2018) when an oxidation process of CNCs was performed to increase the free swelling capacity.

Response surface methodology (RSM) was used to isolate CNCs from RS by acid hydrolysis (Thakur et al., 2020) by studying three different variables (acid concentration, reaction temperature and time) in order to maximize the product yield. Rod-shaped CNCs were obtained with high yield (90.28%) and crystallinity (76%) at 30 °C, 75 wt% of acid concentration and 5 h. Dilamian and Noroozi (2019) used mechanical treatments consisting of high shear homogenisation and high intensity ultrasonication to isolate the CNF fraction. Other advanced techniques have also been used to obtain high purity cellulose fractions from RS that would be later converted into cellulose nanospheres (Fan, Wang, Song, Yan, & Li, 2017). Louis et al. (2022) proposed a two-step process based on microwave-assisted delignification and ultrasonic extraction The purity of the extracted fraction was 93.37 ± 2.43% for cellulose and 98.6 ± 1.3%

for hemicellulose. These fractions were hydrolysed to reduce the cellulose particle size to 198 ± 15 nm. Nanospheres were used as biodegradable fillers to develop packaging materials, improving the thermal and barrier properties of the final material.

4.2. Phenolic compounds in rice straw extracts

Fig. 3.

RS is an excellent source of bioactive compounds, including phenolics with antioxidant and antimicrobial performance. Fig. 3 summarizes the main phenolic compounds identified in RS. Karimi et al. (2014) identified bioactive compounds in RS methanolic extracts from different Iran rice varieties and they found a considerable amount of phenolic and flavonoid compounds with potential possibilities to be applied in medicinal and food industries. Pyrogallol, gallic, caffeic, and salicylic acids were the most abundant phenolic compounds found in RS extracts, whereas the more abundant flavonoids were kaempferol, apigenin, and genistein (Table 2). Furthermore, Hashemi variety extracts displayed an important antioxidant activity, based on the 2,2-diphenyl-1-picrylhydrazyl (DPPH) and nitric oxide free radical scavenging activity assays (Table 3).

Other than alcoholic, aqueous extraction is also interesting to recover phenolic compounds from RS (Menzel et al., 2020), being ferulic, *p*-coumaric, and protocatechuic acids the major phenolic compounds identified in water extracts; although tricin, vanillin, and caffeic and vanillic acids were also present (Table 2). So, this study showed that RS waste can be a valuable source for the extraction of water-soluble phenolic compounds. The antioxidant capacity of three different extracts (methanolic, ethanolic and aqueous) was determined using the DPPH assay (Table 3), showing aqueous extracts lower EC_{50} values than the alcoholic ones due to a higher content in phenolic compounds. The obtained aqueous extracts were used for the development of bioactive potato starch-based films improving the antioxidant properties of the food packaging materials.

4.2.1. Phenolic compounds from alkaline hydrolysates

During the alkali pre-treatment performed to remove part of the lignin in order to produce reactive cellulosic fibres, a considerable amount of hydroxycinnamic acids (ferulic, *p*-coumaric, and vanillic), as well as some phenolic aldehydes (syringaldehyde, *p*-hydroxybenzaldehyde, and vanillin) are released by cleaving the ester linkages with polysaccharides and the ether linkages with lignin (Table 2) (Buranov & Mazza, 2009). The separation and purification of hydroxycinnamic acids from the other components of the alkaline hydrolysate biomass have attracted growing attention due to their high value as health promoters and disease prevention, as well as for their antioxidant, antimicrobial, anti-inflammatory and anticancer properties (Destani, Cassano, Fazio, Vincken, & Gabriele, 2013; Ou & Kwok, 2004). In this context, Li et al. (2015) reported the use of nanofiltration membranes to effectively isolate hydroxycinnamic acids found in alkaline lignocellulosic hydrolysates from Chinese RS. The free phenols obtained from the extraction of RS with 0.5 M NaOH were also analysed by Zheng et al. (2017). The main polyphenols detected were gallic acid, epigallocatechin gallate, phthalic acid, vanillic acid, syringic acid, vanillin, coumaric acid (CA) and ferulic acid (FA), the last two being the predominant phenolic acids at 0.7 and 0.4 wt%, respectively (Table 2). Tannins were also detected in this study, but their extraction was conducted using water, methanol or acetone. Under these conditions, the tannin concentrations were 0.11, 0.19, and 0.23 g/L, respectively, being these extracts free of phenolic acids, suggesting that coumaric and ferulic acids in RS are mainly in ester and ether-bound forms, and the free phenols are present in limited amounts.

