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Review

Sustainable strategies for using natural extracts in smart food packaging

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ABSTRACT

The growing demand for sustainable and eco-friendly food packaging has prompted research on innovative solutions to environmental and consumer health issues. To enhance the properties of smart packaging, the incorporation of bioactive compounds derived from various natural sources has attracted considerable interest because of their functional properties, including antioxidant and antimicrobial effects. However, extracting these compounds from natural sources poses challenges because of their complex chemical structures and low concentrations. Traditional extraction methods are often environmentally harmful, expensive and time-consuming. Thus, green extraction techniques have emerged as promising alternatives, offering sustainable and eco-friendly approaches that minimise the use of hazardous solvents and reduce environmental impact. This review explores cutting-edge research on the green extraction of bioactive compounds and their incorporation into smart packaging systems in the last 10 years. Then, an overview of bioactive compounds, green extraction techniques, integrated techniques, green extraction solvents and their application in smart packaging was provided, and the impact of bioactive compounds incorporated in smart packaging on the shelf lives of food products was explored. Furthermore, it highlights the challenges and opportunities within this field and presents recommendations for future research, aiming to contribute to the advancement of sustainable and efficient smart packaging solutions.

1. Introduction

The demand for eco-friendly and sustainable food packaging is currently experiencing a significant rise because of increasing apprehension over health-related concerns and environmental pollution associated with conventional packaging practices [1–3]. Sustainable packaging is defined as packaging with a relatively minimal environmental impact and is assessed through life-cycle assessment models [4,5]. Consequently, the exploration of innovative solutions has become imperative, leading to the emergence of smart packaging as a promising approach. Smart packaging involves packaging systems incorporating embedded sensor technologies and is applied to various products, such as food and pharmaceuticals [6,7]. The objective of smart packaging is to enhance the safety and quality of packaged food products and their shelf lives by enabling interaction between packaging materials and food products [8,9]. Intelligent packaging refers to packaging materials that can interact with products and monitor and control various parameters, such as humidity, temperature and gas composition [10,11]. However, this feature is achieved by incorporating additives derived from natural sources, which possess functional properties, which render intelligent packaging effective and expand its applications [12,13].

The integration of bioactive compounds derived from natural sources into smart packaging is of paramount importance. Bioactive compounds are naturally occurring compounds that have biological activity and exist within an array of natural reservoirs, including plants, fruit, vegetables and other organic sources [14,15]. These compounds, particularly phenolic compounds, carotenoids and peptides, offer functional properties, including antioxidant, antimicrobial and anti-inflammatory

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effects. They not only enhance the safety and quality of packaged food but also contribute to the development of innovative bioactive films with antioxidant capabilities, antimicrobial functionalities, and innovative coloration. Bioactive films have been proven effective in enhancing the stability and prolonging the shelf lives of food products. Furthermore, the strategic integration of bioactive films as biosensors and colorimetric indicators showcases their ability to ensure customer satisfaction and the safety of packaged food [16]. Recognizing the significance of this relationship, this review paper aims to provide a comprehensive overview of various categories of bioactive compounds, discuss green extraction techniques employed for their extraction, and examine their utilisation in the advancement of smart packaging. Additionally, the paper will highlight challenges and opportunities within this field and present recommendations for future research.

These compounds have a wide range of functional properties, such as antioxidant, antimicrobial, and anti-inflammatory effects, and are thus attractive for use in smart packaging [17]. However, extracting them from natural sources can be a challenging task because of their complex chemical structures and low concentrations [18]. In addition, traditional methods of extraction, such as Soxhlet extraction, solvent extraction, and steam distillation, are environmentally harmful, expensive and time-consuming [19].

To address these challenges, green extraction techniques have been proposed as promising alternatives for the extraction of bioactive compounds from natural sources. Using sustainable and environmentally conscious methods, green extraction minimises the use of harmful solvents and lowers the environmental footprints of extraction procedures [20]. Increased extraction yields, enhanced product quality and shortened extraction duration are among the advantages showcased by these methods [21]. Green extraction techniques can effectively extract a wide range of bioactive compounds from natural sources, including polyphenols, flavonoids, alkaloids and essential oils [22–25]. Among all commonly employed techniques for the green extraction of bioactive compounds are ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), supercritical fluid extraction (SFE) and pressurised liquid extraction (PLE). Different factors, including the nature of bioactive compounds, sources of materials and desired properties of extracted substances, influence the selection of extraction methods [26]. Recent focus on sustainable production and circular economy has led to considerable advancements in the study of bioactive compounds in multifunctional packaging [27,28]. These compounds play a crucial role in this research era, and green techniques are used to recover them. However, previous literature reviews primarily examined specific natural bioactive compounds, such as carotenoids [29], cinnamaldehyde [30], anthocyanins [31] and thymol [32], or specific recovery methods, including deep eutectic solvents (DESs) [33], ionic liquids (ILs) [34] or PLE [35]. This review provides a comprehensive overview of the various categories of bioactive compounds and discusses different green extraction techniques. It also compares bioactive compounds, extraction techniques, and preservation methods for different food categories. The paper also highlights future research challenges and opportunities within this field.

2. Bioactive compounds for smart packaging

A bioactive compound is a substance that offers tailored benefits to enhance food safety, quality or shelf life by integrating it into packaging materials [36]. These compounds actively interact with packaged food and packaging and exert different effects. Fig. 1 shows bioactive compounds and their potential functions in smart packaging. Their structures and functional properties in smart packaging are elucidated in the following section.

2.1. Polyphenols

Polyphenols belong to a diverse group of naturally occurring phenols

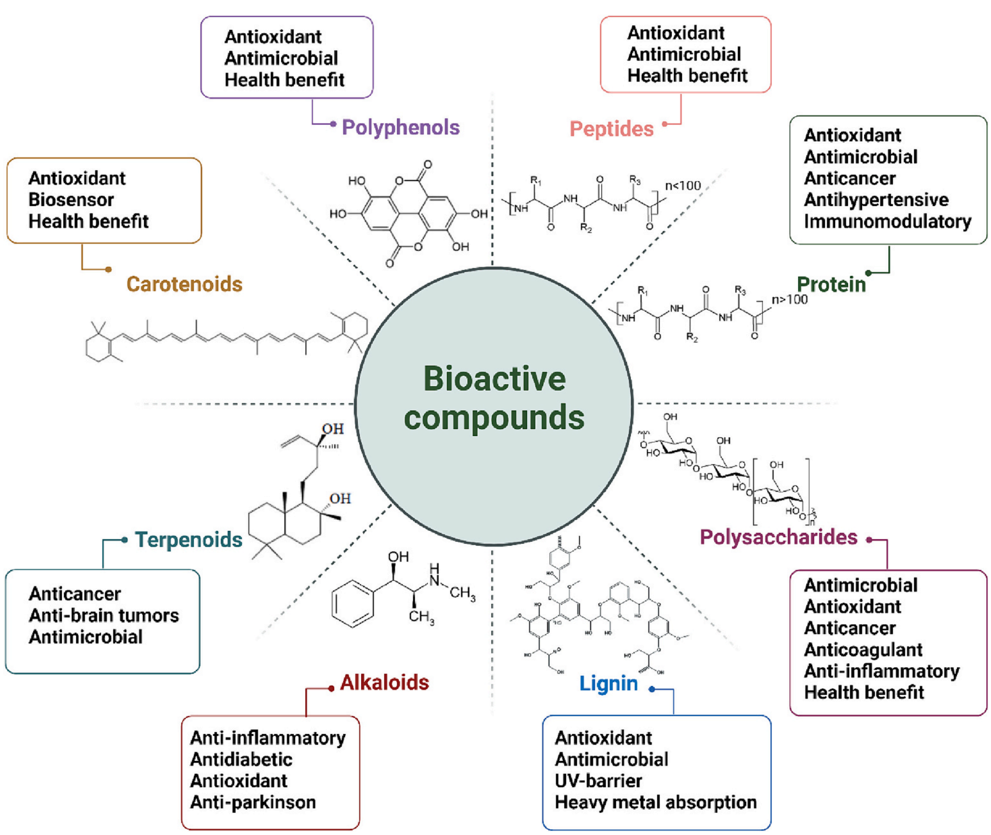

Fig. 1. Different bioactive compounds and their functional properties in smart packaging.

abundant in plants. They contain one or more hydroxyl groups attached to aromatic benzenoid (phenyl) rings. Plant polyphenols possess several functional properties beneficial for human health, including antioxidant and antibacterial effects [37]. Various sources, such as fruit and vegetables, tea, wine, coffee, chocolate and olive oil, contain phenolic compounds and are widely considered safe when utilised as food additives [38,39]. To improve food preservation, recent investigations have focused on incorporating plant polyphenols into degradable food packaging [40,41]. Polyphenols have been added to film matrices to improve the properties of film because they have the potential to generate active and intelligent packaging materials [42]. This approach capitalises on the beneficial effects of natural polyphenols in the food and pharmaceutical industries. Incorporating polyphenols into film matrices not only confers antioxidant and antibacterial characteristics but also bolsters mechanical and barrier properties by functioning as cross-linking agents [43].

Polyphenols are extracted using a combination of organic solvents, including methanol and ethyl acetate with water [44]. For over 100 years, these methods have been employed to separate polyphenols. However, using solvents from organic sources in this process can be expensive, harmful, and inconsistent with the tenets of green chemistry [45]. These limitations have led to investigations into alternative methods that are environmentally friendly and cost-effective for extracting polyphenols from different sources of plants [46]. [47] explored the use of ternary natural deep eutectic solvents (NaDESs) in extracting polyphenols from green tea; these polyphenols improved the chitosan film's resistance attributed to the interaction between the film matrix and polyphenols. Similarly, [48] suggested an eco-friendly polyphenol extraction process from vegetable waste, involving an enzymatic pre-treatment followed by solid-liquid extraction using a designated extractor. This method enabled the efficient extraction of a significant quantity of polyphenols from various vegetable waste materials.

Flavonoids are polyphenolic compounds and secondary metabolites synthesised in plants. They contribute to the colour, flavour, and pharmacological activity of plants [49,50]. Fruit and vegetables are the primary sources of flavonoids, such as black and green tea [51]; berries [52]; plums and cherries [53]; and apples [54]. Flavonoids can be classified into six major groups according to their chemical structure, degree of oxidation and unsaturated linking chains. These groups are isoflavonoids, flavanones, flavanols, flavones, flavan-3-ol and anthocyanidins [55,56].

The hot-water extraction technique is suitable for the extraction of flavonoid glycosides, whereas MAE is commonly applied to the extraction of flavonoids from medicinal plants. Membrane separation is particularly useful for extracting flavonoids from natural plants that contain active and heat-sensitive constituents. The potential application of ultrasonic techniques for the extraction of flavonoids from various plants has been explored [57–60].

[61] introduced an innovative and environmentally friendly extraction method that employs osmosis extraction combined with a salting-out process to improve the extraction efficiency of pharmaceutical compounds from herbal materials; manipulating the osmotic pressure resulted in variations in intracellular osmotic pressure between saline and non-saline solvents; the osmosis extraction biphasic system had a phase interface that facilitated the disruption of the cell walls in medicinal materials, thus greatly improving the efficiency of extraction; in addition, they revealed the impact of osmotic pressure on the structural alterations in the cell wall and cell membrane of *Folium nelumbinis.* Osmosis extraction is a promising environmentally friendly extraction approach owing to its speed, efficiency, and low energy consumption.

Meanwhile, [62] evaluated the efficiency of miniaturised solid-phase dispersion (SPD) was evaluated in the extraction of two different flavonoid glycosides (neohesperidin and naringin) from lime fruit. The ideal extraction parameters were florisil (150 mg) as the sorbent and 1-butyl-3-methylimidazolium tetrafluoroborate (0.4 mL, 250 mM) as the elution solvent; this investigation pioneered the use of ILs as a sustainable eluent for extracting the desired compounds in miniaturised SPD. Compared with conventional methods, this technique offers several benefits, including improved enrichment factor and decreased consumption of reagents.

[57] aimed to determine an optimal technique for extracting flavonoids from cotton fibres; they used a one-factor experiment design to examine the effects of various experimental conditions on the extraction process; ultrasonic temperature, ethanol concentration, sodium hydroxide concentration, liquid–solid ratio and ultrasonic duration markedly affected extraction efficiency, and the optimal conditions were liquid–solid ratio of 1:40, ethanol concentration of 50 %, extraction temperature of 70 °C, extraction time of 1 h and sodium hydroxide concentration of 0.15 %.

2.2. *Carotenoids*

Carotenoids play a critical role in photosynthetic and non-photosynthetic plant organs, serving as pigments, antioxidants, photoprotectors, colour attractants and precursors of plant hormones [63]. They are classified as isoprenoids, consisting of a C40 backbone composed of eight isoprene units in their fundamental structure. Carotenoids are classified by chemical composition: xanthophylls and carotenes. Xanthophylls are oxygenated carotenes with one or more hydroxyl, epoxy or carboxyl groups, whereas carotenes are hydrocarbons composed solely of carbon and hydrogen. Carotenes include beta-carotene, lycopene, and alpha-carotene, and xanthophylls include lutein, zeaxanthin, and astaxanthin [64]. Moreover, carotenoids are known for their potential antioxidant properties and health benefits in addition to pro-oxidant properties and the ability to modulate signalling pathways and absorb visible light. Additionally, the oxidative cleavage derivatives of carotenoids may have biological activity and can offer the health benefits associated with carotenoids [65].

Carotenoids, such as anthocyanins, betalains, curcuminoids and chlorophylls, are commonly used as natural indicators of food quality and safety in intelligent packaging [66]. These pigments can change colour because of environmental stimuli, such as temperature, pH, oxygen, light or microbial activity, providing visual cues to consumers about the freshness, spoilage, ripeness or contamination of food [67,68]. Mixing carotenoids with other active agents can improve their functionality and stability in smart packaging. Carotenoids are often extracted using petrochemical solvents, particularly for vegetables, but this method can lead to degradation because of harsh process conditions. Extracted substances must be soluble in solvents, and similar solvents are effective. Chloroform, hexane, isopropanol, methylene chloride and diethyl ether are the commonly used organic solvents.

[69] applied ultrasonic-assisted extraction and different vegetable oils as alternative solvents to extract carotenoids from pomegranate peels; the study aimed to develop a novel process for naturally obtaining antioxidant-rich oils from discarded pomegranate waste and compared the total carotenoid content obtained through UAE with that obtained through conventional solvent extraction. UAE was employed to enhance the yield and quality of β-carotene extracted from carrots and enriched in sunflower oil [70]. [71] used SFE and supercritical carbon dioxide as a solvent to obtain lycopene-rich extract from tomatoes. According to [72], high-shear dispersion (HSD) is more efficient in extracting carotenoids than UAE. HSD encompasses the physical breakdown of cell walls and membranes, resulting in the release of compounds confined within cells. This approach is faster than traditional methods and requires the use of edible vegetable oils, which are more eco-friendly and require less energy than organic solvents. Furthermore, the carotenoid extract obtained through HSD does not require further purification and is ready for immediate use [73]. [70] and [69] corroborated the results and indicated that HSD outperforms UAE in carotenoid extraction.

2.3. Terpenoids

Terpenes are hydrocarbons extensively found in several organisms, such as plants, microorganisms, marine organisms, fungi and insects. They are structurally composed of multiple isoprene units, each of which contains five carbon atoms. They can be further categorised into monoterpenes (e.g. limonene), sesquiterpenes (e.g. elemene), diterpenes (e.g. camphene) and polyterpenes [74]. Terpenes are potential anti-cancer drugs with few side effects and low toxicity. Elemene is a terpene which inhibits the growth of lung cancer, liver cancer, nasopharyngeal carcinoma and brain tumours [75]. Moreover, terpenes exhibit antimicrobial activity against antibiotic-susceptible and antibiotic-resistant bacteria. This activity primarily stems from their ability to induce cell rupture and impede DNA and protein synthesis [76].

Extracting and isolating terpenoids from natural sources is a crucial step in the production of valuable natural products with various biological activities and industrial applications. Several methods for extracting terpenoids from plant resources have been proposed, including steam distillation, MAE, solvent extraction, UAE, and SFE [77,78]. An extraction method is selected according to several factors, including the types and amounts of plant materials, polarity and volatility of terpenoids, cost and efficiency of the methods, and environmental impact [77,78]. Once extracted, terpenoids can be further purified and analysed by spectroscopy, chromatography, and mass spectrometry. The structures of terpenoids can be characterised by various analytical methods and compared with known standards or databases [79].

Terpenoids offer benefits when used in intelligent packaging, including prolonged food shelf life, decreased use of artificial preservatives and additives, and enhanced sensory properties of food [80].

2.4. Alkaloids

Alkaloids belong to a diverse category of naturally occurring nitrogenous compounds, usually have ring structures and can be found in various plants, fungi and animals [81]. They are known for their diverse biological activities and have been studied extensively for their potential anti-inflammatory [82], antidiabetic [83], antioxidant [84] and anti-Parkinson's effects [85].

Obtaining bioactive alkaloids from plants is a crucial process in numerous applications. However, organic solvents, such as methanol, alcohol, ethyl acetate, acetone and chloroform, are commonly used for alkaloid extraction from herbal medicines [86]. According to [87], alkaloids in fruit and vegetables have been effectively extracted through reflux extraction using methanol, ethanol or trichloromethane as solvent. However, this method has low extraction efficiency and high solvent consumption [88].

Seven NaDESs, which are mixtures of natural compounds, such as sugars, organic acids and amino acids, were employed to extract flavonoids and aporphine alkaloids from *Peumus boldus* leaves. Among the NaDESs, the choline chloride–lactic acid and proline–oxalic acid mixtures resulted in a higher extraction rate for boldine (0.43 and 2.36 mg/g plant, respectively), which was higher than the rates obtained through conventional extraction using methanol and water. The proline–oxalic acid mixture yielded the highest total phenolic content (TPC) of 179.44 $\pm$ 3.79 mg gallic acid equivalents (GAE)/g [89].

Various polyalcohols, aqueous carboxylic acids and their eutectic solvents and UAE were employed for the extraction of berberine, which is a benzylisoquinoline alkaloid from *Coscinium fenestratum*. Among the solvents, lactic acid showed the most promising result for berberine extraction. The optimum extraction conditions obtained through response surface methodology (RSM) were a lactic acid concentration of 60 % (*w*/w), temperature of 66 °C, extraction time of 20 min, and solvent–solid ratio of 17.25 mL/g. These conditions resulted in 38.23 $\pm$ 0.69 mg/g extraction efficiency and 2.22 $\pm$ 0.04 mg/mL barberine concentration [90].

2.5. Proteins and peptides

Proteins and peptides are two different types of natural bioactive compounds that are widely distributed in plants, animals and microorganisms. They have attracted considerable interest in recent years because of their potential health benefits and functional properties. Proteins and peptides are composed of amino acids and are differentiated by their length and structures. Proteins are typically larger than peptides and have complex three-dimensional structures, whereas peptides are smaller and have a simpler structure [91,92]. In plants, proteins and peptides are involved in various physiological functions, such as seed development, germination, and stress responses. For example, the 11S globulin protein in soybean has antioxidant and anticancer properties [93]. In animals, proteins and peptides play essential roles in growth, development, and immune response. Milk proteins, such as casein and whey protein, exert antimicrobial, antihypertensive and immunomodulatory effects [94].

Extracting proteins and peptides from natural sources can be difficult because of their complex structures and sensitivity to processing conditions [92]. Protein degradation caused by extreme pH, temperature, prolonged extraction times, and solvent conditions often reduces extraction yields when conventional methods are employed. However, green extraction techniques, such as aqueous extraction and enzyme-assisted extraction (EAE), are efficient in extracting proteins and peptides from natural sources while preserving their bioactivity [95]. Compared with conventional hydrolysis methods, microwave-assisted methods enhance the enzymatic hydrolysis of chia seed protein, improving bioactivity (specifically antioxidant activity) and accelerating the development of desirable properties, such as emulsification and foaming capabilities [96].

2.6. Polysaccharides and lignin

Polysaccharides derived from different sources are commonly employed in various fields, including food, feed, paper, packaging, medicine and pharmaceuticals. Interest in the use of polysaccharides, especially those with bioactive properties, for novel applications has grown in recent years because of their biodegradability, renewability, biocompatibility, non-toxicity, therapeutic effects and health benefits [97]. Cellulose, hemicellulose, pectin, chitosan and alginate are extensively utilised in food packaging. Moreover, cellulose, hemicellulose, inulin, β-glucan and pectin prevent diseases by reducing blood cholesterol levels, regulating post-meal blood glucose and insulin levels and facilitating food movement in the digestive tract. Alga-derived polysaccharides have beneficial biological activity, particularly antioxidant, antiviral, anticoagulant, antiinflammation, anticancer and antithrombotic activity [98]. In addition, chitin and chitosan have antimicrobial and antifungal activity because their cationic groups react electrostatically with anionic groups (proteins and lipopolysaccharides) on the outer surfaces of bacteria.

Green extraction techniques, such as microbial fermentation, electrochemical extraction (ECE), EAE, MAE, UAE, extraction using subcritical water (SWE), ILs and DES, have been effectively utilised for extracting chitin and chitosan from different resources [99]. In this regard, *Alcaligenes faecalis* and *Bacillus coagulans*-derived protease were employed for chitin deproteinisation from shell waste of *Litopenaeus vannamei* through proteolytic fermentation [100]. In another study, SWE was utilised to extract chitosan from swimming crab shells [101]. Chitosan with a molecular weight of 1187.0 kDa and yield of 12.2 % was obtained at a deacetylation temperature of 90 °C. These values were comparatively lower than the results obtained from shells treated with NaOH. The citric acid (1 %) in the SWE improved the promoted extraction. [102] introduced *N*-acetyl-D-glucosamine to ternary acidic NaDESs to enhance the yield and molecular weight of chitin extracted from the shell of snow crab (*Chionoecetes opilio*); the chitin product had a molecular weight of 392 kDa, purity of 90.2 % and yield of 85.6 %, and the maximum yield of chitin extraction increased 1.57- and 1.39-fold relative to the maximum yields obtained using acids or alkalis and binary acidic NaDESs, respectively.

Lignin, which naturally accounts for 20 %–32 % of plant biomass weight, consists of aromatic p-coumaryl, coniferyl, and synaphyl components. The functional groups of lignin (phenolic, hydroxyl, carboxylic, carbonyl, and methyl) confer various functional properties, such as UV blocking, heavy metal absorption, and antioxidant and antimicrobial capabilities [103]. Chemical pretreatments using sodium hydroxide and sulphuric acid are the most widely used methods for lignin extraction. The DES pretreatment of lignocellulose with acidic hydrogen bond donors cleaves ether bonds and is thus highly efficient in lignin extraction or removal and hemicellulose hydrolysis. [104] performed acid-based DES pretreatments to extract lignin from willow; their findings indicated that the method was more efficient in removing lignin than DESs based on acetic acid and propionic acid. Optimal conditions for lactic acid-based DES pretreatment were choline chloride–lactic acid molar ratio of 1:10, temperature of 160 °C, and time of 15 min and resulted in 80 % lignin removal and purity exceeded 81 %. All the potential bioactive compounds in smart packaging and their functional properties are summarised in Fig. 1.

3. Traditional extraction of bioactive compounds

Procedures for extracting natural substances involve a series of stages: (1) the penetration of a solvent into a solid matrix; (2) the dissolution of a solute in the solvent; (3) the diffusion of the solute out of the solid matrix; and (4) the collection of extracted solutes. Any factor that enhances diffusivity and solubility during these steps improves the extraction process. Several variables affect extraction efficiency, including solvents' characteristics, the ratio of solvent to solid, raw materials' particle sizes, and extraction temperature [105,106]. The selection of an extraction method significantly impacts the quantity and quality of bioactive constituents. Hence, it is imperative to carefully choose a suitable extraction method tailored to the specific compounds of interest.

Traditional extraction refers to the use of conventional methods for the bioactive extraction of compounds from natural sources. These methods, including Soxhlet extraction, hydrodistillation, maceration and agitated solvent extraction, have been used for centuries and use chemical solvents, heat and mechanical force to extract desired compounds [46].

Traditional extraction methods have several advantages, considering factors like their ease of use, affordability and widespread availability. These methods are commonly employed in the food, pharmaceutical and cosmetic industries because of their simplicity and variations in polarity and molecular weight. In addition, traditional methods can be used in the extraction of a wide range of bioactive compounds from natural sources [107]. However, the disadvantages of traditional extraction methods are numerous. A significant drawback is the utilisation of harmful solvents, which can cause environmental pollution and health hazards. Petrochemical solvents, particularly n-hexane are subject to strict regulation following European directives and must undergo a process of chemical registration, evaluation, authorisation and restriction [108]. They have low yield, selectivity and efficiency and require a long extended extraction duration and substantial solvent volume [107]. Moreover, they may cause the thermal degradation or decomposition of some natural products' structures, which are sensitive to high temperatures or light affecting their efficacy and safety [19]. Vinci et al. [109] discovered that using DESs instead of traditional solvents, such as methanol and water, increased the extraction yield of polyphenol compounds in dark chocolate by 35 %. A life cycle assessment (LCA) showed that conventional solvents had a 60 % impact on various damage impact categories, especially in terms of mineral and fossil resource availability. DESs had lower quantitative effects on human health, ecosystems and resources [109]. Garofalo et al. [110] compared UAE and a method that uses isopropanol to extract rice bran oil. The results showed that UAE significantly reduced the extraction time to 1–15 min, while producing the same yield. Another LCA study demonstrated that UAE had less environmental impact than conventional methods, with lower emissions contributing to climate change, ozone depletion and freshwater eutrophication. Additionally, the UAE operated at room temperature, thereby reducing energy consumption and production costs [110].

4. Green extraction techniques for bioactive compounds

The extraction of bioactive compounds from plants, fruit, vegetables and biological materials with sustainable methods involves the use of environmentally friendly techniques. The objective of this approach is to minimise environmental impacts associated with extraction processes by reducing the use of hazardous chemicals.

4.1. Supercritical fluid extraction (SFE)

SFE is a green extraction method that utilises supercritical fluids (SFs) as solvents for extraction. SFs are sustained above their critical temperature and pressure, thus exhibiting the properties of liquids and gases [111]. These distinctive characteristics result in high solubility and diffusion coefficients, which ultimately lead to efficient and selective extraction.

Supercritical carbon dioxide (CO_2) is the prevailing choice of solvent in SFE because of its low critical temperature (31.1 °C), high diffusivity, low viscosity and low toxicity [112]. However, CO_2 is inherently non-polar, making it an exceptional solvent for extracting non-polar compounds and volatile polar compounds with molecular weight [113]. However, its effectiveness in extracting polar phytochemicals embedded in the cell wall is relatively diminished. To address this limitation, small amounts of organic co-solvents, such as water, ethanol and methanol, can be added to CO_2 to increase its polarity and solving power. This procedure is called modified SFE (MSFE) [111].

Terpenoids and some polyphenols are examples of non-polar or weakly polar compounds that are amenable to extraction through SFE. SFE and MSFE can be employed to extract these compounds from a range of plant sources, including herbs, spices, fruit, flowers and seeds [114]. This extraction technique offers several advantages, including the ability to operate at low temperatures and employ short extraction times to prevent the thermal degradation or oxidation of heat-sensitive or unstable bioactive compounds. Furthermore, it allows the adjustment of pressure, temperature and co-solvent composition of the SFs to increase extraction efficiency and selectivity; these parameters influence the solubility, density, viscosity and diffusivity of the SFs [115,116]. Additionally, SFEs reduce the environmental impact and extraction cost by utilising renewable, non-toxic and cost-effective solvents, such as carbon dioxide, water or ethanol, which can be recycled [117].

During extraction, the utilisation of solid or liquid samples depends on structures; solid samples are usually preferred over liquid samples. Pre-treated solid samples are packed into columns. Pressurised supercritical solvents then traverse the columns, effectively dissolving extractable compounds from the solid matrix. The dissolved compounds diffuse outward until they reach the separator and undergo separation, which is often facilitated by a decrease in pressure, an increase in temperature or a combination of these factors [118].

SFE can be employed in two distinct modes, namely, dynamic and static, which can be applied individually or in combination during extraction. In dynamic mode, an SF consistently flows through an extraction column containing a sample. In the static mode, the sample absorbs the SF, and no run-off fluid is produced in the extraction column throughout the process [119].

In SFE, optimising multiple factors is essential, including extraction temperature, pressure, co-solvent type, concentration and sample size. These factors play a pivotal role by augmenting the extraction efficiency of specific compounds and are intricately linked to the solubility and the degree of mass transfer resistance exhibited by raw materials [120]. Ensuring the highest possible solubility of extractable compounds in SFE is of paramount importance because it exerts a substantial impact on the extraction's efficiency and the overall quality of the resulting extract [113]. SFE allows the adjustment of the solvent strength and selectivity of SFs and can thus be seamlessly integrated into gas chromatography or SF chromatography [121]. The benefits of SFE have been thoroughly documented, encompassing its swift processing, applicability for extracting volatile and heat-sensitive compounds, enhanced productivity leading to large yields, diminished solvent usage and environmental compatibility using safe solvents. Thus, SFE holds a central position in diverse fields, including food science, pharmaceuticals, agriculture and cosmetics [122].

Presently, substantial effort has been dedicated to the valorisation of food waste, and SFE remains the optimal technique for extracting valuable compounds from agro-industrial by-products. These extracts have sustainable applications in the food industry because they contain high amounts of phenolic compounds, which exhibit robust antioxidant properties [123–125]. As an example, the extract obtained from mango peel has been effectively employed as a natural antioxidant in sunflower oil to manage lipid oxidation. The ideal extraction parameters for this purpose were identified as 25 MPa pressure, 60 °C temperature and a solvent system consisting of 15 % ethanol in water, utilising a Box–Behnken design for optimisation [126]. SFE has demonstrated its versatility and wide-ranging applications in various fields. These applications include the extraction of cholesterol and lipids from egg yolk [127]; extraction of lipids and cholesterol from meat and meat products [128]; decaffeination of coffee and tea [129,130]; extraction of bioactive compounds [131–133]; fractionation of natural colour, natural flavour and fragrance from various food sources [134,135]; and separation of spices and essential oils [136–139].

4.2. Microwave-assisted extraction (MAE)

MAE employs microwave radiation to facilitate the heating of a combination of solid and liquid materials leading to the removal of solutes from a solid matrix into a solvent. The heating process is initiated through microwave irradiation, which is selectively absorbed by molecules based on their dielectric properties. Temperature is a critical parameter in MAE and can be modulated by adjusting the duration and power of microwave irradiation. Alternatively, power intensity can be directly employed to achieve the desired temperature during extraction [140].

[141] extracted various sugars (inositols and inulin) from artichoke external bracts through MAE in conjunction with temperature control. The findings indicated that the most significant inositol yield was achieved at a lower heat of 50 °C, whereas better extraction efficiency for inulin was achieved at temperatures above 120 °C. [142] investigated the influence of solvent choice on the extraction of polyphenols from apple tree wood by using various alcohol–water mixtures; these solvent mixtures led to a higher TPC than that obtained using pure methanol, ethanol or water as solvents at 100 °C.

MAE is a relatively new method that has gained popularity for its high extraction efficiency, short extraction time and low solvent consumption. MAE is considered an effective and eco-friendly method to extract various compounds from different plants, such as alkaloids, polyphenols and carbohydrates [143].

[144] demonstrated that MAE is appropriate for extracting alkaloids and polyphenols from berberis roots, which are widely used for their medicinal properties; they optimised the MAE conditions using multiple-component analysis and reported higher berberine, palmatine, TPC and antioxidant activity than those obtained with conventional methods. [145] reported that MAE is suitable for extracting carbohydrates from roasted coffee beans, which are important for the flavour and aroma of coffee. The study found that MAE increased the extraction of mannose, galactose, arabinose, xylose, glucose and fructose from coffee beans compared to conventional methods. However, MAE is not suitable for extracting compounds that are sensitive to high temperatures, such as some vitamins, enzymes and proteins [146]. MAE may also degrade some thermolabile compounds, such as anthocyanins, flavonoids and carotenoids [147]. Moreover, MAE may not be suitable for extracting compounds that are strongly bound to the matrix or have low solubility in the solvent [146].

The choice of MAE relies on various factors, including the types and properties of the bioactive compound, such as polarity, stability, solubility and molecular weight, and the type and properties of solvents, including polarity, dielectric constant, boiling point, viscosity and toxicity. The microwave power and temperature affect the heating rate, extraction time and extraction yield, while the sample–solvent ratio affects the solubility. Moreover, the contact sample surface area and mass transfer of the compounds depend on the penetration and absorption of microwave radiation, and the uniqueness of the matrix, such as its composition, structure, moisture content and particle size [144,146,148]. In research by [144] a multi-component analysis and MAE were employed to extract berberine and palmatine from berberis roots. The highest recovery of the berberine and palmatine was obtained at microwave power of 598 W, irradiation time of 2 min, solvent of methanol 100 % at pH 2.0 and sample to solvent ratio of 1:70 (g/mL), which yielded 46.38 mg/g berberine and 20.54 mg/g palmatine.

4.3. Ultrasound-assisted extraction (UAE)

UAE is a method that employs ultrasound energy and solvents to extract specific compounds from diverse plant matrices [149]. This technique relies on the occurrence of acoustic cavitation, wherein bubbles form and collapse within a liquid medium under the influence of ultrasound waves. The implosion of these bubbles results in the generation of shockwaves, shear forces and localised heating, all of which contribute to the disruption of cell walls and enhance the transfer of solutes to solvents [150].

Some of the compounds that can be extracted by UAE are phenolic compounds, such as phenolic acids and flavone glycosides [150–152]. The ultrasonic technique is a well-established eco-friendly bio-refining technology primarily because of its capacity to lower cost, minimise energy consumption and yield high output. Furthermore, the ultrasonic technique has found widespread application in the food industry because of its effectiveness in expediting chemical reactions through cavitation [153]. Ultrasonic waves can induce alterations in the internal structure of food matrices [154]. Therefore, this process promotes the liberation of bioactive compounds from plant matrices after cell disruption [155]. Ultrasound generates more biomolecules within a short extraction period than conventional extraction methods [156]. The quality of phenolic compounds and the overall concentration of polyphenols in various matrices extracted using ultrasound are contingent on factors, such as solvent volume and polarity, ultrasound intensity and extraction temperature [157] in addition to extraction time [158].

UAE inhibits enzyme-induced browning, which has a substantial effect on a product's quality and shelf life. To reduce losses, the problem of browning in freshly cut fruit and vegetables must be solved [159]. Ultrasonic treatment with purslane water extract effectively mitigated browning in potatoes, demonstrating the potential anti-browning benefits of ultrasonic technology. Ultrasonic waves can enhance the various physical properties of compounds, including suspension, particle size, viscosity, colour, pH, acidity and stability. The stability of bioactive compounds is a critical factor in the assessment of bio-accessibility. [160] demonstrated that UAE extracts had low oxygen levels, providing an environment conducive to carotenoid retention. Additionally, ultrasound can enhance the bio-accessibility of compounds in food. Ultrasonic energy can penetrate cell walls, facilitating the release of target compounds during gastrointestinal digestion. Furthermore, ultrasonication improves the physicochemical attributes and overall quality of food products. [161] investigated the effects of UAE on phenolic compounds in young and aged red wine and utilised ultrasonic baths and ultrasonic probes. Treatments with low frequency, amplitude, temperature and treatment duration showed moderate impact on the chemical composition of wine.

Ultrasonic energy has been preferentially used to extract bioactive substances, such as phenolics [162,163], and flavonoids [164–166]. However, UAE is limited because it can promote the degradation or oxidation of sensitive compounds because of the elevated temperature and pressure produced by cavitation bubbles. Thus, the method requires expensive equipment for industrial applications. The effectiveness of UAE depends on several factors, including ultrasound frequency and intensity, sonotrode size and configuration, distance between sonotrodes and samples and characteristics of solvents and samples. These factors need to be optimised and controlled for large-scale production and mitigation of issues related to the exposure of operators to ultrasound waves and organic solvents [167]. [168] showed that UAE augmented the extraction yield and maintaining the physicochemical attributes of proteins obtained from chickpea, kidney bean and soybean. Similarly, [169] examined the impacts of MAE and UAE on the extraction yield and functional characteristics of proteins obtained from peanut flour. The findings revealed that MAE and UAE exerted a substantial impact on the extraction yields and physicochemical properties of proteins [170].

4.4. Enzyme-assisted extraction (EAE)

EAE employs specialised enzymes to break down the cell wall of a source material, thereby enhancing the extraction yield of bioactive compounds [171]. EAE offers several advantages over traditional extraction techniques; it is highly selective, reducing the use of organic solvents, increasing quality and bioactivity, and lowering energy consumption; moreover, it uses extracts with low toxicity and mild extraction conditions and is cost effective and environmentally friendly [171,172]. The most frequently utilised enzymes for EAE are cellulases, hemicellulases and pectinases, which can degrade the complex polysaccharides of the cell wall and cause the release of bioactive compounds [173].

However, EAE may be unsuitable for compounds that are sensitive to enzymatic degradation or have low solubility. Its effectiveness depends on the type and activity of enzymes used and extraction parameters, such as pH, temperature and duration. Hence, the meticulous selection of enzymes and modulation of extraction parameters are essential to produce bioactive compounds with high yields and quality [171]. EAE methods vary according to bioactive compounds and matrices. Proteases, such as trypsin or papain, can be used in protein extraction, and enzymes, such as cellulase and pectinase, can be used in carbohydrate extraction. Matrices can affect the effectiveness of EAE. Soft matrices are generally more suitable to EAE than hard matrices.