Similarly, De et al. (2020) fractionated RS by extracting lignin using two different treatment processes, with alkali and organic acids. The total phenolic content of the resulting lignin extracts (28.87 mg gallic acid equivalent (GAE) per g in the alkaline extract and 24.75 mg GAE per g in the acid extract, Table 2) and their antioxidant activity analysis by DPPH radical scavenging (59.50% in the alkaline extract and 45.74% in the acid extract, Table 3) indicated that alkaline lignin extracts contained more OH-phenolic groups compared to extracts obtained after the acid treatment. The structural characterization of these extracts was carried out by UV-vis spectroscopy, FTIR, and ^{1}H NMR showing that alkaline extracts had more purity with more content of aromatic compounds compared to the acid ones, probably because of the major discriminatory cleavage of β-O-4 linkages of alkaline treatment in the lignocellulosic biomass, resulting in higher phenolic content.

4.2.2. Phenolic compounds from RS using new extraction technologies

Regarding the use of innovative methodologies for the extraction of bioactive compounds from RS, Freitas et al. (2020) studied the phenolic compounds content (Table 2) and antioxidant activity (Table 3) of different aqueous extracts from RS obtained by stirring (ST) at room temperature, reflux heating (HT) , ultrasounds (US) and a combination of US and ST or HT. The application of ultrasounds was notably more effective for extracting water-soluble phenolic compounds than simple stirring, according to the higher yields (from 256 to 342 mg GAE per 100 g RS for ST and US, respectively) and antioxidant activity of the extracts. On the other hand, the high temperature applied to the extraction processes produced RS materials with improved antioxidant activities, since applying temperature promoted the cleavage of covalent bonds between the phenolic compounds and the lignocellulosic fraction. This thermal impact was significantly enhanced when the ultrasounds pre-treatment was applied, due to the increase in the substrate surface exposed to the extraction. Therefore, the combined ultrasound-heating method (30 min ultrasound plus 60 min thermal treatment under water reflux) resulted the best extraction process from RS in terms of obtaining extracts with the highest content of phenolic compounds (486 mg GAE/100 g RS) and good antioxidant activity (EC_{50} = 4.6 ± 0.3 g RS/mg DPPH), with potential use in the food and pharmaceutical industries.

A completely different strategy was followed by Nurika et al. (2020) who evaluated the potential of using RS inoculated with *Serpula lacrymans* fungi to produce a mixture of high-value bio-based compounds including vanillin. This novel but cost-effective route to produce high-value chemicals takes place by the breakdown of lignocellulose, although this transformation is not specific and results in a mixture of different compounds, requiring a subsequent extraction for their separation. The vanillin compounds extracted from RS solid-state fungus fermentation were confirmed by LC-ESI MS/MS. The best concentration and yield were 0.408% and 3.957 µg/g, respectively, using ethyl acetate; whereas when using ethanol as solvent, the highest concentration and yields of vanillin were 0.165% and 2.596 μg/g, respectively (Table 2). These results confirmed that fungal conversion of RS to vanillin could consequently offer a cost-effective alternative to other modes of production.

Table 2. Biocompounds identified and quantified in rice straw.