4.5. Pressurised liquid extraction (PLE)

PLE uses high temperature and pressure (~10 MPa) and accelerates extraction, increases extraction yield and improves the recovery of valuable compounds, such as phenolic compounds, from biomass. PLE is considered an environmentally friendly and sustainable method because it allows the use of non-toxic and recyclable food-grade solvents, such as ethanol and water. It maintains a solvent in a liquid state by applying high pressure and temperature. Compared with conventional extraction methods, PLE is effective in extracting phenolic compounds. When processing temperature is higher than a solvent's boiling point, PLE systems reduce solvent viscosity and enhance the solubilisation of target compounds and improve extraction performance by increasing diffusion and mass transfer coefficients [174,175]. PLE is used to extract various components, such as proteins, sugars, phenolics and phlorotannins from six algal species found in Algeria's west coast [176]. Additionally, PLE was used to extract pectin and phenolic compounds from apple pomace using a 6.5 % (*w/v*) citric acid solution at a flow rate of 5 mL/min for 40 min [177]. The highest yield of pectin and TPC were achieved at 110 °C, 20 MPa and a solid–liquid ratio of 10, with values of 20.05 % and 16.3 ± 0.3 mg GAE/g, respectively. Although conventional extraction (2 h with a 6.5 % w/v citric acid solution) resulted in higher pectin yield (25.27 ± 1.78 %), PLE yielded higher TPC. The advantages and limitations of various techniques for the extraction of bioactive compounds are summarised in Fig. 2.

5. Green extraction solvents

The challenging aspects of green extraction are the creation of eco-friendly solvents and their appropriate selection and application for specific purposes. Green extraction solvents are more sustainable than traditional organic solvents, biodegradable and non-toxic. Thus, they are suitable for the extraction of bioactive compounds from natural sources. Green extraction solvents have been increasingly used in natural product extraction because of their minimal impact on the environment and human health. The data book of green solvents [178] classifies over 300 environmentally friendly solvents and offers comprehensive details about their properties and safety implications and potential alternative options for each solvent.

[179] categorised green solvents for separation methods into five primary solvent classes, including aqueous solvent, ILs, DES, bio-based solvents (such as ethanol, ethyl lactate and D-limonene) and switchable solvent systems. The choice of green solvent for a particular extraction process relies on a multitude of factors, including the type of the compound, the extraction technique principal and the downstream processing requirements [180]. For instance, in MAE, polar solvents with high dielectric constants, including water and ethanol can absorb and release energy, heat the system. By contrast, solvents with low dielectric constants, such as hexane, do not respond to microwaves [140]. Similarly, PLE relies on a large change in solvent dielectric constant at a high temperature [181]. SFE is suitable for extracting oils and lipids because of the low polarity of CO_2, but extracting polyphenols may require highly polar modifiers that may be incompatible with supercritical CO_2 [140]. Regardless of the extraction method, the chemical properties of solvents are essential for enhancing solubility, extraction recovery and selectivity of target compounds. Understanding these chemical properties facilitates the selection of suitable solvents for the optimisation of the yields or purity of desired molecules. Various scales, such as Rohrschneider polarity, log P and Hansen solubility parameter, can assist solvent selection [124,140]. The selectivity of solvents depends on specific compounds and can be achieved by using polar or non-polar solvents or blending them to produce solvents with intermediate polarity. ILs can act as catalytic agents and facilitate the extraction of compounds that may not be extractable by other selective solvents. Similarly, the selectivity of extraction using DESs can be customised by using specific DESs [140].

The efficacy of green solvents for the extraction of bioactive compounds from natural sources and their potential large-scale applications have been demonstrated [182,183]. However, additional research is necessary to enhance extraction conditions and scale up processes and to make green solvents practical and economically viable.

5.1. Aqueous solvents

Water is the most plentiful and eco-friendly solvent and can be employed for the extraction of a wide range of bioactive compounds [184]. Studies on the impact of aqueous extraction conditions (temperature, time and solid–liquid ratio) on antioxidant activity demonstrated that water extraction is a simple, cheap and environmentally

Extraction method	Advantages	Disadvantages
Conventional	• Ease of use • Affordability • Availability	• Toxic solvents usage • High energy consumption • Low selectivity • Low yield and efficiency • Time consuming • Thermal degradation
Supercritical fluid	• Short extraction time • High extraction efficiency • Selectivity • High purity of extract • Reduced solvent usage • Mild extraction condition	• Low efficiency for highly polar and low volatile compounds
Microwave	• High extraction efficiency • Short extraction time • Low solvent consumption	• Thermal degradation of heat-sensitive compounds
Ultrasonic	• Short extraction time • High extraction efficiency • Expediting the chemical reaction • Inhibiting enzymatic activity	• Degradation or oxidation of sensitive compounds to ultrasonic • High equipment costs
Enzymatic	• High extraction efficiency • Selectively • High quality bioactive product • Low toxicity of the extract • Low energY consumption • Mild extraction condition	• Enzyme sensitive degradation • Not suitable for low soluble material
Pressurized Liquid	• High extraction efficiency • Short extraction time • Low solvent consumption	• Degradation of heat/pressure sensitive compounds

Fig. 2. Advantages and limitations of different techniques for extraction of bioactive compounds.

friendly solvent for the valorisation of grape pomace as a reservoir of various compounds [184,185].

5.2. ILs

ILs are essentially organic salts with melting points below room temperature and are in a liquid state at room temperature and within a wide temperature range. They have unique properties, such as low volatility, high solubility and tunable polarity. They can serve as substitutes for conventional organic solvents in various sample preparation procedures [186]. ILs are sustainable, non-flammable, easy to prepare, biodegradable and biocompatible and can dissolve natural compounds [187,188]. The carotenoid profiles of *Chlorella saccharophila* were analysed using four different ILs (1-decyl-3-methylimidazolium chloride, tetrabutyl phosphonium hydroxide, tetrabutyl hexadecyl phosphonium bromide and tetrabutyl ammonium hydroxide) and compared with a methanol solvent. Meanwhile, 40 % (*w/v*) tetrabutyl phosphonium hydroxide (recovery of 2.26 mg/g dry cell weight [DCW] of lutein) was more efficient for carotenoid extraction than methanol (0.10 mg/g DCW of lutein) at room temperature. Further optimisation of the extraction conditions (IL concentration of 40 % w/v, extraction time of 5 min, solvent: biomass ratio of 0.5 mL/mg and temperature of 25 °C) led to a 10 % increase in lutein extraction. Lutein was three times as stable as methanol at high temperatures [189]. However, ILs can exert environmental impacts, including groundwater contamination, soil sorption, accumulation in aquatic organisms and ecotoxicity [190]. Their solubility in water can negatively affect aquatic life, and their high stability reduces their biodegradability. The toxicity of ILs is mainly influenced by the structure of cation and alkyl chain length determining its hydrophobicity [191]. Long hydrophobic ILs can persist in the environment, while hydrophilic ILs are more likely to enter aquatic ecosystems [190]. ILs also have drawbacks, such as high viscosity, high production cost, limited solute solubility, corrosivity and poor degradability [191]. Segatto et al. [192] evaluated the sustainability of ILs for the extraction of mangiferin and hyperoside from mango residue and compared it with that of ethanol. The results showed that 1-octyl-3-methylimidazolium chloride had higher mangiferin and hyperoside concentrations than choline acetate and ethanolic extracts; however, the yield of the aqueous ethanolic extract was higher than that of the choline acetate–water mixture; they suggested that the advantages of ethanolic extracts outweigh those of ILs in terms of economic and environmental factors, especially when ethanol is obtained through bioeconomy approaches [192].

5.3. DES

Owing to the limitations of traditional ILs, DESs were developed from hydrophilic components [193]. DESs are derived from natural compounds, such as sugars, organic acids, alcohols, amino acids and choline derivatives [194] through a combination of two or more components in a precise ratio; thus, they have distinct attributes, including minimal toxicity, heightened solubility and adjustable polarity [195]. These mixtures exhibit a eutectic point temperature below that of an ideal liquid mixture and demonstrate substantial negative differences from an ideal mixture. DESs are suitable alternatives to traditional solvents because they are natural, safe, inexpensive, environmentally friendly, biodegradable and non-toxic and have low synthesis cost and wide polarity [196]. Moreover, DESs have low vapor pressure; however, this property can disrupt the separation of phenolic compounds [197]. Thus, scale-up studies are essential for research on industrial applications [198].

The effectiveness of the NADES combined with UAE in extracting polyphenols from *Michelia alba* was evaluated. The method utilised nine NADES components. Choline chloride, betaine and L-proline were used as hydrogen bond acceptors, and ethylene glycol, propylene glycol, urea, 1,4-butanediol, acetic acid, lactic acid and glycerol were used as hydrogen bond donors. The NADES composed of L-proline and lactic acid was found to be the most suitable solvent for extracting polyphenols from *M. alba*. The high yield of polyphenols (169.17 mg/g) was obtained under optimal extraction conditions (17.98 min ultrasonication, 48.52 % water content of NADES and 59.79 g/mL liquid–solid ratio) [199]. Similarly, a study explored the extraction and stability of phenolic compounds from sunflower meal and used various NADES formulations as extractors; then, the compounds were compared with 40 % ethanol; the NADES formulated with lactic acid and glucose in a 5:1 ratio was the most effective among the formulations, resulting in an extract containing 1786 mg/L chlorogenic acid; ethanol at 40 % concentration yielded an extract with 1305 mg/L chlorogenic acid, whereas the choline chloride–glycerol formulation produced an extract with 807 mg/L chlorogenic acid. Notably, the antioxidant activity of the extracts did not align with the chlorogenic acid concentration, and the ethanolic extract exhibited high antioxidant activity. In terms of stability, the NADES composed of lactic acid and glucose demonstrated better protection against heat treatment and storage than the other formulations, and ethanol showed excellent under light exposure [200].

5.4. Bio-based solvents

Solvents derived from renewable natural residues, such as plants, fruit and vegetables, exhibit comparable properties to standard solvents [201]. Commonly utilised bio-based solvents, such as limonene, ethanol, ethyl lactate, terpenes and CO_2, can be categorised into esters and ethers [202]. CO_2 as SF is widely used as an extraction solvent because of its distinct characteristics, such as minimal toxicity, high diffusivity and tunable solubility [120]. Various bio-based solvents, such as alkanediols, dihydrolevoglucosenone (cyrene) and gamma-valerolactone (GVL), are potential alternatives to volatile organic compounds for extracting bioactive compounds from natural sources. [203] utilised aqueous and ethanolic mixtures of bio-based solvents, such as cyrene, GVL and alkanediols in combination with UAE and MAE to extract phenolic compounds from kiwifruit peels. The optimal mixture of GVL and ethanol (7:3 wt/wt) yielded extracts with the highest levels of TPC and antioxidant activity. Of the extraction techniques utilised, MAE demonstrated the most promising results, yielding extracts with high levels of TPC and the highest antioxidant activity in a shorter extraction time. In a similar study, aqueous solutions of 1,2-ethanediol and 1,2-propanediol showed high effectiveness for the extraction of phenolic compounds (quercetin, coumaroylquinic acid, caffeoylquinic acid) from walnut leaves [204]. A study by Cañadas et al. [205] evaluated the potential use of bio-based solvents, namely, 2-methyltetrahydrofuran (2-MeTHF) and cyclopentyl methyl ether, as alternatives to ethyl acetate in the extraction of bioactive compounds from winery effluents obtained through liquid–liquid extraction; the results showed that 2-MeTHF exhibited the highest extraction efficiency among the compounds; gallic acid, protocatechuic acid, 4-hydroxybenzoic acid, caffeic acid, vanillic acid and syringic acid exhibited extraction efficiency of 96.46 %, 87.44 %, 80.82 %, 92.24 %, 75.18 % and 38.19 %, respectively; moreover, 2-MeTHF can be recycled without losing its effectiveness and can be used in the isolation of phenolic antioxidants as solid fractions [205]. Table 1 summarises the key findings of various extraction techniques with green solvents to recover bioactive compounds.

6. Bioactive compounds in smart food packaging

Bioactive compounds as natural substances can be utilised to regulate the environment within the packaging, preserve the quality and visual appearance of packed food and increase shelf life. They can also be utilised in smart packaging to ensure the freshness, safety and quality of food products and facilitate the detection of chemical and physical alterations [214]. Selecting bioactive compounds for food packaging depends on compatibility with food products, effectiveness and purpose. They can be encapsulated into nanoemulsions, polymeric nanoparticles, liposomes or nanofibres and incorporated into packaging materials or sprayed onto food surfaces [215]. These compounds have drawn attention because plants contain various pigments, such as carotenoids and anthocyanins, which can be obtained from agricultural by-products [216]. Smart packaging using biocarriers includes the use of various biopolymers and bio-based polymers in the form of encapsulating, composite and nanocomposite polymeric films. The loading of extract of *Ocimum tenuiflorum* in a blend of chitosan and polyvinyl alcohol films [217], the incorporation of Açaí oil in chitosan plasticised films with DES (choline chloride: glycerol) and the production of starch nanocomposite films containing cellulose nanocrystal and polyaniline [219] demonstrate the versatility of biocarriers in smart packaging.

Smart packaging systems can be categorised into active and intelligent packaging [220]. Bioactive compounds can be integrated as indicators that can detect microorganisms or alterations in food products' chemical structures or as antioxidant and antibacterial that enhance the shelf lives of products through the controlled release of bioactive compounds into the packaging environment (Fig. 3) [221].

The particular attributes and efficacy of such packaging can considerably vary because of numerous factors, which encompass active ingredients employed, the composition of packaging materials, the control regulation of internal gas composition and the characteristics of enclosed food products [222,223].

However, the use of bioactive compounds for food packaging has presented challenges related to stability, solubility, bioavailability and sensory acceptability. The active film of cellulose acetate with natural antioxidants (such as norbixin, zeaxanthin and lycopene) exerted a protective effect on the shelf life of sunflower oil, and the films with norbixin or lycopene exerted a more considerable protective effect under controlled oxidation condition than zeaxanthin because of the stability of these pigments [224]. Sensory characteristics (odour, taste and colour) were below the acceptable limit in flaxseed oil packed with a bilayer film made of pumpkin oil cake as a source of carotenoids and maize zein within 25–30 days [225]. Shrimp muscle protein-derived films containing astaxanthin from shrimp cephalothorax and lycopene from tomato peel waste showed carotenoid degradation after 1 month of storage, and commercial β-carotene, lycopene and astaxanthin had degradation rates of 32 %, 32 % and 17 %, respectively; all the films released carotenoids in 95 % ethanol, and the highest amount of astaxanthin was released initially, followed by commercial β-carotene and lycopene. Lycopene exhibited slower release than the other carotenoids because of its interaction with the protein network [226]. In addition, the stability of bioactive compounds can be affected by film formation conditions. Carotenoids are stable under low acidity and neutral conditions, but their stability decreases under alkaline and acidic conditions. They may be used to enhance the solubility of proteins or chitosan and promote oxidation and isomerisation [29]. Therefore,

Table 1
Summary of extraction techniques used for bioactive compounds.

Extraction method	Solvent type	Optimum condition	Biomass	Bioactive compounds	Yield	Reference
Supercritical CO_2 and UAE	Aqueous methanol	T 66.1 °C, t 44.9 min, SS 49.9 mL/g and aqueous methanol 70.1 %	*Phacelia tanacetifolia* Benth. pollen	Flavonoid glycosides and phenolamides	ND	[206]
NaDES and UAE	Lactic acid	Lactic acid, citric acid and glycerol ratio 3:1:2, t 60 min, solvent volume 35 mL and water amount in NaDES 30 % (v/v)	*Rosa damascene* Mill	Phenolic compounds (Flavonoids)	ND	[207]
UAE, MAE and PLE	Ethanol	UAE: Ethanol 71 %, t 10 min, T 50 °C, SS 1.50/20 g/mL MAE: Ethanol 80 %, t 5 min, T 50 °C, SS 0.85/20 g/mL PLE: Ethanol 80 %, t 20 min, T 65 °C, SS 2/20 g/mL	Sesame cake	Polyphenolic lignan [sesaminol triglucoside (SETRI) and sesaminol diglucoside (SEDI)]	UAE: 8.28 %, 105.98 mg SETRI/g and 16.93 mg SEDI/g MAE: 8.75 %, 105.41 mg SETRI/g and 18.76 mg SEDI/g PLE: 9.34 %, 108.00 mg SETRI/g and 18.34 m SEDIg/g	[208]
UAE	Aqueous ethanol	Low ripped: t 75 min, T 40 °C and SS 1:15 m/v High ripped: t 40 min, T50 °C and SS 1:15 w/v	Low/high ripped purple tomatoes	Anthocyanins	*Low ripped*: 12.487 mg/100 g *High ripped*: 8.802 mg/100 g	[209]
UAE	Ethanol	Ethanol 94 %, SS 1:25 w/v, t 20 min and T 20 °C	Babassu mesocarp (*Attalea speciosa*)	Phenolic (flavonoid)	TPC 5124.86 ± 350.13 mg GAE/100 g Flavonoids 477.45 ± 23.07 mg QE/100 g	[210]
NaDES	Oxalic acid	Choline chloride–oxalic acid with a molar ratio of 2:1, SS 1:90 w/v, t 30 min	Toona sinensis seeds	Phenolic (ellagic acid)	TPC 32.58 mg GAE/g DW	[211]
PLE	Ethanol	T 86 °C and t 39 min	Silver birch (*Betula pendula* Roth) leaves	Hyperoside and other valuable polar antioxidant-rich extracts	Yield: 32.2 % TPC 97.3 mg GAE/g Flavonoid 37.3 mg QE/g Proanthocyanidin 301.2 mg catechin hydrate E/g. Hyperoside 54.1 mg/g Betuloside 18.3 mg/g Chlorogenic acid 11.5 mg/g	[175]
PLE	Distilled water	T 120 °C, rate 9 $mL.min^{-1}$ and P 10 MPa	Yerba mate (*Ilex paraguariensis* St.-Hil.) waste	ND	TPC 1256.18 mg GAE/100 g	[174]
MAE pre-treated UAE	Ethanol	MAE: P 675.76 and 669.70 W, t 150 s, UAE: T 30 °C and t 19.70 and 16.46 min	Papaya pulp and peel	ND	Pulp: TPC 2.38 % Peel: TPC 1.31 %	[212]
DES	Malic acid	Malic acid/choline chloride 2:1, T 120 °C, t 4 h	Poplar wood	Lignin	86.9 %	[213]
Acidic NaDES	Formic acid	Choline chloride/*N*-acetyl-D-Glucosamine/formic acid 1:0.6:1.4, T 130 °C, t 3 h, SS 1:20	Crab shell	Chitin	85.6 %	[102]
Bio-based solvent, UAE and MAE	Ethanol and/or water	T 50 °C, gamma-valerolactone:ethanol in a ratio of 7:3 (w/w), SS 1:17 and t 6 min	Kiwi waste	Phenolic compounds (epicatechin derivatives)	TPC (29.7 ± 0.6 mg GAE/g DW) Epicatechin (2.295 ± 0.005 mg/g DW) Quercetin (0.023 ± 0.002 mg/g DW) Caffeic acid (0.013 ± 0.003 mg/g DW)	[203]

Abbreviations: ND not determined; T temperature; t time; P pressure; SS solid-solvent ratio; E equivalent; TPC total phenolic content; QE quercetin equivalent; GAE gallic acid equivalent; DW dry weight.

bioactive substances should be carefully incorporated into smart food packaging to ensure the stability and effectiveness of the substances. This approach prevents the degradation and oxidation of the compounds, thereby preserving their functionality [227,228].