Extraction method	Biocompound extracted	Bioactive and biocompounds identified/quantified	Reference
Aqueous extract	Polyphenols	Total phenolic content (mg GAE per 100 g dry milled rice straw): 1st Extraction 225 ± 21; 2nd Extraction 107 ± 31; 3rd Extraction 33 ± 3 (mg per g extract): ferulic acid (36), *p*-coumaric acid (16), protocatechuic acid (25)	(Menzel et al., 2020)
Ethanolic extract		Total phenolic content in mg GAE per 100 g dry milled RS: 1st Extraction 138 ± 1; 2nd Extraction 62 ± 13; 3rd Extraction 33 ± 3 (mg per g extract): ferulic acid (4.0), *p*-coumaric acid (8.6), protocatechuic acid (4.0)	
Methanolic extract		Total phenolic content in mg GAE per 100 g dry milled RS: 1st Extraction 153 ± 22; 2nd Extraction 56 ± 6; 3rd Extraction 34 ± 3 (mg per g extract): ferulic acid (4.3), *p*-coumaric acid (14), protocatechuic acid (3.2)	
	Polyphenols, flavonoids and isoflavonoids	(µg per·g dry sample) *Ali Kazemi* var.: gallic acid (16.83), kaempferol (1107.43), apigenin (152.86), rutin (3.9), genistein (51.14) *Hashemi* var.: gallic acid (34.45), caffeic acid (1019.81), pyrogallol (944.41), apigenin (188.70), rutin (6.7), genistein (78.63) *Khazar* var.: gallic acid (30.5), caffeic acid (35.92), pyrogallol (60.42), apigenin (123.59), rutin (10.1)	(Karimi et al., 2014)
Stirring treatment	Polyphenols	Total phenolic content: 256 ± 3 mg GAE per 100 g RS; 45.7 ± 0.1 mg GAE per g dry extract	(Freitas et al., 2020)
HT treatment		Total phenolic content: 459 ± 6 mg GAE per 100 g RS; 47.0 ± 3.0 mg GAE per g dry extract	
US treatment		Total phenolic content: 354 ± 12 mg GAE per 100 g RS; 37.4 ± 1.9 mg GAE per g dry extract	
US + HT treatment		Total phenolic content: 486 ± 4 mg GAE per 100 g RS; 34.8 ± 0.5 mg GAE per g dry extract	
Acid process	Polyphenols	Total phenolic content: 24.75 mg GAE per g	(De et al., 2020)
Alkaline extraction		Total phenolic content: 28.87 mg GAE per g	
		(g per L)	(Li et al., 2015)

		Ferulic acid (0.634), *p*-coumaric acid (0.180), vanillic acid (0.042), syringaldehyde (0.038), p-hydroxybenzaldehyde (0.117) and vanillin (0.052)	
		(wt% in RS) Gallic acid (0.017%), epicatechin (0.029%), phthalic acid (0.074%), vanillic acid (0.029%), syringic acid (0.065%), vanillin (0.022%), coumaric acid (0.701%), ferulic acid (0.426%), tannins (0.19%)	(Zheng et al., 2017)
Ethyl acetate treatment	Polyphenols	Vanillin concentration:0.408% Vanillin yield: 3.957 µg per g	(Nurika et al., 2020)
Ethanol treatment		Vanillin concentration: 0.165% Vanillin yield: 2.596 µg/g	
Hydrotropic delignification Acid hydrolysis	Microcrystalline cellulose	1.5 M sulfuric acid (50min): crystalline cellulose fraction of 63.23% with 55.91% yield 1.5 M hydrochloric acid (50 min): crystalline cellulose fraction of 60.70% with 59.16% yield	(Raudhatussyarifah et al., 2022)
Mechanical extraction	Cellulose microfibers	Pachchaperumal variety yield: 16% Mottai Karupan variety yield: 19%	(Ratnakumar, Samarasekara, Amarasinghe, & Karunanayake, 2021)
Chemical conventional extraction	Cellulose fibres	Pachchaperumal variety yield: 33.63 ± 0.10 % Mottai Karupan variety yield: 38.31 ± 0.86%	
Alkaline pulping		Cellulose yield: 84.90%	(Nur Amirah Mamat Razali et al., 2022)
Chemo-mechanical extraction		Cellulose yield: 75.90%	
Mechanical extraction	Nanocellulose	Yield: 37% (50 min ultrasonication)	(Dilamian & Noroozi, 2019)
Chemical conventional extraction	Cellulose	Cellulose yield: 88.5 %	
MW (acidified sodium chlorite)+US (alkali)		Delignification: 84.51 ± 1.21% 0.282 ± 0.011 g per g cellulose (purity 93.37 ± 2.43%) 0.19 ± 0.008 g per g hemicellulose (purity 98.6 ± 1.32%)	(Louis et al., 2022)
Chemical treatment		Cellulose yield: 56-68 wt%	

(eco-friendly method) Montmorillonite K-10/LiOH			(Das, Hazarika, Goswami, Yadav, & Khound, 2016)
Chemo-mechanical treatment			
Chemical treatment (15% NaOH)	Carboxyl methyl cellulose	Yield: 62.4-97.6%	(Masrullita et al., 2021)
Maceration process			
Esterification process			

GAE: gallic acid equivalents; HT: High temperature (reflux heating); US: ultrasounds; MW: microwaves.

Table 3. Antioxidant capacity of RS extracts based on polyphenols.

Extraction method	Antioxidant capacity of the different extracts		Reference
Aqueous extract	IC_{50} values: 153 mg dry RS per mg DPPH 12 mg freeze-dried extract per mg DPPH		(Menzel et al., 2020)
Methanolic extract	IC_{50} values: 334 mg dry RS per mg DPPH 20.3 mg freeze-dried extract per mg DPPH		
Ethanolic extract	IC_{50} values: 400 mg dry RS per mg DPPH 19.8 mg freeze-dried extract per mg DPPH		
Methanolic extract	IC_{50} values (µg/mL) Free radical (DPPH) scavenging activity • *Ali Kazemi* var.: 258.7 ± 2.65 • *Hashemi* var.: 218.5 ± 3.01 • *Khazar* var.: 248 ± 1.87	IC_{50} values (µg/mL) Nitric oxide scavenging activity • *Ali Kazemi* var.: >300 • *Hashemi* var.: 275 ± 3.35 • *Khazar* var.: 292.1 ± 2.51	(Karimi et al., 2014)
Stirring treatment	EC_{50} = 19.7 ± 0.6 g RS. per mg DPPH EC_{50} = 11.0 ± 0.5 mg dry extract per mg DPPH		(Freitas et al., 2020)
HT treatment	EC_{50} = 7.8 ± 0.5 g RS per mg DPPH EC_{50} = 7.49 ± 0.05 mg dry extract per mg DPPH		
US treatment	EC_{50} = 9.8 ± 0.3 g RS per mg DPPH EC_{50} = 9.3 ± 0.3 mg dry extract per mg DPPH		
US + HT treatment	EC_{50} = 4.6 ± 0.3g RS per mg DPPH EC_{50} = 6.3 ± 0.4 mg dry extract per mg DPPH		
Alkaline process	DPPH assay (%): 55.91 (15 min), 59.50 (30 min)		(De et al., 2020)
Acid process	DPPH assay (%): 42.25 (15 min), 45.74 (30 min)		

DPPH: 2,2-Diphenyl-1-picrylhydrazyl assay; IC_{50}: half-maximal inhibitory concentration; EC_{50}: half-maximal effective concentration; HT: High temperature (reflux heating); US: ultrasounds.

5. Applications of rice straw as a source of cellulose and polyphenols in the food industry and nutrition

Rice by-products are a rich source of functional biocompounds with potential application in several sectors as natural antioxidants and ingredients of functional foods for food industry. Their protective effects against a range of diseases, including cancer, hyperlipidemia, fatty liver, hypercalciuria, kidney stones and heart disease could also be of interest in pharmaceutical or dietary applications (Moirangthem, Ramakrishna, Amer, & Tucker, 2021; Parrado et al., 2006). This section reviews the main applications and uses of polyphenol-rich extracts and cellulosic fractions extracted from RS by-products in selected industries (Table 4).