One promising solution to overcome these challenges is encapsulation technology, which involves the entrapment of bioactive compounds within a protective matrix or shell. Encapsulation can improve the stability, solubility and release of bioactive compounds and mask their undesirable flavour or odour [17]. It also allows the controlled release of bioactive compounds in response to specific stimuli, such as pH, temperature and moisture. Assis et al. demonstrated that the incorporation of β-carotene nanocapsules compared with free β-carotene improved the interaction with the starch matrix, increasing solubility in aqueous media and improving distribution without altering the rapid biodegradability and thermal stability of films [229].

Recent advancements in intelligent and active biopolymer-based films and smart bio-packaging containing bioactive compounds have been explored [230]. Natural pigments with a wide range of bioactive properties are suitable colorimetric indicators because of their ability to detect variations in food pH and intrinsic antibacterial and antioxidant characteristics.

In general, attention must be directed towards the selection of materials and additives for smart packaging because they serve as indicators for the immediate environment and products. Moreover, packaging must be disposable and should maintain its eco-friendly characteristics after being removed from food items. Consequently,

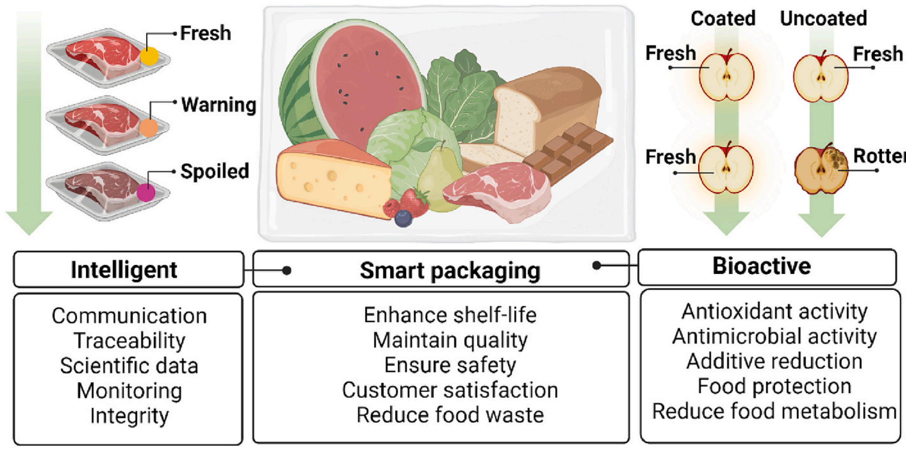

Fig. 3. Application of bioactive compounds in smart packaging.

integrating bio-based polymers infused with naturally occurring bioactive compounds used as additives emerges as a highly advantageous solution for the overall betterment of the food industry [231,232].

Continuous advancements in smart packaging technologies emphasise the need continual research and development to fully unlock their benefits [233]. The incorporation of bioactive components extracted from natural sources, such as plants and minerals, in smart packaging have been attracting widespread interest because of their potential contributions to environmental sustainability and ethical production methods.

6.1. Bioactive compounds in active packaging

Bioactive compounds are utilised as antimicrobial or antioxidant agents in active packaging to inhibit the proliferation of microorganisms or prevent the oxidation of lipids in food products. Some substances can inhibit or kill microorganisms that cause the spoilage or contamination of food, including nisin, lysozyme, lactoferrin, chitosan, essential oils and plant extracts [215]. These agents can prolong the shelf life and maintain the quality of food items. For example, phenolic compounds have strong antioxidant and antimicrobial activities. Their potential use as agents that prevent rancidity or microbial spoilage of food products is of high interest to researchers [234].

Active substances have been incorporated into packaging or coating matrices to enhance the stability and shelf lives of food products. Active packaging was prepared using bioactive compounds. For example, bioactive compounds in rosemary (*Rosmarinus officinalis* L.) and green tea (*Camellia sinensis* L.) were extracted using ethanol and water and incorporated into a polylactic acid film [235]. Similarly, bioactive compounds from *Penganum harmala* were incorporated into sago starch [236], tea polyphenols were combined with alginate [40] and bioactive compounds from green tea were incorporated into chitosan [237]. These applications demonstrated that bioactive materials in packaging or coating matrices enhance the stability of packaging materials and ensure the quality and safety of food products. Bioactive compounds extracted from mango leaf by the mixed solvent extraction of ethanol–CO_2 have been used in the production of active nanocellulose films. Active films showed high antioxidant (84 % inhibition) and antibacterial activity against *Escherichia coli* and *Staphylococcus aureus* [238].

6.2. Bioactive compounds in intelligent packaging

Intelligent packaging is defined as a technological system that can transmit information, support decision-making processes, ensure product quality and issue alerts in response to changes observed in the external and internal environments of packaging [239,240]. Typically, indicators for intelligent packaging are small components positioned inside a packaging material or affixed to the exterior of the packaging material [241].

Bioactive compounds in intelligent packaging can be used as natural colorants that can undergo colour changes in response to specific stimuli, such as alterations in pH or temperature. These colorants can act as visual indicators of the freshness or spoilage of food products. Indicator bioactive compounds include anthocyanins, betalains, curcumin, chlorophyll and enzymes [242].

Active compounds as intelligent indicators enhance the stability and function of packaging or coating matrices. As bio-sensors, anthocyanin-rich compounds extracted from diverse plant sources mostly with bio-based solvents, such as ethanol and water, are essential to intelligent food packaging systems [243–245]. Anthocyanins are colorimetric pH-responsive agents that facilitate the reliable and real-time assessment of the qualitative attributes of packaged food items.

Key findings of various studies on smart packaging are summarised in Table 2.

7. Impact of bioactive compounds on the characteristics of smart packaging

In addition to providing various functionalities to packaging materials, natural extracts can influence the technological properties of smart packaging materials. The type and concentration of these extracts determine the extent of changes in packaging material characteristics. Chemical interactions between polymers and extracts influence the structure of packaging materials, thereby affecting their techno-functionalities [263]. For instance, incorporating red radish anthocyanin to the blend matrix of chitosan and zein film significantly altered the properties of smart films compared to the control. Anthocyanin addition enhanced the compatibility between zein and chitosan through new hydrogen bonding, resulted in a more compact, uniform, and homogenous composite. Lower concentration of anthocyanin increased the amorphous complex, while higher concentration led to a more ordered and crystalline structure in chitosan-zein complex. This structural change was reflected in barrier properties of composite, with lower anthocyanin concentration enhancing the barrier properties against the water vapor and gas, while higher concentration decreased them. Similarly, mechanical properties of composite were affected, so that tensile strength of composite increased and the elongation at break decreased. However thermal stability remains unaffected [264].

Furthermore, mixing bioactive compounds can enhance their functional properties, leading to different impacts on matrix characteristics compared to single bioactive compound. For example, adding anthocyanin extract from red cabbage leaves to the polyvinyl alcohol (PVA)-starch film crosslinked with glutaraldehyde resulted in a partially homogeneous structure compared to the rough surface with unmixed PVA

Table 2
Summary of the key findings on bioactive compounds in smart packaging.

Bioactive compounds	Extraction methods	Biomass	Film	Function	References
Flavonoids	Ethanolic extract	*Sophora japonica*	*Artemisia sphaerocephala* Krasch. gum	Antioxidant	[246]
Flavonoids	Ethanolic extract	Mangosteen peel	Porang glucomannan	Antioxidant Antimicrobial	[247]
Anthocyanin	Ethanolic extract	Black soybean seed	Chitosan	Antioxidant and pH-sensitive sensor	[248]
Phenolics, flavonoids, terpenes	Ethanolic extract	*Eriobotrya japonica* Lindl. leaves	Banana peel flour	Antioxidant	[249]
Flavonoid	Ethanolic extract	Hawthorn berry (*Crataegus pinnatifida*)	Alginate	Antimicrobial	[250]
Phenolic compound	Aqueous extract	Rosmarinus officials L.	Gelatin	Antioxidant and antimicrobial	[251]
Anthocyanins	Ethanolic extract	Coleus grass	Chitosan	pH-sensitive sensor	[252]
Anthocyanins	Aqueous extract	*Bougainvillea glabra*	Potato starch	pH-sensitive sensor	[253]
Anthocyanins	Aqueous extract	Purple cauliflower	Alginate/chitosan	pH-sensitive sensor	[254]
Phenolic compound	Aqueous extract	Rosemary extracts	Whey protein concentrate	Oxidative stability enhancement (sunflower seeds)	[255]
Phenolic compounds	Aqueous extract	Fenugreek seeds	Carrageenan	Antioxidant and antimicrobial activities	[256]
Phenolics (chlorogenic acids)	Ethanol-water ultrasonic	Green coffee oil	Carboxymethyl cellulose	Antioxidant and antimicrobial agents	[257]
Phenolic compounds	Aqueous extract	Guabiroba pulp	Gelatin and corn starch	Active biodegradable packaging	[258]
Protein, vitamin, polyphenols, carotenoids, tocopherol	Aqueous extract	Seaweeds	Chitosan	Antioxidant	[259]
Phenolic compounds	Ethanol aqueous solution	Apple	Chitosan	Antioxidant activity Antimicrobial properties	[260]
Phenolic compounds	Ethanolic extract	Spirulina extract	Chitosan	Antioxidant activities Antibacterial activities	[261]
Polyphenols	Aqueous extract	Immortelle (*Helichrysum italicum*)	Alginate	Antioxidant	[262]

granules in control. Addition of propolis extract to mixture intensified the homogeneity and smoothness of the composite surface, possibly due to the reducing intermolecular forces between polymer chains and increasing chain distance. Anthocyanin alone (5 %) did not affect the crystallinity and mechanical properties of PVA-starch matrix, while propolis extract incorporation decreased crystallinity and elongation while improved tensile strength in presence of anthocyanins. The cross-linking effect of propolis was attributed for this observation. Phenolic compounds in both bioactive compounds reduced water vapor permeability due to the possible hydrogen interactions with PVA-starch matrix [265]. Similarly, integrating a layer of antibacterial agents of chitosan and tea polyphenols to polylactic acid (PLA)-starch acetate composite enhanced the matrix crystallinity. Although chitosan coating alone reduced the thermal stability of composite, addition of tea polyphenols to chitosan improved thermal stability due to strong hydrogen bonding with PLA-Starch acetate complex. Chitosan coating improved the mechanical properties of composite due to the possible crosslinking of amino and hydroxyl groups of chitosan with PLA, whereas integration of tea polyphenols had no significant effect the mechanical properties [266].

Moreover, the interaction between the extracting solvent and matrix can affect the final characteristic of the smart film. For instance, incorporating anthocyanin extracted from black rice (*Oryza sativa* L.) using NaDES (lactic acid and fructose) into PVA reduced PVA crystallinity due to the hydrogen bonding and plasticizing of effect of NaDES. This resulted in improved elongation and flexibility of the film and reduced tensile strength and water vapor permeability. NaDES extract led to a rough surface morphology of the PVA film due to the probable solvent-matrix interactions and faster solvent uptake ratio. The bioactive film exhibited lower glass transition (T_g) and melting temperatures (T_m) compared to the control PVA, suggesting easier processing for commercial application [267]. The effects of various bioactive compounds on physicochemical and structural properties of different smart packaging are summarised in Table 3.

8. Application of smart packaging to various food products

8.1. Fruit and vegetables

The incorporation of bioactive compounds into packaging materials to preserve the quality and extend the shelf life of fruit and vegetables has been extensively explored. Bioactive compounds, including anthocyanins, carotenoids, phenolic compounds, antioxidants and antimicrobials, in packaging materials have used to preserve various types of fruit and vegetables [249]. Herbal extracts have incorporated into edible polysaccharide films and coatings. Herbs are rich in vitamins, minerals and antioxidants and have potential applications as nutraceuticals and medicine. These extracts, including *aloe vera* gel, lemongrass, rosemary, tulsi and turmeric, are integrated into edible coating, thereby extending the shelf lives of fruit and vegetables [274].

[275] investigated the use of pectin-based films incorporating essential oils for strawberry preservation; the packaging significantly improved the antimicrobial properties of strawberries, effectively reducing fungal infections and enhancing their antioxidant capacities. [249] investigated the extract of *Eriobotrya japonica* Lindl. leaves into films made from banana peel flour. The films remained biodegradable and showed potential for use as coatings to extend the shelf life of perishable food. In a similar study, a composite film made of chitosan and banana peel extract with varying content (4 %, 8 % and 12 %) was developed. The composite film containing 4 % banana peel extract exhibited the best properties among the tested formulations. These films showed reduced hydrophilicity, improved mechanical properties and excellent antioxidant activity when compared with pure films. When used to coat apple fruit, composite films enhanced the postharvest quality of fruit [39].

8.2. Meat

Bioactive compounds can be incorporated into edible films or coatings applied to the surfaces of meat products to prevent spoilage and deterioration. For meat products, this feature is crucial to the prevention of microbial growth and the oxidation of products. Food packaging with

Table 3
The key findings of various bioactive compounds impact on the different characteristics of smart packaging.

Type of polymer	Type of bioactive compound	Characteristics	Reference
Chitosan	Chitosan nanoparticle (CN, 49.47 % wt) and propolis extract (PE, 0.89 % wt with concentrations of 10-30 %)	Crystallinity: ↑ with CN and ↓ with PE. Morphology: The average roughness ↓with CN and 20 % PE. Contact angle: ↑ with CN without (from 0 to 15.23°) and with 30 % PE (21.17°). Barrier: WVDC ↓ with CN without (from 7.44 to 6.22 × 10^{-6} cm^2/s) and with 30 % PE (2.11 × 10^{-6} cm^2/s). Mechanical: hardness ↑ with CN without (from 19.1 to 30.0 MPa) and with 20 % PE (34.4 MPa) - Elasticity ↔ with CN; it ↑ with the blend of CN and 10 % PE (from 1 to 2.6 GPa).	[268]
Cellulose nanofibre	Purple sweet potato anthocyanin (PSPA) (83.33 % wt) and oregano essential oil (OEO) (4 % wt)	Crystallinity: ↓ with either PSPA or OEO. Morphology: PSPA and OEO ↑ surface homogeneity and microstructure density without phase separation. Optical: PSPA and OEO ↓ the UV–Vis transmission rate. Contact angle: ↑ with OEO (from 49.4 to 52.9°), ↓ with PSPA (30.1°), ↑ with PSPA-OEO (57.6°). Mechanical: TS and YM ↑ with PSPA, OEO, and PSPA-OEO – EAB ↓ except with PSPA.	[244]
K-Carrageenan	Lignin (0-30 % wt)	Crystallinity: ↓ with lignin. Morphology: homogenous distribution of lignin up to 10 % without aggregation, void, and crack. Thermal: T_g, T_m, and thermal stability ↑with lignin. Optical: UV$_A$ (320-400 nm), UV$_B$ (280-320 nm) and visible transmittance (600 nm) ↓ with lignin (1-30 wt %). Contact angle: ↑ (from 58.7 to 78.5°) with lignin. Water sensitivity: moisture content and swelling ratio ↓ with lignin. Barrier: WVP ↓ (from 2.59 to 1.41 × 10-9 g/m^2 Pa) with lignin concentration < 25 wt %. Mechanical: TS ↑ (from 18.8 to 27 MPa) and EAB ↑ (from 17.9 to 28 %) with 15 % lignin.	[269]
Sago starch	*Bauhinia Kockiana* extract (BKE) (1-3.75 mg/g)	Morphology: ↑ the surface roughness and ↓the compactness with BKE. Water sensitivity: Moisture content, water solubility and swelling index ↑ with BKE. Barrier: WVP ↑ with BKE. Mechanical: TS ↑ and EAB ↓ with low concentration of BKE (<1.25 mg/1 g).	[270]
Cassava starch-polyvinyl alcohol	*Aronia melanocarpa* anthocyanins (AMA) (1-2 % wt)	Morphology: with 1 % AMA, more particles on the surface and smooth microstructure without phase separation- with 2 % AMA rough surface and porous microstructure. Thermal: T_m ↓and melting enthalpy (ΔHm) ↑ with AMA. Optical: ↓ luminosity, ↑ red tonality, and colour diversity -↓ the UV–Visible transmittance with AMA. Moisture content: ↓ (from 28.18 to 19.29 and 20.09 %) with AMA concentration 1 and 2 %. Barrier: WVP ↓ (from 1.42 to 1.22 × 10^{-10} g m^{-1} s^{-1} Pa) with 1 % AMA and ↑ (1.49 × 10^{-10} g m^{-1} s^{-1} Pa) with 2 % AMA Mechanical: TS ↓ (from 23.07 to ~10.00 MPa) - EAB ↑ from (~291 to 340 %) with 1 % AMA and ↓ (~240 %) with 2 % AMA.	[271]
Carrageenan-cellulose nanofiber	Eugenol (Eu) (0.1-0.5 v/v)	Morphology: ↑ microstructure roughness and heterogeneity. Thermal: stability ↑ with Eu. Optical: transparency ↓ with Eu. Water sensitivity: water solubility and moisture content ↓ with Eu. Mechanical: TS ↓ (from 56.63 to 34.85 MPa) and EAB ↑ (from 16.15 to 21.47 %) with Eu.	[272]
Potato starch	Tannin from *Castanea sativa* (CT) (0-3 % wt)	Morphology: surface heterogenicity roughness ↑ and compactness and uniformity of microstructure ↔ with CT. Thermal: thermal conductivity ↓ with CT	[273]

(continued on next page)

Table 3 (*continued*)

Type of polymer	Type of bioactive compound	Characteristics	Reference
		(from 0.197 to 0.178 W/Mk). Colour: a* ↑ and b* ↓ with CT. Contact angle: ↑ (from18.6 to 95°) with 1.7 % wt CT. Water sensitivity: water solubility ↑ with CT. Mechanical: YM ↑ (from 5 to12 MPa) and EAB ↑ (from 54 to 189 %) with 3 and 1.7 % wt CT.	

Abbreviations and marks: ↑ Increase; ↓ decrease; ↔ did not change; T_g glass transition temperature; T_m melting temperature; WVDC: water vapor diffusion coefficient; WVP water vapor permeability; TS tensile strength; EAB elongation at break; YM Young's modulus.

high antimicrobial and antioxidant activity due to bioactive compounds has been extensively investigated for meat preservation. The antimicrobial and antioxidant mechanisms of bioactive compounds released over the shelf life of meat are presented in Fig. 4. The active edible packaging film was developed using semi-refined κ-carrageenan containing a water extract of germinated fenugreek seeds. The phenolic content and antioxidant activity of the films increased as the amount of germinated fenugreek seeds increased, effectively controlling microbial growth on fresh chicken breast, showing up to 2.39 log reduction relative to the control on day 7 and demonstrating its potential for active food packaging [256].

The composites of PLA and varying limonene concentrations (0 %, 4 %, 6 % and 8 %) extend the shelf life of fresh beef during cold storage. Increasing limonene content improved the barrier properties of the composites. The shelf life of beef packed with PLA–limonene films containing 6 % and 8 % limonene was extended to at least 9 and 12 days, respectively; the shelf lives of the control and the film containing 4 % limonene were both 6 days [80]. The incorporation of rosemary and green tea extracts effectively reduced lipid oxidation in beef, as indicated by decreased malondialdehyde formation during 11 days of storage. This result showed that such packaging preserves beef preservation by combating lipid oxidation [235].