Table 4. The main applications of RS by-products in selected industries.

Source	Treatment	Key product	Application	Reference
Prebiotic effect				
Xylan from RS	Enzymatic hydrolysis	Xylooligosaccharides	Production of value-added food ingredient	(Chapla, Dholakiya, Madamwar, & Shah, 2013; Otieno & Ahring, 2012; Surek & Buyukkileci, 2017)
Arabinoxylan from RS	Hydrothermal process + enzymatic hydrolysis		Rice drink product	(Jaichakan et al., 2021)
β-Galactosidase enzyme production				
RS	Incubation of *Lactobacillus paracasei*	Production of β-galactosidase	Low-lactose yogurt formulation	(Abdel Wahab, Ahmed, Kholif, Abd El Ghani, & Wehaidy, 2021)
Dietary fibre as a potential ingredient in food processes				
RS	Alkaline hydrogen peroxide treatment	Dietary fiber	Bread preparation	(Sangnark & Noomhorm, 2004)
RS	Biocompatible ionic liquid synthesis + saccharification	Food-grade glucose	Artificial meat in the future	(Asim et al., 2021)
Lignocellulosic biomass from RS	high-density steam flash-explosion + enzymatic catalysis	Nanofibrillated cellulose	Elaboration of high-quality dietary fiber	(Yan, Hu, Yang, Zhang, & Zhao, 2018)
Source of antioxidants for functional foods				
Lignans and saccharides linked to phenolic compounds	Enzymatic saccharification	*p*-Coumaric acid and ferulic acid	Production of phenolic acids as added-value products during saccharification	(Xue et al., 2017)
Manipur black RS	Microwave-assisted subcritical water extraction	Anthocyanins	Natural antioxidants and/or functional ingredients	(Moirangthem et al., 2021)
Food packaging				
RS	Naviglio extractor + trifluoroacetic acid treatment	Cellulose + other organic matter	Sustainable bioplastic	(Bilo et al., 2018)
RS fibres	Cellulose nanocrystals + montmorillonite clay mineral + polyvinyl alcohol	Montmorillonite-polyvinyl alcohol biocomposite packaging film	Packaging items to enhance the storage of post-harvest mango fruit	(Perumal et al., 2018)
RS	Extraction of phenolic compounds + addition into the bio-based packaging materials	Water-soluble phenolic compounds	Biodegradable films with good radical scavenging activity	(Menzel et al., 2020)
Cellulose from RS	Chemical transformation + incorporation into an edible film matrix with starch	Hydroxyl propyl cellulose	Edible films used for coating apple slices, strawberry fruits, and potato scripts	(Rohaim, 2020)

5.1. Source of antioxidants for functional foods

Most polyphenols from RS are present in free acid, conjugated and insoluble-bond forms (Hou et al., 2020). According to Xue et al. (2017), *p*-coumaric and ferulic acids are linked to lignans and saccharides of RS, and enzymatic saccharification is needed to extract them. The production of phenolic acids during saccharification is the best way to reduce the cost of cellulosic ethanol production, knowing that the use of enzymes of *Acremonium cellullolyticus* could produce about 0.2 kg each of *p*-coumaric acid and ferulic acid from 100 kg of RS. These phenolic acids might be used as potential sources of antioxidants in functional food (Xue et al., 2017). Moirangthem et al.(2021) found 62.8 mg of cyanidin 3-glucoside per 100 g of the unfractionated straw from black rice using a microwave-assisted subcritical water extraction, suggesting that straw is a promising source of anthocyanins with antioxidant potential. The anthocyanins extract had a non-cytotoxic effect and inhibited the colony formation on human colorectal cancer cells. Although the antioxidant capacity of polyphenols from RS has been reported in several publications, there are still few applications in the field of human nutrition or food industry.

5.2. Potential use as dietary fibre ingredients

Regarding dietary fibre-process, Sangnark and Noomhorm (2004) showed that the alkaline hydrogen peroxide (AHP) approach affected the amount of cellulose, hemicellulose A, hemicellulose B and lignin extracted from RS after 10 h, obtaining a sub-product with particles smaller than 0.075 mm diameter that might be used in bread elaboration with good quality and acceptability. Asim et al. (2021) produced high-quality food-grade glucose from rice and wheat straw using a biocompatible ionic liquid synthetized from choline hydroxide and lysine, followed by the use of saccharification enzymes at 100 ºC for 8 h to remove lignocellulosic products present in the straw. This food-grade glucose might be applied in the synthesis of mycoprotein or "artificial meat" (Asim et al., 2021). Yan et al. (2018) converted lignocellulosic biomass from RS into nanofibrillated cellulose (NFC) using an integrated approach that combines high-density steam flash-explosion (HDSF) at a pressure of 2.0 MPa and enzymatic catalysis (xylanase, laccase and cellulose). HDSF breaks the lignocellulosic complex removing hemicelluloses and lignin by the mechanical force, increasing the cellulose content to obtain an innovative dietary fibre. Results indicated the high capacity of NFC in the adsorption of common bile acids, cholic acid and dexycholic acid as well as oil absorption shown *in vivo* and *in vitro*. These results also proved the possibilities for using fibre-RS in the elaboration of dietary ingredients by the food industry as well as a possible dietary fibre supplement to improve cholesterol protection.

On the other hand, RS is mostly composed of fibre components, such as cellulose, hemicelluloses and lignin, which can be used as dietary ingredients with suitable treatments (Sangnark & Noomhorm, 2004). Additionally, the xylan present in RS wastes can be transformed into xylooligosaccharides (XOS), which are added-value compounds with prebiotic effects (Otieno & Ahring, 2012). Prebiotics have been defined as 'non-digestible food ingredients that beneficially affect the host by selectively stimulating the growth and/or activity of one or a limited number of bacteria in the colon, thus improving host health' (Gibson & Roberfroid, 1995). XOS can be obtained by enzymatic hydrolysis of xylan found in RS (Chapla et al., 2013; Otieno & Ahring, 2012; Surek & Buyukkileci, 2017). Chapla et al. (2013) studied the enzymatic production of XOS from xylan of wheat straw and RS using β-xylosidase-free xylanase, and their prebiotic properties were confirmed by *in vitro* fermentation of XOS using *Bifidobacterium* spp. Quantitative evaluation of reducing sugars and thin-layer chromatographic analysis revealed that XOS preparations were highly stable, even when being exposed to a low pH (2.0) and high temperatures (121 °C) (Chapla et al., 2013). In another study, Jaichakan et al. (2021) designed an approach to convert 88.34% of initial Hommali RS arabinoxylan (RS_AX) in XOS, using a combination of two saccharification processes: a hydrothermal process at 180 ºC for 10 min followed by enzymatic hydrolysis to recover XOS from residual RS_AX. The maximum yield of XOS liquor obtained after the hydrothermal process was 9.84 g per 100 g RS. Moreover, 810.42 mg/L of oligosaccharide content was acquired from the RS_AX residue liquor after the incubation at 50 ºC and pH 5.5 for 24 h with 100 U of *endo*-1,4-β-xylanase per g substrat. Finally, the prebiotic properties of these XOS were evaluated on lactic acid-producing bacteria in rice drink products in a high-pressure process, revealing the stronger prebiotic effect of XOS on the growth of *Lactobacillus sakei* and *Lactobacillus brevis* (Jaichakan et al., 2021). These results indicate that XOS are suitable for their addition into acid foods and those undergoing thermal processing.

5.3. β-Galactosidase enzyme production

Abdel Wahab et al. (2021) identified RS as the second factor most influencing in the production of β-galactosidase enzyme, which is required needed in the low-lactose yogurt formulation. The optimized incubation of *Lactobacillus paracasei* MK852178 with 6 g per flask (f) RS, 5 g per f wheat bran, 6 g per f orange peel, 10 g per f lactose, 6 g per L KH_2PO_4, and 1 g per L $MgSO_4$, for two days, showed a great effect on the enzyme production. The addition of 0.3% of β-galactosidase to the yogurt reduced lactose without showing significant changes in chemical composition as well as in sensory properties. Finally, authors suggested that the use of RS and orange peel is an economic and eco-friendly way to use residues in the production of β-galactosidase reducing the cost of low-lactose yogurt elaboration.