[230] developed pH-sensitive smart edible films using cassava starch and pomegranate peel powder (PPP) to monitor the freshness of lamb meat. The incorporation of PPP affected the mechanical properties and colour of the films, resulting in darker and redder films with increased TPC and antioxidant activity. These intelligent films changed colour from red to green during lamb meat storage at 25 °C, enabling the detection of total volatile basic nitrogen (TVB-N) levels and serving as a pH-sensitive indicator for meat freshness monitoring.

In another study, sago starch film containing TiO_2 nanoparticles and *Penganum harmala* extract was developed to extend the shelf life of chicken fillets. The films exhibited increased antibacterial activity against gram-positive bacteria, reduced water vapor permeability and improved oxygen barrier properties. Chicken fillets packaged with these films showed a significant extension in shelf life, with improvements in various physicochemical and microbiological properties, lasting at least 8 days longer than the control samples during cold storage [236].

8.3. Other food

Beyond the limitations of safeguarding meat and fruit, active and intelligent packaging is versatile in its ability to protect a wide range of food products [276]. Smart packaging can help to extend the shelf life and quality of dairy products, such as milk, cheese, yogurt and butter, by releasing antimicrobial or antioxidant agents to inhibit the growth of spoilage microorganisms or prevent oxidation of fats [277]. The antioxidant films produced by blending *Artemisia sphaerocephala Krasch* gum and *sophora japonica* extract, resulted in films with enhanced antioxidant properties for packaging the lard. The active packaging demonstrated the potential to reduce oil deterioration, improve quality and preserve oil effectively [246]. Smart packaging can also be applied to bakery products, such as bread, cakes and cookies. There are several research discuss how functional polymers can incorporate active substances, such

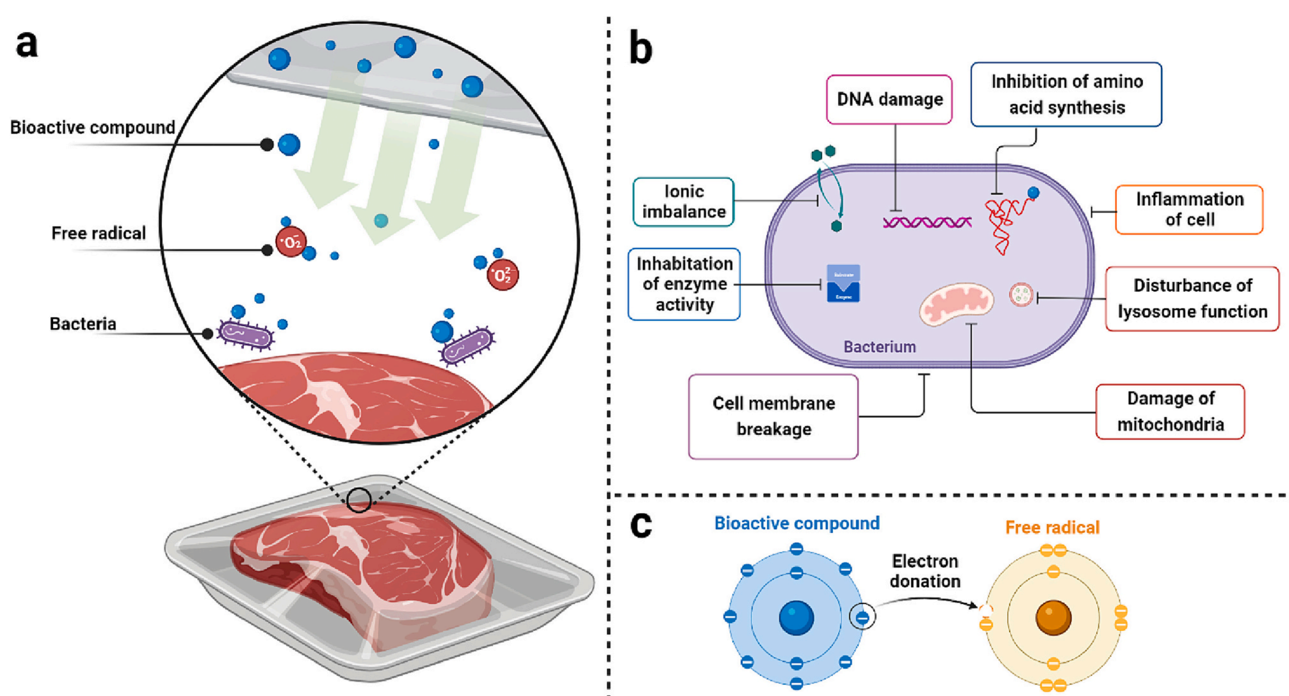

Fig. 4. (a) Illustration of controlled release of bioactive compounds from smart packaging for meat preservation and their (b) antimicrobial and (c) antioxidant mechanisms.

as antimicrobial or antioxidant agents, to improve the shelf life and quality of bakery products [278].

Smart packaging can also enhance the safety and quality of seafood products, such as fish, shrimp and crab. Active packaging films fabricated using PVA containing 2 % green tea extract exhibited the best performance, reducing moisture absorption and providing effective antioxidant properties. When applied to packaging dried eel, the active film significantly preserved eel quality by preventing moisture absorption and lipid oxidation [41]. In another study, biodegradable packaging films were developed by alginate and carboxymethyl chitosan hybrid polymers containing purple cauliflower-extracted anthocyanins. The smart films exhibited enhanced storage stability, antioxidant capabilities and sensitivity for monitoring shrimp freshness [254].

A user-friendly intelligent food packaging with pH and ammonia sensitivity was developed by incorporating betacyanin from paper flowers (*Bougainvillea glabra*) into potato starch film. The film exhibited colour changes from pink to yellow in response to pH adjustments from 2 to 13 and detected ammonia levels in water. Although the betacyanin incorporation improved surface hydrophobicity and water vapor barrier capacity, the mechanical strength of the film was weakened. When used as a label for *Caspian sprat* storage at 4 °C, the colour changes in the label corresponded with increases in TVB-N and microbial count [253].

In another study, a biodegradable intelligent packaging system by combining chitosan/fucoidan with *coleus grass* leaves anthocyanins was developed to monitor salmon spoilage. The resulting intelligent films demonstrated improved properties and enhanced antioxidant and antimicrobial activity and sensitivity to pH changes and ammonia gas [252].

The application of active packaging has also been explored to extend the shelf life of nuts. PLA active films incorporating rosemary extract demonstrated the effective reduction of lipid oxidation in almonds, resulting in an extended shelf life even after 60 days of storage at room temperature [235]. Besides, active packaging can be considered to preserve cooked food against oxidation and bacterial growth. Active edible films created using seaweed (*Himanthalia elongate*) extracts indicated higher antioxidant activity and effectively prolonged the shelf life of fish burgers by controlling pH, reducing microbial growth and minimising lipid oxidation [259].

9. Green extraction principles, concepts and challenges

Green extraction is a rapidly evolving field that has gained considerable interest in recent years. It involves the development and implementation of extraction methods that are environmentally friendly and use green solvents, alternative energy sources and innovative technologies [20]. One of the main challenges facing green extraction is the need to balance sustainability and efficiency [21]. Green extraction methods should be effective in extracting target compounds while being economically feasible, scalable and compatible with existing industrial processes [279]. Another challenge is the lack of standardised methodologies for assessing the sustainability of green extraction methods. One of the reasons is that sustainability is a complex and multifaceted concept that is difficult to quantify and measure [280].

9.1. Principles and concepts

The concept of green extraction is rooted in the principles of green chemistry, which aim to reduce the use and generation of hazardous materials throughout the entire lifecycle of a product, including production, use and disposal [280]. To safeguard the environment, ensure consumer protection and promote competitiveness in industries through ecological, economic and innovative practices, the concept of extraction, adhering to the six principles of environmentally friendly extraction of natural products, has emerged as a solution to address the current issues. Central to this approach is the notion of the ‘green extract’, obtained through methods that minimise environmental impact and prioritise eventual recycling. This green extract represents a comprehensive value chain encompassing economic and responsible practices throughout the entire process, including plant production, harvesting, extraction and separation, formulation and marketing. [21] have evaluated the six principles of green extraction as follows (Fig. 5).

9.2. Emerging trends and challenges

Plant-based extracts and products have a rich historical legacy in diverse cultures and have been used in cosmetics, perfumes, medicine, food ingredients and dyes. However, the emergence of petroleum-based methods resulted in a transition from biomass as a primary source [281]. Plant-based extraction offers a solution as an ecologically and economically sound chemistry, aligning with the principles of green chemistry [282]. Extraction plays a crucial role in the separation primary and secondary metabolites from plant materials, but conventional processes have limitations, such as low recovery rates and high energy consumption [19]. The demand for efficient and green extraction methods is crucially important. The concept of green extraction address challenges by intensifying processes, reducing solvent usage and considering the environmental impact [283]. It involves a comprehensive approach that encompasses the entire value chain, from production and harvesting to formulation and marketing, and focused on economic and responsible practices. Green extraction represents an opportunity to protect the environment, meet consumer demands, enhance industry competitiveness and foster innovation in the 21st century [20].

Green extraction is a rapidly growing field that offers a sustainable and efficient alternative to conventional extraction techniques owing to the development of non-toxic, non-flammable and biodegradable alternative solvents. Research into green extraction has expanded, encompassing an extensive array of solvents, technologies and practical applications. The future of green extraction is promising, and continued research and innovation has led to the formulation of novel and enhanced approaches for extracting bioactive compounds, natural products and other valuable materials.

10. Conclusion

The demand for eco-friendly food packaging has necessitated the development of innovative solutions, leading to the emergence of intelligent packaging. Integrating bioactive elements obtained from natural sources, such as phenolic compounds, carotenoids and peptides, into smart packaging improves functionality and expands applications. This research underscores the pivotal role of bioactive compounds in the enhancement of the functionality of smart packaging and improvements in food stability and shelf life. The strategic integration of bioactive films as biosensors and colorimetric indicators showcases their versatility, ensuring consumer satisfaction and food safety.

This approach involves the fabrication of bioactive films that confer antioxidant properties, antimicrobial capabilities and innovative coloration. Bioactive films are effective in enhancing the stability and prolonging the shelf lives of food products.

However, the extraction of bioactive compounds presents challenges because of their complex chemical structures and low concentrations. Traditional extraction methods are not only time-consuming but also detrimental to the environment. Green extraction techniques have emerged as promising alternatives, offering sustainable and eco-friendly approaches that increase yields, improve product quality and reduce extraction time. UAE, MAE, PLE and SFE are effective in extracting bioactive compounds from diverse natural origins. By embracing green extraction methods, the development of smart packaging can be advanced, promoting sustainability and efficiency.

Future directions in this field involve the utilisation of bioactive resources that possess enhanced functional properties to address challenges associated with incorporation of high amounts of bioactive substances. To comprehend the impact of these new bioactive compounds on the food packaging industry, the environment, human health

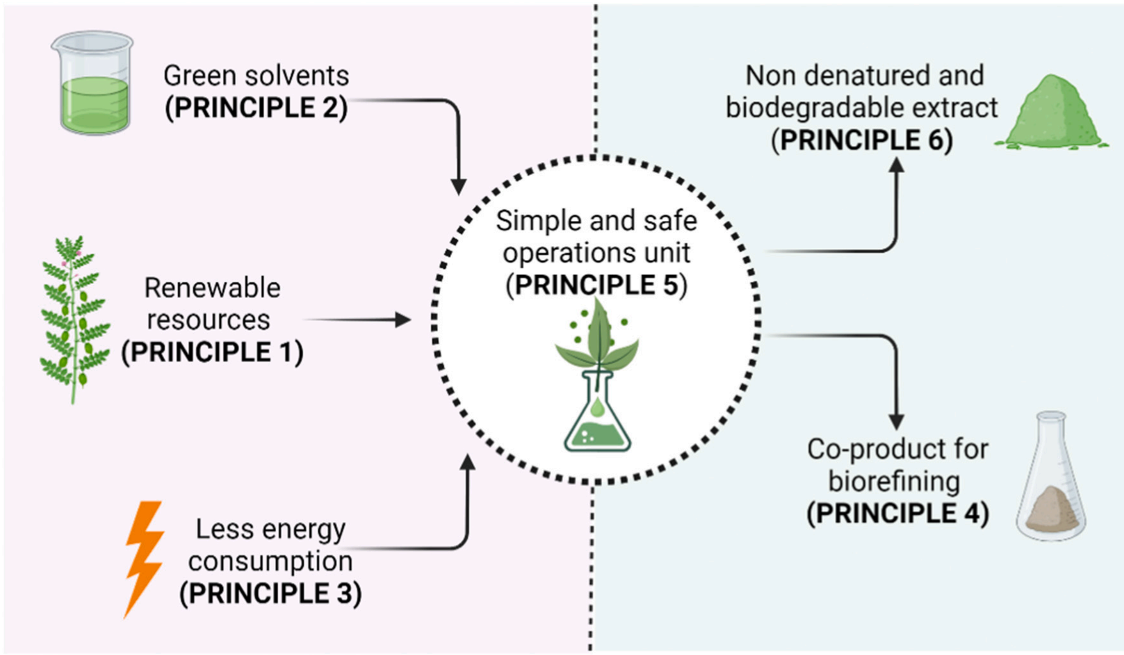

Fig. 5. Six principles of green extraction based on essential inputs and outputs.

and safety, further research is needed. Collaborations among academia, industry and regulatory bodies are crucial because the demand for sustainable and intelligent packaging solutions is growing.

One specific area of research might involve advancing extraction techniques and investigating the synergistic integration of various green methods to improve efficiency and selectivity. Optimal process conditions are essential to the development of stable, environmentally friendly and cost-effective materials that do not alter the physical, biochemical and sensory properties of food. These developments should align with the principles of circular bioeconomy and sustainable production, and residues generated during extraction may find novel applications as biofertilisers, additives or energy sources. Innovative formulations and delivery systems can enhance the stability, bioavailability and targeted delivery of bioactive compounds. Another important aspect of the future is in-depth compound characterisation, going beyond identification and quantification to explore the biological activities and mechanisms of action of the extracted compounds. Overcoming challenges and capitalising on opportunities in this field will contribute to the realisation of smart packaging solutions that are environmentally friendly and economically viable.

CRediT authorship contribution statement

Samira Sheibani: Writing – original draft. **Shima Jafarzadeh:** Writing – review & editing, Writing – original draft. **Zeinab Qazanfarzadeh:** Writing – original draft. **M.M. Jeevani Osadee Wijekoon:** Writing – review & editing. **Norazatul Hanim Mohd Rozalli:** Writing – review & editing. **Abdorreza Mohammadi Nafchi:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no potential conflicts of interest with respect to the research, authorship and publication of this article.

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References

[1] H. Saygin, A. Baysal, Similarities and discrepancies between bio-based and conventional submicron-sized plastics: in relation to clinically important bacteria, Bull. Environ. Contam. Toxicol. 105 (2020) 26–35.
[2] S. Jafarzadeh, M. Zargar, M. Forough, Renewable and recyclable polymeric materials for food packaging: a new open special issue in materials, Materials 15 (2022) 5845.
[3] S. Jafarzadeh, M. Golgoli, M. Azizi-Lalabadi, J. Farahbakhsh, M. Forough, N. Rabiee, M. Zargar, Enhanced carbohydrate-based plastic performance by incorporating cerium-based metal-organic framework for food packaging application, Int. J. Biol. Macromol. 265 (2024) 130899.
[4] S. Jafarzadeh, M. Zargar, M. Forough, Renewable and recyclable polymeric materials for food packaging: a new open special issue in materials, Materials 15 (2022) 5845.
[5] S. Jafarzadeh, A. Salehabadi, S.M. Jafari, Handbook of Food Nanotechnology: Applications and Approaches, 2020, p. 379.
[6] W. Zhang, M. Azizi-Lalabadi, S. Jafarzadeh, S.M. Jafari, Starch-gelatin blend films: a promising approach for high-performance degradable food packaging, Carbohydr. Polym. 320 (2023) 121266.
[7] S. Jafarzadeh, J. Rhim, A. Abd Karim, F. Ariffin, S. Mahmud, Application of antimicrobial active packaging film made of semolina flour, nano zinc oxide and nano-kaolin to maintain the quality of low-moisture mozzarella cheese during low-temperature storage, J. Sci. Food Agric. 99 (2018) 2716–2725.
[8] J. Alves, P.D. Gaspar, T.M. Lima, P.D. Silva, What is the role of active packaging in the future of food sustainability? A systematic review, J Sci Food Agric 103 (2023) 1004–1020.
[9] S. Jafarzadeh, Z. Yildiz, P. Yildiz, P. Strachowski, M. Forough, Y. Esmaeili, M. Naebe, M. Abdollahi, Advanced Technologies in Biodegradable Packaging Using Intelligent Sensing to Fight Food Waste, 2024.
[10] P.P. Sarma, K. Barman, P.K. Baruah, Industrial barriers for the application of active and intelligent packaging, in: Green Sustainable Process for Chemical and Environmental Engineering and Science, Elsevier, 2023, pp. 71–96.
[11] S. Jafarzadeh, M. Forough, V.J. Kouzegaran, M. Zargar, F. Garavand, M. Azizi-Lalabadi, M. Abdollahi, S.M. Jafari, Improving the functionality of biodegradable food packaging materials via porous nanomaterials, Compr. Rev. Food Sci. Food Saf. 22 (2023) 2850–2886.
[12] S.Y. Lee, S.J. Lee, D.S. Choi, S.J. Hur, Current topics in active and intelligent food packaging for preservation of fresh foods, J. Sci. Food Agric. 95 (2015) 2799–2810.
[13] R. Syarifa, Y. Esmaeili, S. Jafarzadeh, F. Garavand, S. Mahmud, F. Ariffin, An investigation of the morphological, thermal, mechanical, and barrier properties of an active packaging containing micro-and nano-sized ZnO particles, Food Sci. Nutr. 11 (2023) 7373–7382.
[14] T. Mohammadi-Moghaddam, M. Kariminejad, S. Hadad, S. Jafarzadeh, D. Shahrampour, Physical properties, antioxidant activity, and antimicrobial properties of edible film prepared from black plum peel extract as a valuable by-product of plum processing, J Food Chem Nanotechnol 9 (2023) 156–162.