5.4. Other uses of rice by-products

5.4.1. Food preservatives and stabilizers

Foods containing a high fat content are prone to go rancid during storage because of lipids oxidation, which produces off-flavours and reduces nutritional value and safety. Rice by-products contain natural antioxidants that can efficiently inhibit biologically harmful oxidation reactions and they can be applied in food production to avoid or minimize the use of synthetic additives. Some studies have reported that antioxidant-rich extracts from rice by-products can improve the stability of high-fat food products. In this context, Farahmandfar et al. mixed canola oil with *Tarom Mahali* rice bran extract in various doses (100, 800, and 1200 ppm). (x) The following variables were used to evaluate how well rice bran extract stabilized canola oil: free fatty acids, peroxide value, carbonyl value, total polar compounds, and oxidative stability index. Results showed that the extract, at 800 ppm, might function better than 100 ppm *tert*-Butylhydroquinone in preventing lipid oxidation in canola oil during the frying process and could be used as a main alternative to synthetic antioxidants. On the other hand, Bhanger et al. (2008) investigated the effect of rice extracts on the oxidative stability of cookies stored at room temperature, without

Comentado [MPB1]: Farahmandfar R, Asnaashari M, Sayyad R. Comparison antioxidant activity of Tarom Mahali rice bran extracted from different extraction methods and its effect on canola oil stabilization. J Food Sci Technol. 2015 Oct;52(10):6385-94. doi: 10.1007/s13197-014-1702-2. Epub 2015 Jan 29. PMID: 26396383; PMCID: PMC4573143.

being expos to light, which was analysed every two months for one year. The control sample gave the highest peroxide values throughout storage, indicating a high level of oxidation. Conversely, cookies supplemented with the rice extract, BHT or α-tocopherol showed a slower rate of peroxides production. Accordingly, rice by-products are a potential source of antioxidants that can effectively extend the shelf-life of cookies.

5.4.2. The application of rice bran in food enrichment

An enzymatic extract prepared from rice bran containing essential amino acids and the powerful antioxidant γ-oryzanol was found to inhibit the *in vitro* cell growth of a leukemia tumour (Parrado et al., 2006). The extract was therefore proposed as a potential functional food able to treat or prevent cancer and other chronic diseases associated with the abnormal proliferation of cells and free radicals. In addition, such a product would also benefit the elderly and sport practitioners. Irakli et al. (2015) reported that mixing wheat flour with rice bran in a ratio of up to 1:4 (w/w) improved the antioxidant activity and bioactive components of bread without affecting its overall quality and sensory attributes. It was concluded that rice bran, a natural and inexpensive by-product rich in bioactive compounds, can be applied to produce nutritionally enhanced bread.

5.4.3 Food packaging

Packaging is essential for the protection of food products. Biodegradable food packaging obtained from different types of polysaccharides and polyphenols from RS has been proposed to replace non-renewable synthetic plastics without affecting the environment. Bilo et al. (2018) developed a bioplastic using cellulose from RS with good mechanical performance, in terms of tensile strength and elongation at break values, which were comparable to conventional plastics. This bioplastic was totally decomposed within 105 days embedded in soil. Perumal et al. (2018) also investigated the potential use of RS fibres in the elaboration of packaging items to enhance the storability of post-harvest mango fruit. Cellulose nanocrystals were incorporated into a film formulation with montmorillonite clay mineral and polyvinyl alcohol (PVA), producing a final product capable of increasing the shelf-life of mango fruit until 19 days with good quality parameters. According to Menzel et al. (2020), the biodegradable film based on potato starch (40

g) and polyphenols-extract from RS (2-4 g) demonstrated superior radical scavenging activity, improving oxygen barrier properties compared to commonly synthetic ethylene-vinyl alcohol, suggesting the application of films developed from RS as a good alternative to food packaging in order to prolong the shelf-life of food. Recently, rice by-products, mainly broken rice enriched with RS, have been also used as edible films used for coating apple slices, strawberry fruits and potato scripts to extend their shelf-life when stored at 4 ºC (Rohaim, 2020). The addition of 40 wt.% of a cellulose derivative extracted from RS to a starch-based emulsion composite film showed a beneficial effect on its mechanical and structural properties and reduced weight loss and number of infected coated samples during 4 weeks of storage at 4 ºC. The visual quality and the oxygen permeability of these films were also enhanced. These films presented a potential antimicrobial performance by the incorporation of 2.0 wt.% rosemary extracts during 28 days storage of samples at 4 ºC. The sensory evaluation of the coated samples with 2 wt.% rosemary as antimicrobial agent maintained the consumer acceptance up to 28 days storage at 4 ºC for apple and potato samples and up to 21 days for strawberry fruit samples. Chollakup et al. (2021) evaluated the antibacterial activity of active paper from rice straw fibers with longan (*Dimocarpus longan*) peel.

5.4.4. Food colorants

The colour of food products is a key factor in improving their appearance and attracting consumer interest. Pigmented rice is a potential plant source of anthocyanins, which are natural colorants that also have beneficial effects on human health. Some recent studies have extracted natural colorants from the by-products of pigmented rice and have applied them in food products. Loypimai, Moongngarm, and Naksawat (2017) used the anthocyanin pigment from black glutinous rice as an alternative to nitrates/nitrites, which are commonly used to develop colour and inhibit the growth of pathogenic bacteria such as *Listeria* spp. and *Clostridium botulinum* in fermented Thai pork sausages. These food additives, however, can react with secondary amines present in the stomach to form the carcinogenic nitrosamines. Sausages produced with black rice bran extract powder contained higher levels of anthocyanins, total phenolics and antioxidants than sausages with 0% or 120 ppm of nitrite. Furthermore, lipid oxidation was retarded and the overall acceptance score was comparable to that of sausages containing 120 ppm of nitrite (Loypimai et al., 2017). These results suggested that black rice bran extract powder could partially eplace nitrites in fermented sausage production.

Nontasan, Moongngarm, and Deeseenthum (2012) improved the colour of flavoured yogurt by using an extract from back glutinous rice bran containing anthocyanins, phenolic compounds and γ-oryzanol. The extract afforded a stable purplish pink colour, which was due to the low pH of the yogurt, and increased the phytochemical content of the final product.

6. Conclusions

The rice plant generates a large amount of post-harvest straw, which is currently managed by incineration. Due to EU restrictions, alternatives for its management have to be sought. The valorisation of this by-product is one of them and it is aligned with the agenda set by the European Union in the Sustainable Development Goals and Agenda 2030. This review shows how by using different extraction strategies, this by-product generated in the field can be valorised and bio-based compounds with high added value can be obtained from it. In particular, cellulose and polyphenols have been the focus of this work and they can be successfully extracted from rice straw. Both extracts show great potential in the food sector as antioxidants, in the case of polyphenols, or as a nutritional component for the development of new foods or packaging materials, in the case of cellulose and its derivatives. Thus, it has been demonstrated that the revaluation of this waste, which currently generates serious environmental and human problems due to its management and incineration, is possible.

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Figure Captions:

- **Fig. 1.** Overall workflow for rice production, generation of RS, the most representative alternatives to valorise it, bioactive compounds obtained and potential applications.
- **Fig. 2.** Main advantages and limitations of some techniques used to obtain cellulosic or polyphenol-rich extracts (Garcia-Vaquero et al., 2020; Mao, Abushammala, Brown, & Laborie, 2017; Picot-Allain et al., 2021).
- **Fig. 3**. Structure and classification of phenolic compounds identified in rice straw extracts (Phenol Explorer DataBase. Retrieved July 24)