[15] S. Jafarzadeh, Z. Yildiz, P. Yildiz, P. Strachowski, M. Forough, Y. Esmaeili, M. Naebe, M. Abdollahi, Advanced macromolecular technologies in biodegradable packaging using intelligent sensing to fight food waste; a review, Int. J. Biol. Macromol. 261 (2024) 129647.
[16] S. Jafarzadeh, M. Forough, S. Amjadi, V. Javan Kouzegaran, H. Almasi, F. Garavand, M. Zargar, Plant protein-based nanocomposite films: a review on the used nanomaterials, characteristics, and food packaging applications, Crit. Rev. Food Sci. Nutr. (2022) 1–27.
[17] S. Ghasemi, E. Assadpour, M.S. Kharazmi, S. Jafarzadeh, M. Zargar, S.M. Jafari, Encapsulation of orange peel oil in biopolymeric nanocomposites to control its release under different conditions, Foods 12 (2023) 831.
[18] A. Altemimi, N. Lakhssassi, A. Baharlouei, D.G. Watson, D.A. Lightfoot, Phytochemicals: extraction, isolation, and identification of bioactive compounds from plant extracts, Plants 6 (2017) 42.
[19] L. Masoodi, A. Gull, F.A. Masoodi, A. Gani, J. Nissar, T. Ahad, G.A. Nayik, S. A. Mukarram, B. Kovács, J. Prokisch, An overview on traditional vs. green technology of extraction methods for producing high quality walnut oil, Agronomy 12 (2022) 2258.
[20] M. Calderón-Oliver, E. Ponce-Alquicira, Environmentally friendly techniques and their comparison in the extraction of natural antioxidants from green tea, rosemary, clove, and oregano, Molecules 26 (2021) 1869.
[21] F. Chemat, M.A. Vian, G. Cravotto, Green extraction of natural products: concept and principles, Int. J. Mol. Sci. 13 (2012) 8615–8627.
[22] A.M. Awad, P. Kumar, M.R. Ismail-Fitry, S. Jusoh, M.F. Ab Aziz, A.Q. Sazili, Green extraction of bioactive compounds from plant biomass and their application in meat as natural antioxidant, Antioxidants 10 (2021) 1465.
[23] A. Saini, P.S. Panesar, M.B. Bera, Valorization of fruits and vegetables waste through green extraction of bioactive compounds and their nanoemulsions-based delivery system, Bioresour. Bioprocess. 6 (2019) 1–12.
[24] S. Jafarzadeh, M. Nooshkam, M. Zargar, F. Garavand, S. Ghosh, M. Hadidi, M. Forough, Green synthesis of nanomaterials for smart biopolymer packaging: challenges and outlooks, J. Nanostructure Chem. (2023) 1–24.
[25] S. Jafarzadeh, S.M. Jafari, A. Salehabadi, A.M. Nafchi, U.S. Uthaya, H.P.S. A. Khalil, Biodegradable green packaging with antimicrobial functions based on the bioactive compounds from tropical plants and their by-products, Trends Food Sci. Technol. 100 (2020) 262–277.
[26] M.B. Soquetta, L. de M. Terra, C.P. Bastos, Green technologies for the extraction of bioactive compounds in fruits and vegetables, CyTA-Journal of Food 16 (2018) 400–412.
[27] F. Garavand, D. Khodaei, N. Mahmud, J. Islam, I. Khan, S. Jafarzadeh, R. Tahergorabi, I. Cacciotti, Recent progress in using zein nanoparticles-loaded nanocomposites for food packaging applications, Crit. Rev. Food Sci. Nutr. (2022) 1–21.
[28] A. Ayaseh, K. Alirezalu, M. Yaghoubi, Z. Razmjouei, S. Jafarzadeh, K. Marszałek, A.M. Khaneghah, Production of nitrite-free frankfurter-type sausages by combining ε-polylysine with beetroot extracts: an assessment of microbial, physicochemical, and sensory properties, Food Biosci. 49 (2022) 101936.
[29] J.G. de Oliveira Filho, M.R.V. Bertolo, S.S. Fernandes, A.C. Lemes, G. da Cruz Silva, S.B. Junior, H.M.C. de Azeredo, L.H.C. Mattoso, M.B. Egea, Intelligent and active biodegradable biopolymeric films containing carotenoids, Food Chem 434 (2023) 137454.
[30] J. Sun, X. Leng, J. Zang, G. Zhao, Bio-based antibacterial food packaging films and coatings containing cinnamaldehyde: a review, Crit. Rev. Food Sci. Nutr. (2022) 1–13.
[31] S.S. Rosales-Murillo, J. Sánchez-Bodón, S.L. Hernández Olmos, M.F. Ibarra-Vázquez, L.G. Guerrero-Ramírez, L. Pérez-Álvarez, J.L. Vilas-Vilela, Anthocyanin-loaded polymers as promising nature-based, responsive, and bioactive materials, Polymers (Basel) 16 (2024) 163.
[32] A. Rojas, D. Misic, C.L. de Dicastillo, I. Zizovic, E. Velásquez, D. Gutiérrez, G. Aguila, C.P. Vidal, A. Guarda, M.J. Galotto, A review on thymol-based bioactive materials for food packaging, Ind. Crop. Prod. 202 (2023) 116977.
[33] A. Gonzalez-Diaz, J.A. García-Núñez, Hydrophilic deep eutectic solvents: a new generation of green and safe extraction systems for bioactive compounds obtaining from natural oil & fats–a review, Sustain. Chem. Pharm. 36 (2023) 101278.
[34] J. Yu, X. Liu, S. Xu, P. Shao, J. Li, Z. Chen, X. Wang, Y. Lin, C.M.G.C. Renard, Advances in green solvents for production of polysaccharide-based packaging films: insights of ionic liquids and deep eutectic solvents, Compr. Rev. Food Sci. Food Saf. 22 (2023) 1030–1057.
[35] A. Perez-Vazquez, M. Carpena, P. Barciela, L. Cassani, J. Simal-Gandara, M. A. Prieto, Pressurized liquid extraction for the recovery of bioactive compounds from seaweeds for food industry application: a review, Antioxidants 12 (2023) 612.
[36] S. Jafarzadeh, K. Abdolmaleki, F. Javanmardi, M. Hadidi, A. Mousavi Khaneghah, Recent advances in plant-based compounds for mitigation of mycotoxin contamination in food products: current status, challenges and perspectives, Int. J. Food Sci. Technol. 57 (2022) 2159–2170.
[37] K.C. Marquardt, R.R. Watson, Polyphenols and public health, in: Polyphenols in Human Health and Disease, Elsevier, 2014, pp. 9–15.
[38] F. Visioli, C.A.D. La Lastra, C. Andres-Lacueva, M. Aviram, C. Calhau, A. Cassano, M. D`Archivio, A. Faria, G. Favé, V. Fogliano, Polyphenols and human health: a prospectus, Crit. Rev. Food Sci. Nutr. 51 (2011) 524–546.
[39] W. Zhang, X. Li, W. Jiang, Development of antioxidant chitosan film with banana peels extract and its application as coating in maintaining the storage quality of apple, Int. J. Biol. Macromol. 154 (2020) 1205–1214.
[40] Y. Biao, C. Yuxuan, T. Qi, Y. Ziqi, Z. Yourong, D.J. McClements, C. Chongjiang, Enhanced performance and functionality of active edible films by incorporating tea polyphenols into thin calcium alginate hydrogels, Food Hydrocoll. 97 (2019) 105197.
[41] C. Chen, J. Xie, F. Yang, H. Zhang, Z. Xu, J. Liu, Y. Chen, Development of moisture-absorbing and antioxidant active packaging film based on poly (vinyl alcohol) incorporated with green tea extract and its effect on the quality of dried eel, J. Food Process. Preserv. 42 (2018) e13374.
[42] F. Zhu, Polysaccharide based films and coatings for food packaging: effect of added polyphenols, Food Chem. 359 (2021) 129871.
[43] Y. Lei, H. Wu, C. Jiao, Y. Jiang, R. Liu, D. Xiao, J. Lu, Z. Zhang, G. Shen, S. Li, Investigation of the structural and physical properties, antioxidant and antimicrobial activity of pectin-konjac glucomannan composite edible films incorporated with tea polyphenol, Food Hydrocoll. 94 (2019) 128–135.
[44] L. Wu, L. Li, S. Chen, L. Wang, X. Lin, Deep eutectic solvent-based ultrasonic-assisted extraction of phenolic compounds from *Moringa oleifera* L. leaves: optimization, comparison and antioxidant activity, Sep. Purif. Technol. 247 (2020) 117014.
[45] M. Ruesgas-Ramón, M.C. Figueroa-Espinoza, E. Durand, Application of deep eutectic solvents (DES) for phenolic compounds extraction: overview, challenges, and opportunities, J. Agric. Food Chem. 65 (2017) 3591–3601.
[46] J. Azmir, I.S.M. Zaidul, M.M. Rahman, K.M. Sharif, A. Mohamed, F. Sahena, M.H. A. Jahurul, K. Ghafoor, N.A.N. Norulaini, A.K.M. Omar, Techniques for extraction of bioactive compounds from plant materials: a review, J. Food Eng. 117 (2013) 426–436.
[47] T.F.P. Alves, N. Teixeira, J. Vieira, A.A. Vicente, N. Mateus, V. de Freitas, H.K. S. Souza, Sustainable chitosan packaging films: green tea polyphenolic extraction strategies using deep eutectic solvents, J. Clean. Prod. 372 (2022) 133589.
[48] E. Doria, E. Boncompagni, A. Marra, M. Dossena, M. Verri, D. Buonocore, Polyphenols extraction from vegetable wastes using a green and sustainable method, Front Sustain Food Syst 5 (2021) 690399.
[49] A. Scarano, M. Chieppa, A. Santino, Looking at flavonoid biodiversity in horticultural crops: a colored mine with nutritional benefits, Plants 7 (2018) 98.
[50] S.M. Nabavi, D. Šamec, M. Tomczyk, L. Milella, D. Russo, S. Habtemariam, I. Suntar, L. Rastrelli, M. Daglia, J. Xiao, Flavonoid biosynthetic pathways in plants: versatile targets for metabolic engineering, Biotechnol. Adv. 38 (2020) 107316.
[51] C. Braicu, M.R. Ladomery, V.S. Chedea, A. Irimie, I. Berindan-Neagoe, The relationship between the structure and biological actions of green tea catechins, Food Chem. 141 (2013) 3282–3289.
[52] E. Cataldo, A. Eichmeier, G.B. Mattii, Effects of global warming on grapevine berries phenolic compounds—a review, Agronomy 13 (2023) 2192.
[53] C. Chen, Y. Zhang, W. Tang, H. Chen, R. Gong, Insights into the coloring mechanism of dark-red and yellow fruits in sweet cherry through transcriptome and metabolome analysis, Agronomy 13 (2023) 2397.
[54] A. Millán-Laleona, F.J. Bielsa, E. Aranda-Cañada, C. Gómez-Rincón, P. Errea, V. López, Antioxidant, antidiabetic, and anti-obesity properties of apple pulp extracts (Malus domestica Bork): a comparative study of 15 local and commercial cultivars from Spain, Biology (Basel) 12 (2023) 891.
[55] M. Abotaleb, S.M. Samuel, E. Varghese, S. Varghese, P. Kubatka, A. Liskova, D. Büsselberg, Flavonoids in cancer and apoptosis, Cancers (Basel) 11 (2018) 28.
[56] A. Durazzo, M. Lucarini, E.B. Souto, C. Cicala, E. Caiazzo, A.A. Izzo, E. Novellino, A. Santini, Polyphenols: a concise overview on the chemistry, occurrence, and human health, Phytother. Res. 33 (2019) 2221–2243.
[57] M. Chen, T. Zhang, D. Sun, S. Wu, K. Wang, L. He, X. Wang, Y. Chen, Study on extraction technology of flavonoids from natural green cotton fiber, The Journal of The Textile Institute 111 (2020) 869–873.
[58] J.H. Xie, X.H. Hu, Z.M. Li, J. Pang, Z.F. Zheng, Ultrasonic-assisted technology for extracting flavonoids from the asparagus skin and their anti-oxidation, Journal of Southwest China Normal University 37 (2012) 92–98.
[59] Q. Zhang, X. Fan, T. Li, Z. Zhang, Y. Liu, X. Li, Optimisation of ultrasound extraction for flavonoids from semen astragali complanati and its identification by HPLC-DAD-MS/MS, Int. J. Food Sci. Technol. 48 (2013) 1970–1976.
[60] J. Zhou, X. Zheng, Q. Yang, Z. Liang, D. Li, X. Yang, J. Xu, Optimization of ultrasonic-assisted extraction and radical-scavenging capacity of phenols and flavonoids from Clerodendrum cyrtophyllum Turcz leaves, PLoS One 8 (2013) e68392.
[61] H.-Y. Fang, Y.-Q. Wei, M.-L. Zhang, W. Liu, A novel green extraction technique for extracting flavonoids from Folium nelumbinis by changing osmosis pressure, Materials 13 (2020) 4192.
[62] J.-J. Xu, R. Yang, L.-H. Ye, J. Cao, W. Cao, S.-S. Hu, L.-Q. Peng, Application of ionic liquids for elution of bioactive flavonoid glycosides from lime fruit by miniaturized matrix solid-phase dispersion, Food Chem. 204 (2016) 167–175.
[63] T. Maoka, Carotenoids as natural functional pigments, J. Nat. Med. 74 (2020) 1–16.
[64] A.Z. Mercadante, Structures, nomenclature and general chemistry of carotenoids and their esters, in: Carotenoid Esters in Foods: Physical, Chemical and Biological Properties, Royal Society of Chemistry, 2019.
[65] A.J. Meléndez-Martínez, An overview of carotenoids, apocarotenoids, and vitamin A in agro-food, nutrition, health, and disease, Mol. Nutr. Food Res. 63 (2019) 1801045.
[66] N. Bhargava, V.S. Sharanagat, R.S. Mor, K. Kumar, Active and intelligent biodegradable packaging films using food and food waste-derived bioactive compounds: a review, Trends Food Sci. Technol. 105 (2020) 385–401.

[67] H. Cheng, H. Xu, D.J. McClements, L. Chen, A. Jiao, Y. Tian, M. Miao, Z. Jin, Recent advances in intelligent food packaging materials: principles, preparation and applications, Food Chem. 375 (2022) 131738.
[68] P. Shao, L. Liu, J. Yu, Y. Lin, H. Gao, H. Chen, P. Sun, An overview of intelligent freshness indicator packaging for food quality and safety monitoring, Trends Food Sci. Technol. 118 (2021) 285–296.
[69] A.M. Goula, M. Ververi, A. Adamopoulou, K. Kaderides, Green ultrasound-assisted extraction of carotenoids from pomegranate wastes using vegetable oils, Ultrason. Sonochem. 34 (2017) 821–830.
[70] H.R.P. da Silva, I.J. Iwassa, J. Marques, N. Postaue, N. Stevanato, C. da Silva, Enrichment of sunflower oil with β-carotene from carrots: maximization and thermodynamic parameters of the β-carotene extraction and oil characterization, J. Food Process. Preserv. 44 (2020) e14399.
[71] M.A.V. Condori, G.J.P. Chagman, M. Barriga-Sanchez, L.F.V. Vilchez, S. Ursetta, A.G. Pérez, A. Hidalgo, Effect of tomato (Solanum lycopersicum L.) lycopene-rich extract on the kinetics of rancidity and shelf-life of linseed (Linum usitatissimum L.) oil, Food Chem. 302 (2020) 125327.
[72] B. Baria, N. Upadhyay, A.K. Singh, R.K. Malhotra, Optimization of 'green' extraction of carotenoids from mango pulp using split plot design and its characterization, LWT 104 (2019) 186–194.
[73] E. Kultys, M.A. Kurek, Green extraction of carotenoids from fruit and vegetable byproducts: a review, Molecules 27 (2022) 518.
[74] J.H. Zhang, W.J. Liu, H.M. Luo, Research progress in the activity of terpenoids in medicinal plants, World Sci, Technol.–Modernization Trad. Chinese Med 20 (2018) 419–430.
[75] X. Zhang, C. Wang, L. Wang, S. Chen, Y. Xu, Optimization and validation of a head space solid-phase microextraction-arrow gas chromatography-mass spectrometry method using central composite design for determination of aroma compounds in Chinese liquor (Baijiu), J. Chromatogr. A 1610 (2020) 460584.
[76] F.J. Álvarez-Martínez, E. Barrajón-Catalán, M. Herranz-López, V. Micol, Antibacterial plant compounds, extracts and essential oils: an updated review on their effects and putative mechanisms of action, Phytomedicine 90 (2021) 153626.
[77] L. Chen, Y. Pang, Y. Luo, X. Cheng, B. Lv, C. Li, Separation and purification of plant terpenoids from biotransformation, Eng. Life Sci. 21 (2021) 724–738.
[78] Z. Jiang, C. Kempinski, J. Chappell, Extraction and analysis of terpenes/terpenoids, Curr Protoc, Plant Biol. 1 (2016) 345–358.
[79] A. Masyita, R.M. Sari, A.D. Astuti, B. Yasir, N.R. Rumata, T. Bin Emran, F. Nainu, J. Simal-Gandara, Terpenes and terpenoids as main bioactive compounds of essential oils, their roles in human health and potential application as natural food preservatives, Food Chem X 13 (2022) 100217.
[80] S. Sangkasanya, P. Naknaen, N. Petchwattana, Feasibility application of biodegradable active films produced by poly (lactic acid) incorporating with limonene as an antimicrobial packaging for fresh beef meat, in: Proceedings of the 2018 8th International Conference on Bioscience, Biochemistry and Bioinformatics, 2018: pp. 60–64.
[81] J.P. Michael, Indolizidine and quinolizidine alkaloids, Nat. Prod. Rep. 24 (2007) 191–222.
[82] L. Qian, Z. Xu, W. Zhang, B. Wilson, J.-S. Hong, P.M. Flood, Sinomenine, a natural dextrorotatory morphinan analog, is anti-inflammatory and neuroprotective through inhibition of microglial NADPH oxidase, J. Neuroinflammation 4 (2007) 1–14.
[83] O.P.S. Patel, A. Mishra, R. Maurya, D. Saini, J. Pandey, I. Taneja, K.S.R. Raju, S. Kanojiya, S.K. Shukla, M.N. Srivastava, Naturally occurring carbazole alkaloids from Murraya koenigii as potential antidiabetic agents, J. Nat. Prod. 79 (2016) 1276–1284.
[84] H.-F. Zhang, L.-J. Shi, G.-Y. Song, Z.-G. Cai, C. Wang, R.-J. An, Protective effects of matrine against progression of high-fructose diet-induced steatohepatitis by enhancing antioxidant and anti-inflammatory defences involving Nrf2 translocation, Food Chem. Toxicol. 55 (2013) 70–77.
[85] G. Ribaudo, E. Zanforlin, M. Canton, S. Bova, G. Zagotto, Preliminary studies of berberine and its semi-synthetic derivatives as a promising class of multi-target anti-parkinson agents, Nat. Prod. Res. 32 (2018) 1395–1401.
[86] L. Duan, W.-H. Zhang, Z.-H. Zhang, E.-H. Liu, L. Guo, Evaluation of natural deep eutectic solvents for the extraction of bioactive flavone C-glycosides from Flos Trollii, Microchem. J. 145 (2019) 180–186.
[87] Y. Jiang, R. Liu, M. Liu, L. Yi, S. Liu, An integrated strategy to rapidly characterize non-targeted benzylisoquinoline alkaloids from Plumula nelumbinis ethanol extract using UHPLC/Q-orbitrap HRMS, Int. J. Mass Spectrom. 432 (2018) 26–35.
[88] N. Bao, D. Wang, X. Fu, H. Xie, G. Gao, Z. Luo, Green extraction of phenolic compounds from lotus seedpod (receptaculum nelumbinis) assisted by ultrasound coupled with glycerol, Foods 10 (2021) 239.
[89] J. Torres-Vega, S. Gómez-Alonso, J. Pérez-Navarro, E. Pastene-Navarrete, Green extraction of alkaloids and polyphenols from Peumus boldus leaves with natural deep eutectic solvents and profiling by HPLC-PDA-IT-MS/MS and HPLC-QTOF-MS/MS, Plants 9 (2020) 242.
[90] N.T. Le, N.H.T. Chau, P.Q.D. Nguyen, L.T.T. Tran, H.T. Phung, H.T. Nguyen, Green extraction of berberine from Coscinium fenestratum (Gaertn.) Colebr. using ultrasound-assisted aqueous solutions of organic acids, polyalcohols, and deep eutectic solvents, Sep. Purif. Technol. 330 (2024) 125541.
[91] L. Day, J.A. Cakebread, S.M. Loveday, Food proteins from animals and plants: differences in the nutritional and functional properties, Trends Food Sci. Technol. 119 (2022) 428–442.
[92] J. Li, S. Hu, W. Jian, C. Xie, X. Yang, Plant antimicrobial peptides: structures, functions, and applications, Bot. Stud. 62 (2021) 1–15.
[93] C. Chatterjee, S. Gleddie, C.-W. Xiao, Soybean bioactive peptides and their functional properties, Nutrients 10 (2018) 1211.
[94] S. Guha, H. Sharma, G.K. Deshwal, P.S. Rao, A comprehensive review on bioactive peptides derived from milk and milk products of minor dairy species, Food Prod. Process. Nutr. 3 (2021) 1–21.
[95] G. Franca-Oliveira, T. Fornari, B. Hernández-Ledesma, A review on the extraction and processing of natural source-derived proteins through eco-innovative approaches, Processes 9 (2021) 1626.
[96] U. Urbizo-Reyes, M.F. San Martin-González, J. Garcia-Bravo, A.L.M. Vigil, A. M. Liceaga, Physicochemical characteristics of chia seed (Salvia hispanica) protein hydrolysates produced using ultrasonication followed by microwave-assisted hydrolysis, Food Hydrocoll. 97 (2019) 105187.
[97] J. Liu, S. Willför, C. Xu, A review of bioactive plant polysaccharides: biological activities, functionalization, and biomedical applications, Bioact. Carbohydr. Diet. Fibre 5 (2015) 31–61.
[98] S.-K. Kim, Y.-X. Li, Medicinal benefits of sulfated polysaccharides from sea vegetables, Adv. Food Nutr. Res. 64 (2011) 391–402.
[99] K. Mohan, A.R. Ganesan, P.N. Ezhilarasi, K.K. Kondamareddy, D.K. Rajan, P. Sathishkumar, J. Rajarajeswaran, L. Conterno, Green and eco-friendly approaches for the extraction of chitin and chitosan: a review, Carbohydr. Polym. 287 (2022) 119349.
[100] S. Rakshit, S. Mondal, K. Pal, A. Jana, J.P. Soren, P. Barman, K.C. Mondal, S. K. Halder, Extraction of chitin from Litopenaeus vannamei shell and its subsequent characterization: an approach of waste valorization through microbial bioprocessing, Bioprocess Biosyst. Eng. 44 (2021) 1943–1956.
[101] G. Hao, Y. Hu, L. Shi, J. Chen, A. Cui, W. Weng, K. Osako, Physicochemical characteristics of chitosan from swimming crab (Portunus trituberculatus) shells prepared by subcritical water pretreatment, Sci. Rep. 11 (2021) 1646.
[102] Y. Wang, Y. Yang, R. Wang, Y. Zhu, P. Yang, Z. Lin, Z. Wang, W. Cong, Efficient extraction of chitin from crustacean waste via a novel ternary natural deep eutectic solvents, Carbohydr. Polym. 286 (2022) 119281.
[103] Y. Lu, M. Jiang, Y. Pan, F. Wang, W. Xu, Y. Zhou, X. Du, Preparation of Ag@ lignin nanotubes for the development of antimicrobial biodegradable films from corn straw, Int. J. Biol. Macromol. 254 (2024) 127630.
[104] X. Kang, C. Deng, R. Shinde, R. Lin, J.D. Murphy, Renewable deep eutectic solvents pretreatment improved the efficiency of anaerobic digestion by lignin extraction from willow, Energy Convers. Manag. 288 (2023) 117115.
[105] P. Li, G. Xu, S.-P. Li, Y.-T. Wang, T.-P. Fan, Q.-S. Zhao, Q.-W. Zhang, Optimizing ultraperformance liquid chromatographic analysis of 10 diterpenoid compounds in Salvia miltiorrhiza using central composite design, J. Agric. Food Chem. 56 (2008) 1164–1171.
[106] G. Du, H. Zhao, Y. Song, Q. Zhang, Y. Wang, Rapid simultaneous determination of isoflavones in Radix puerariae using high-performance liquid chromatography–triple quadrupole mass spectrometry with novel shell-type column, J. Sep. Sci. 34 (2011) 2576–2585.
[107] Q.-W. Zhang, L.-G. Lin, W.-C. Ye, Techniques for extraction and isolation of natural products: a comprehensive review, Chin. Med. 13 (2018) 1–26.
[108] E. Yara-Varon, A.-S. Fabiano-Tixier, M. Balcells, R. Canela-Garayoa, A. Bily, F. Chemat, Is it possible to substitute hexane with green solvents for extraction of carotenoids? A theoretical versus experimental solubility study, RSC Adv 6 (2016) 27750–27759.
[109] G. Vinci, L. Maddaloni, S.A. Prencipe, E. Orlandini, M. Sambucci, Simple and reliable eco-extraction of bioactive compounds from dark chocolate by Deep Eutectic Solvents. A sustainable study, Int. J. Food Sci. Technol. 58 (2023) 4051–4065.
[110] S.F. Garofalo, F. Demichelis, G. Mancini, T. Tommasi, D. Fino, Conventional and ultrasound-assisted extraction of rice bran oil with isopropanol as solvent, Sustain. Chem. Pharm. 29 (2022) 100741.
[111] K.-Y. Khaw, M.-O. Parat, P.N. Shaw, J.R. Falconer, Solvent supercritical fluid technologies to extract bioactive compounds from natural sources: a review, Molecules 22 (2017) 1186.
[112] E. Ghasemi, F. Raofie, N.M. Najafi, Application of response surface methodology and central composite design for the optimisation of supercritical fluid extraction of essential oils from Myrtus communis L. leaves, Food Chem. 126 (2011) 1449–1453.
[113] O. Wrona, K. Rafińska, C. Możeński, B. Buszewski, Supercritical fluid extraction of bioactive compounds from plant materials, J. AOAC Int. 100 (2017) 1624–1635.
[114] K. Tyśkiewicz, M. Konkol, E. Rój, The application of supercritical fluid extraction in phenolic compounds isolation from natural plant materials, Molecules 23 (2018) 2625.
[115] M. Herrero, A. Cifuentes, E. Ibañez, Sub-and supercritical fluid extraction of functional ingredients from different natural sources: plants, food-by-products, algae and microalgae: a review, Food Chem. 98 (2006) 136–148.
[116] M. Khajeh, Y. Yamini, N. Bahramifar, F. Sefidkon, M.R. Pirmoradei, Comparison of essential oils compositions of Ferula assa-foetida obtained by supercritical carbon dioxide extraction and hydrodistillation methods, Food Chem. 91 (2005) 639–644.
[117] H.M.A. Barbosa, M.M.R. de Melo, M.A. Coimbra, C.P. Passos, C.M. Silva, Optimization of the supercritical fluid coextraction of oil and diterpenes from spent coffee grounds using experimental design and response surface methodology, J. Supercrit. Fluids 85 (2014) 165–172.
[118] J.J. Schuster, L.A. Bahr, L. Fehr, M. Tippelt, J. Schulmeyr, A. Wuzik, A.S. Braeuer, Online monitoring of the supercritical CO2 extraction of hop, J. Supercrit. Fluids 133 (2018) 139–145.
[119] J.R. Williams, A.A. Clifford, Supercritical fluid methods and protocols, in: Methods in Biotechnology, Springer, 2000.

[120] R.P.F.F. Da Silva, T.A.P. Rocha-Santos, A.C. Duarte, Supercritical fluid extraction of bioactive compounds, TrAC Trends Anal. Chem. 76 (2016) 40–51.
[121] E. Reverchon, I. De Marco, Supercritical fluid extraction and fractionation of natural matter, J. Supercrit. Fluids 38 (2006) 146–166.
[122] C.G. Pereira, M.A.A. Meireles, Supercritical fluid extraction of bioactive compounds: fundamentals, applications and economic perspectives, Food Bioprocess Technol. 3 (2010) 340–372.
[123] M.V. Alvarez, S. Cabred, C.L. Ramirez, M.A. Fanovich, Valorization of an agroindustrial soybean residue by supercritical fluid extraction of phytochemical compounds, J. Supercrit. Fluids 143 (2019) 90–96.
[124] A. del Pilar Sanchez-Camargo, L.-F. Gutierrez, S.M. Vargas, H.A. Martinez-Correa, F. Parada-Alfonso, C.-E. Narvaez-Cuenca, Valorisation of mango peel: proximate composition, supercritical fluid extraction of carotenoids, and application as an antioxidant additive for an edible oil, J. Supercrit. Fluids 152 (2019) 104574.
[125] L. Valadez-Carmona, A. Ortiz-Moreno, G. Ceballos-Reyes, J.A. Mendiola, E. Ibáñez, Valorization of cacao pod husk through supercritical fluid extraction of phenolic compounds, J. Supercrit. Fluids 131 (2018) 99–105.
[126] M. de Andrade Lima, I. Kestekoglou, D. Charalampopoulos, A. Chatzifragkou, Supercritical fluid extraction of carotenoids from vegetable waste matrices, Molecules 24 (2019) 466.
[127] E.D.N.S. Abeyrathne, K.-C. Nam, X. Huang, D.U. Ahn, Egg yolk lipids: separation, characterization, and utilization, Food Sci. Biotechnol. 31 (2022) 1243–1256.
[128] A. Aditya, N.P. Kim, 3D printing of meat following supercritical fluid extraction, Foods 11 (2022) 554.
[129] S. Machmudah, K. Kitada, M. Sasaki, M. Goto, J. Munemasa, M. Yamagata, Simultaneous extraction and separation process for coffee beans with supercritical CO2 and water, Ind. Eng. Chem. Res. 50 (2011) 2227–2235.
[130] D.V. Bermejo, E. Ibáñez, G. Reglero, T. Fornari, Effect of cosolvents (ethyl lactate, ethyl acetate and ethanol) on the supercritical CO2 extraction of caffeine from green tea, J. Supercrit. Fluids 107 (2016) 507–512.
[131] M. de Andrade Lima, D. Charalampopoulos, A. Chatzifragkou, Optimisation and modelling of supercritical CO2 extraction process of carotenoids from carrot peels, J. Supercrit. Fluids 133 (2018) 94–102.
[132] R. Vardanega, G.C. Nogueira, C.D.O. Nascimento, A.F. Faria-Machado, M.A. A. Meireles, Selective extraction of bioactive compounds from annatto seeds by sequential supercritical CO2 process, J. Supercrit. Fluids 150 (2019) 122–127.
[133] L.C. Soto-Armenta, J.C. Sacramento-Rivero, C.A. Ruiz-Mercado, M.C. Lope-Navarrete, J.A. Rocha-Uribe, Extraction yield and kinetic study of Lippia graveolens with supercritical CO2, J. Supercrit. Fluids 145 (2019) 205–210.
[134] H.I.O. Basegmez, D. Povilaitis, V. Kitrytė, V. Kraujalienė, V. Šulniūtė, C. Alasalvar, P.R. Venskutonis, Biorefining of blackcurrant pomace into high value functional ingredients using supercritical CO2, pressurized liquid and enzyme assisted extractions, J. Supercrit. Fluids 124 (2017) 10–19.
[135] M. Durante, M.S. Lenucci, G. Mita, Supercritical carbon dioxide extraction of carotenoids from pumpkin (Cucurbita spp.): a review, Int. J. Mol. Sci. 15 (2014) 6725–6740.
[136] L.A. Conde-Hernández, J.R. Espinosa-Victoria, J.Á. Guerrero-Beltrán, Supercritical extraction of essential oils of Piper auritum and Porophyllum ruderale, J. Supercrit. Fluids 127 (2017) 97–102.
[137] L.A. Conde-Hernández, J.R. Espinosa-Victoria, A. Trejo, J.Á. Guerrero-Beltrán, CO2-supercritical extraction, hydrodistillation and steam distillation of essential oil of rosemary (Rosmarinus officinalis), J. Food Eng. 200 (2017) 81–86.
[138] L.T. Danh, P. Truong, R. Mammucari, N. Foster, Extraction of vetiver essential oil by ethanol-modified supercritical carbon dioxide, Chem. Eng. J. 165 (2010) 26–34.
[139] M. Shahsavarpour, M. Lashkarbolooki, M.J. Eftekhari, F. Esmaeilzadeh, Extraction of essential oils from Mentha spicata L.(Labiatae) via optimized supercritical carbon dioxide process, J. Supercrit. Fluids 130 (2017) 253–260.
[140] T. Lefebvre, E. Destandau, E. Lesellier, Selective extraction of bioactive compounds from plants using recent extraction techniques: a review, J. Chromatogr. A 1635 (2021) 461770.
[141] L. Ruiz-Aceituno, M.J. García-Sarrió, B. Alonso-Rodriguez, L. Ramos, M.L. Sanz, Extraction of bioactive carbohydrates from artichoke (Cynara scolymus L.) external bracts using microwave assisted extraction and pressurized liquid extraction, Food Chem. 196 (2016) 1156–1162.
[142] M.M. Moreira, M.F. Barroso, A. Boeykens, H. Withouck, S. Morais, C. Delerue-Matos, Valorization of apple tree wood residues by polyphenols extraction: comparison between conventional and microwave-assisted extraction, Ind. Crop. Prod. 104 (2017) 210–220.
[143] H. López-Salazar, B.H. Camacho-Díaz, M.L.A. Ocampo, A.R. Jiménez-Aparicio, Microwave-assisted extraction of functional compounds from plants: a review, Bioresources 18 (2023) 6614.
[144] T. Belwal, A. Pandey, I.D. Bhatt, R.S. Rawal, Optimized microwave assisted extraction (MAE) of alkaloids and polyphenols from Berberis roots using multiple-component analysis, Sci. Rep. 10 (2020) 917.
[145] G.R. Lopes, C.P. Passos, C. Rodrigues, J.A. Teixeira, M.A. Coimbra, Impact of microwave-assisted extraction on roasted coffee carbohydrates, caffeine, chlorogenic acids and coloured compounds, Food Res. Int. 129 (2020) 108864.
[146] P.C. Veggi, J. Martinez, M.A.A. Meireles, Fundamentals of microwave extraction, in: Microwave-Assisted Extraction for Bioactive Compounds: Theory and Practice, Springer, 2012, pp. 15–52.
[147] I. Akhtar, S. Javad, Z. Yousaf, S. Iqbal, K. Jabeen, Microwave assisted extraction of phytochemicals an efficient and modern approach for botanicals and pharmaceuticals, Pak. J. Pharm. Sci. 32 (2019).
[148] A.H. Nour, A.R. Oluwaseun, A.H. Nour, M.S. Omer, N. Ahmed, Microwave-assisted extraction of bioactive compounds, in: Microwave Heating. Electromagnetic Fields Causing Thermal and Non-thermal Effects, 2021: pp. 1–31.
[149] I. Lavilla, C. Bendicho, Fundamentals of ultrasound-assisted extraction, in: Water Extraction of Bioactive Compounds, Elsevier, 2017: pp. 291–316.
[150] K. Kumar, S. Srivastav, V.S. Sharanagat, Ultrasound assisted extraction (UAE) of bioactive compounds from fruit and vegetable processing by-products: a review, Ultrason. Sonochem. 70 (2021) 105325.
[151] Y. Ez Zoubi, M. Fadil, D. Bousta, A. El Ouali Lalami, M. Lachkar, A. Farah, Ultrasound-assisted extraction of phenolic compounds from Moroccan Lavandula stoechas L.: optimization using response surface methodology, J Chem 2021 (2021) 1–11.
[152] E. Roselló-Soto, C.M. Galanakis, M. Brnčić, V. Orlien, F.J. Trujillo, R. Mawson, K. Knoerzer, B.K. Tiwari, F.J. Barba, Clean recovery of antioxidant compounds from plant foods, by-products and algae assisted by ultrasounds processing, Modeling approaches to optimize processing conditions, Trends Food Sci Technol 42 (2015) 134–149.
[153] Q. Cui, L. Wang, G. Wang, A. Zhang, X. Wang, L. Jiang, Ultrasonication effects on physicochemical and emulsifying properties of Cyperus esculentus seed (tiger nut) proteins, Lwt 142 (2021) 110979.
[154] A. Rahaman, X.-A. Zeng, A. Kumari, M. Rafiq, A. Siddeeg, M.F. Manzoor, Z. Baloch, Z. Ahmed, Influence of ultrasound-assisted osmotic dehydration on texture, bioactive compounds and metabolites analysis of plum, Ultrason. Sonochem. 58 (2019) 104643.
[155] M. Hadidi, A. Ibarz, J. Pagan, Optimisation and kinetic study of the ultrasonic-assisted extraction of total saponins from alfalfa (Medicago sativa) and its bioaccessibility using the response surface methodology, Food Chem. 309 (2020) 125786.
[156] M. Saifullah, R. McCullum, A. McCluskey, Q. Vuong, Comparison of conventional extraction technique with ultrasound assisted extraction on recovery of phenolic compounds from lemon scented tea tree (Leptospermum petersonii) leaves, Heliyon 6 (2020).
[157] C. Chen, L. Wang, R. Wang, X. Luo, Y. Li, J. Li, Y. Li, Z. Chen, Ultrasound-assisted extraction from defatted oat (Avena sativa L.) bran to simultaneously enhance phenolic compounds and β-glucan contents: compositional and kinetic studies, J. Food Eng. 222 (2018) 1–10.
[158] M. Irakli, P. Chatzopoulou, L. Ekateriniadou, Optimization of ultrasound-assisted extraction of phenolic compounds: Oleuropein, phenolic acids, phenolic alcohols and flavonoids from olive leaves and evaluation of its antioxidant activities, Ind. Crop. Prod. 124 (2018) 382–388.
[159] Y. Zhu, X. Du, J. Zheng, T. Wang, X. You, H. Liu, X. Liu, The effect of ultrasonic on reducing anti-browning minimum effective concentration of purslane extract on fresh-cut potato slices during storage, Food Chem. 343 (2021) 128401.
[160] J. Wang, B. Xie, Z. Sun, Quality parameters and bioactive compound bioaccessibility changes in probiotics fermented mango juice using ultraviolet-assisted ultrasonic pre-treatment during cold storage, Lwt 137 (2021) 110438.
[161] K. Lukić, M. Brnčić, N. Ćurko, M. Tomašević, D. Valinger, G.I. Denoya, F.J. Barba, K.K. Ganić, Effects of high power ultrasound treatments on the phenolic, chromatic and aroma composition of young and aged red wine, Ultrason. Sonochem. 59 (2019) 104725.
[162] M. Bouafia, N. Colak, F.A. Ayaz, A. Benarfa, M. Harrat, N. Gourine, M. Yousfi, The optimization of ultrasonic-assisted extraction of Centaurea sp. antioxidative phenolic compounds using response surface methodology, J Appl Res Med Aromat Plants 25 (2021) 100330.
[163] T. Martínez-Ramos, J. Benedito-Fort, N.J. Watson, I.I. Ruiz-López, G. Che-Galicia, E. Corona-Jiménez, Effect of solvent composition and its interaction with ultrasonic energy on the ultrasound-assisted extraction of phenolic compounds from Mango peels (Mangifera indica L.), Food Bioprod. Process. 122 (2020) 41–54.
[164] D.M. Kopustinskiene, V. Jakstas, A. Savickas, J. Bernatoniene, Flavonoids as anticancer agents, Nutrients 12 (2020) 457.
[165] X. Lin, L. Wu, X. Wang, L. Yao, L. Wang, Ultrasonic-assisted extraction for flavonoid compounds content and antioxidant activities of India Moringa oleifera L. leaves: simultaneous optimization, HPLC characterization and comparison with other methods, J Appl Res Med Aromat Plants 20 (2021) 100284.
[166] X. Mai, Y. Liu, X. Tang, L. Wang, Y. Lin, H. Zeng, L. Luo, H. Fan, P. Li, Sequential extraction and enrichment of flavonoids from Euonymus alatus by ultrasonic-assisted polyethylene glycol-based extraction coupled to temperature-induced cloud point extraction, Ultrason. Sonochem. 66 (2020) 105073.
[167] A. Carreira-Casais, P. Otero, P. Garcia-Perez, P. Garcia-Oliveira, A.G. Pereira, M. Carpena, A. Soria-Lopez, J. Simal-Gandara, M.A. Prieto, Benefits and drawbacks of ultrasound-assisted extraction for the recovery of bioactive compounds from marine algae, Int. J. Environ. Res. Public Health 18 (2021) 9153.
[168] B. Byanju, M.M. Rahman, M.P. Hojilla-Evangelista, B.P. Lamsal, Effect of high-power sonication pretreatment on extraction and some physicochemical properties of proteins from chickpea, kidney bean, and soybean, Int. J. Biol. Macromol. 145 (2020) 712–721.
[169] A. Ochoa-Rivas, Y. Nava-Valdez, S.O. Serna-Saldívar, C. Chuck-Hernández, Microwave and ultrasound to enhance protein extraction from peanut flour under alkaline conditions: effects in yield and functional properties of protein isolates, Food Bioprocess Technol. 10 (2017) 543–555.
[170] X. Li, J. Shi, M. Scanlon, S.J. Xue, J. Lu, Effects of pretreatments on physicochemical and structural properties of proteins isolated from canola seeds after oil extraction by supercritical-CO2 process, Lwt 137 (2021) 110415.

[171] S.J. Marathe, S.B. Jadhav, S.B. Bankar, R.S. Singhal, Enzyme-assisted extraction of bioactives, in: Food Bioactives: Extraction and Biotechnology Applications, Springer, 2017, pp. 171–201.
[172] T. Wang, X. Lü, Overcome saccharification barrier: advances in hydrolysis technology, in: Advances in 2nd Generation of Bioethanol Production, Elsevier, 2021, pp. 137–159.
[173] E. Hernández Becerra, E. De Jesús Pérez López, J.W. Zartha Sossa, Recovery of biomolecules from agroindustry by solid-liquid enzyme-assisted extraction: a review, Food Anal, Methods 14 (2021) 1744–1777.
[174] J.M.F. Rodriguez, M.L. Corazza, R.L. Kruger, N.M. Khalil, D. de Campos, V.R. da Silva, Pressurized liquid extraction as a strategy to recover bioactive compounds from yerba mate (Ilex paraguariensis St.-Hil.) processing waste, J. Supercrit. Fluids 203 (2023) 106088.
[175] N.E. Nagybákay, L. Sarapinaitė, M. Syrpas, P.R. Venskutonis, V. Kitrytė-Syrpa, Optimization of pressurized ethanol extraction for efficient recovery of hyperoside and other valuable polar antioxidant-rich extracts from Betula pendula Roth leaves, Ind. Crop. Prod. 205 (2023) 117565.
[176] B. Keramane, A. del Pilar Sánchez-Camargo, L. Montero, F. Laincer, F. Bedjou, E. Ibañez, Pressurized liquid extraction of bioactive extracts with antioxidant and antibacterial activity from green, red and brown Algerian algae, Algal Res. 76 (2023) 103293.
[177] J.M. Costa, T. Forster-Carneiro, Valorization of apple pomace by-products from the juice processing industry using pressurized liquid technology, J. Environ. Chem. Eng. 11 (2023) 110907.
[178] G. Wypych, Databook of Green Solvents, Elsevier, 2019.
[179] B. Schuur, T. Brouwer, D. Smink, L.M.J. Sprakel, Green solvents for sustainable separation processes, Curr Opin Green Sustain Chem 18 (2019) 57–65.
[180] F.P. Byrne, S. Jin, G. Paggiola, T.H.M. Petchey, J.H. Clark, T.J. Farmer, A.J. Hunt, C. Robert McElroy, J. Sherwood, Tools and techniques for solvent selection: green solvent selection guides, Sustainable Chemical Processes 4 (2016) 1–24.
[181] D. Luong, M.A. Sephton, J.S. Watson, Subcritical water extraction of organic matter from sedimentary rocks, Anal. Chim. Acta 879 (2015) 48–57.
[182] Y.H. Choi, R. Verpoorte, Green solvents for the extraction of bioactive compounds from natural products using ionic liquids and deep eutectic solvents, Curr. Opin. Food Sci. 26 (2019) 87–93.
[183] J.K.U. Ling, K. Hadinoto, Deep eutectic solvent as green solvent in extraction of biological macromolecules: a review, Int. J. Mol. Sci. 23 (2022) 3381.
[184] N. Flórez, E. Conde, H. Domínguez, Microwave assisted water extraction of plant compounds, J. Chem. Technol. Biotechnol. 90 (2015) 590–607.
[185] M. Meshksar, F. Afshariani, M.R. Rahimpour, Industrial applications of green solvents for sustainable development of technologies in organic synthesis, in: A. Inamuddin (Ed.), Applications of Nanotechnology for Green Synthesis, Springer, 2020, pp. 435–455.
[186] C.F. Poole, Chromatographic and spectroscopic methods for the determination of solvent properties of room temperature ionic liquids, J. Chromatogr. A 1037 (2004) 49–82.
[187] X. Ding, Q. Liu, X. Hou, T. Fang, Supercritical fluid extraction of metal chelate: a review, Crit. Rev. Anal. Chem. 47 (2017) 99–118.
[188] M. de los Ángeles Fernández, J. Boiteux, M. Espino, F.J.V Gomez, M.F. Silva, Natural deep eutectic solvents-mediated extractions: the way forward for sustainable analytical developments, Anal. Chim. Acta 1038 (2018) 1–10.
[189] C. Paliwal, M. Rehmanji, K.M. Shaikh, S.U. Zafar, P.P. Jutur, Green extraction processing of lutein from Chlorella saccharophila in water-based ionic liquids as a sustainable innovation in algal biorefineries, Algal Res. 66 (2022) 102809.
[190] M.C. Bubalo, K. Radošević, I.R. Redovniković, J. Halambek, V.G. Srček, A brief overview of the potential environmental hazards of ionic liquids, Ecotoxicol. Environ. Saf. 99 (2014) 1–12.
[191] A. Prabhune, R. Dey, Green and sustainable solvents of the future: deep eutectic solvents, J. Mol. Liq. 379 (2023) 121676.
[192] M.L. Segatto, L. Schnarr, O. Olsson, K. Kümmerer, V.G. Zuin, Ionic liquids vs. ethanol as extraction media of algicidal compounds from mango processing waste, Front. Chem. 10 (2022) 986987.
[193] A.P. Abbott, G. Capper, D.L. Davies, R.K. Rasheed, V. Tambyrajah, Novel solvent properties of choline chloride/urea mixtures, Chem. Commun. (2003) 70–71.
[194] Y.H. Choi, J. van Spronsen, Y. Dai, M. Verberne, F. Hollmann, I.W.C.E. Arends, G.-J. Witkamp, R. Verpoorte, Are natural deep eutectic solvents the missing link in understanding cellular metabolism and physiology? Plant Physiol. 156 (2011) 1701–1705.
[195] Y. Liu, J.B. Friesen, J.B. McAlpine, D.C. Lankin, S.-N. Chen, G.F. Pauli, Natural deep eutectic solvents: properties, applications, and perspectives, J. Nat. Prod. 81 (2018) 679–690.
[196] M.A.R. Martins, S.P. Pinho, J.A.P. Coutinho, Insights into the nature of eutectic and deep eutectic mixtures, J. Solut. Chem. 48 (2019) 962–982.
[197] C.B.T. Pal, G.C. Jadeja, Deep eutectic solvent-based extraction of polyphenolic antioxidants from onion (Allium cepa L.) peel, J. Sci. Food Agric. 99 (2019) 1969–1979.
[198] A. del Pilar Sánchez-Camargo, M. Bueno, F. Parada-Alfonso, A. Cifuentes, E. Ibáñez, Hansen solubility parameters for selection of green extraction solvents, TrAC Trends Anal. Chem. 118 (2019) 227–237.
[199] W. Wang, Y. Pan, J. Zhao, Y. Wang, Q. Yao, S. Li, Development and optimization of green extraction of polyphenols in Michelia alba using natural deep eutectic solvents (NADES) and evaluation of bioactivity, Sustain. Chem. Pharm. 37 (2024) 101425.
[200] F. de Sousa Bezerra, G.S.M. Ramos, M.G. de Oliveira Carvalho, M.G.B. Koblitz, Natural deep eutectic solvents characteristics determine their extracting and protective power on chlorogenic acids from sunflower meal, Sustain. Chem. Pharm. 37 (2024) 101430.
[201] J. Vovers, K.H. Smith, G.W. Stevens, Bio-based molecular solvents, in: The Application of Green Solvents in Separation Processes, Elsevier, 2017, pp. 91–110.
[202] A. Alves Costa Pacheco, J. Sherwood, A. Zhenova, C.R. McElroy, A.J. Hunt, H. L. Parker, T.J. Farmer, A. Constantinou, M. De Bruyn, A.C. Whitwood, Intelligent approach to solvent substitution: the identification of a new class of levoglucosenone derivatives, ChemSusChem 9 (2016) 3503–3512.
[203] S.S. Silva, M. Justi, J.-B. Chagnoleau, N. Papaiconomou, X. Fernandez, S.A. O. Santos, H. Passos, A.M. Ferreira, J.A.P. Coutinho, Using biobased solvents for the extraction of phenolic compounds from kiwifruit industry waste, Sep. Purif. Technol. 304 (2023) 122344.
[204] V. Vieira, R.C. Calhelha, L. Barros, J.A.P. Coutinho, I.C.F.R. Ferreira, O. Ferreira, Insights on the extraction performance of alkanediols and glycerol: using Juglans regia L. leaves as a source of bioactive compounds, Molecules 25 (2020) 2497.
[205] R. Cañadas, I. Díaz, M. Rodríguez, E.J. González, M. González-Miquel, An integrated approach for sustainable valorization of winery wastewater using bio-based solvents for recovery of natural antioxidants, J. Clean. Prod. 334 (2022) 130181.
[206] P.M. Kuś, I. Jerković, K. Aladić, S. Jokić, Supercritical CO2 and ultrasound extraction and characterization of lipids and polyphenols from Phacelia tanacetifolia Benth. pollen, Ind Crops, Prod 206 (2023) 117646.
[207] H. Koraqi, A.Y. Aydar, W. Khalid, S. Ercisli, S. Rustagi, S. Ramniwas, R. Pandiselvam, Ultrasound-assisted extraction with natural deep eutectic solvent for phenolic compounds recovery from Rosa damascene Mill.: experimental design optimization using central composite design, Microchem. J. 196 (2024) 109585.
[208] E. Bouloumpasi, A. Skendi, S. Christaki, C.C. Biliaderis, M. Irakli, Optimizing conditions for the recovery of lignans from sesame cake using three green extraction methods: microwave-, ultrasound-and accelerated-assisted solvent extraction, Ind. Crop. Prod. 207 (2024) 117770.
[209] B.A. Teixeira, M.C.T.R. Vidigal, P.C. Stringheta, Optimization of ultrasound-assisted extraction of anthocyanins from purple tomatoes, Ciência Rural 54 (2023) e20220604.
[210] R.C. Lima, A.P.A. de Carvalho, B.D. da Silva, L.T. Neto, M.R. da S. de Figueiredo, P.H.T. Chaves, A.E.C.C. de Almeida, C.A. Conte-Junior, Green ultrasound-assisted extraction of bioactive compounds of babassu (Attalea speciosa) mesocarp: effects of solid-liquid ratio extraction, antioxidant capacity, and antimicrobial activity, Applied, Food Res. 3 (2023) 100331.
[211] J. Wang, L. Zhou, Z. Wang, Y. Tao, L. Chen, W. Zhang, Effects of natural deep eutectic solvent on the extraction efficiency and antioxidant activities of Toona sinensis seed polyphenols: composition and mechanism, Food Biosci. 56 (2023) 103151.
[212] R. Biswas, A. Sarkar, M. Alam, M. Roy, M.M.M. Hasan, Microwave and ultrasound-assisted extraction of bioactive compounds from papaya: a sustainable green process, Ultrason, Sonochem 101 (2023) 106677.
[213] R. Tian, M. Zhang, Y. Zhu, K. Wu, Y. Liu, B. Wang, H. Lu, B. Liang, Two-step separation of lignin from poplar wood powder using malic acid/choline chloride deep eutectic solvents, New J. Chem. 47 (2023) 19608–19616.
[214] M. Flórez, E. Guerra-Rodríguez, P. Cazón, M. Vázquez, Chitosan for food packaging: recent advances in active and intelligent films, Food Hydrocoll. 124 (2022) 107328.
[215] A. Brandelli, L.F.W. Brum, J.H.Z. dos Santos, Nanostructured bioactive compounds for ecological food packaging, Environ. Chem. Lett. 15 (2017) 193–204.
[216] M. Sharma, Z. Usmani, V.K. Gupta, R. Bhat, Valorization of fruits and vegetable wastes and by-products to produce natural pigments, Crit. Rev. Biotechnol. 41 (2021) 535–563.
[217] A. Ali, S. Ahmed, Eco-friendly natural extract loaded antioxidative chitosan/ polyvinyl alcohol based active films for food packaging, Heliyon 7 (2021).
[219] M.R. Chia, S.-W. Phang, I. Ahmad, Influence of polyaniline and cellulose nanocrystals on starch biopolymer film for intelligent food packaging, Food Biosci. 56 (2023) 103212.
[220] S. Jafarzadeh, A.K. Alias, F. Ariffin, S. Mahmud, A. Najafi, M. Ahmad, Fabrication and characterization of novel semolina-based antimicrobial films derived from the combination of ZnO nanorods and nanokaolin, J. Food Sci. Technol. 54 (2017) 105–113.
[221] B. Kuswandi, Y. Wicaksono, A. Jayus, L.Y. Abdullah, M. Ahmad Heng, Smart packaging: sensors for monitoring of food quality and safety, Sens. & Instrumen. Food Qual. 5 (2011) 137–146.
[222] R.K. Dhall, Advances in edible coatings for fresh fruits and vegetables: a review, Crit. Rev. Food Sci. Nutr. 53 (2013) 435–450.
[223] S. Jafarzadeh, F. Ariffin, S. Mahmud, A.K. Alias, A. Najafi, M. Ahmad, Characterization of semolina biopolymer films enriched with zinc oxide nano rods, Italian Journal of Food Science 29 (2017).
[224] R.Q. Assis, P.D. Rios, A. de Oliveira Rios, F.C. Olivera, Biodegradable packaging of cellulose acetate incorporated with norbixin, lycopene or zeaxanthin, Ind Crops, Prod 147 (2020) 112212.
[225] N. Hromiš, V. Lazić, S. Popović, D. Šuput, S. Bulut, S. Kravić, R. Romanić, The possible application of edible pumpkin oil cake film as pouches for flaxseed oil protection, Food Chem. 371 (2022) 131197.
[226] J. Gómez-Estaca, M.M. Calvo, A. Sánchez-Faure, P. Montero, M.C. Gómez-Guillén, Development, properties, and stability of antioxidant shrimp muscle protein films incorporating carotenoid-containing extracts from food by-products, LWT-Food, Sci. Technol. 64 (2015) 189–196.

[227] H.M.C. Azeredo, D.S. Correa, Smart choices: mechanisms of intelligent food packaging, Curr Res Food Sci 4 (2021) 932–936.
[228] B.E. Teixeira-Costa, W.H. Ferreira, F.M. Goycoolea, B.S. Murray, C.T. Andrade, Improved antioxidant and mechanical properties of food packaging films based on chitosan/deep eutectic solvent, containing açaí-filled microcapsules, Molecules 28 (2023) 1507.
[229] R.Q. Assis, C.H. Pagno, T.M.H. Costa, S.H. Flôres, A. de O. Rios, Synthesis of biodegradable films based on cassava starch containing free and nanoencapsulated β-carotene, Packag. Technol. Sci. 31 (2018) 157–166.
[230] A. Esfahani, A. Mohammadi Nafchi, H. Baghaei, L. Nouri, Fabrication and characterization of a smart film based on cassava starch and pomegranate peel powder for monitoring lamb meat freshness, Food Sci. Nutr. 10 (2022) 3293–3301.
[231] S. Jafarzadeh, A. Salehabadi, S.M. Jafari, 10 Metal Nanoparticles as Antimicrobial Agents in Food Packaging, 2020.
[232] Z. Moslehi, A. Mohammadi Nafchi, M. Moslehi, S. Jafarzadeh, Aflatoxin, microbial contamination, sensory attributes, and morphological analysis of pistachio nut coated with methylcellulose, Food Sci Nutr 9 (2021) 2576–2584.
[233] T. Bhattacharya, S. Ahmed, Nanotechnology in Intelligent Food Packaging, John Wiley & Sons, 2022.
[234] K.F. Kasim, Development and characterization of antimicrobial film from Clinacanthus nutans and polyvinyl alcohol (PVA) mixture for food packaging, Malaysian Journal of Microscopy 16 (2020).
[235] M.A. Andrade, C.H. Barbosa, M.A. Cerqueira, A.G. Azevedo, C. Barros, A. V. Machado, A. Coelho, R. Furtado, C.B. Correia, M. Saraiva, PLA films loaded with green tea and rosemary polyphenolic extracts as an active packaging for almond and beef, Food Packag. Shelf Life 36 (2023) 101041.
[236] A. Bagher Abiri, H. Baghaei, A. Mohammadi Nafchi, Preparation and application of active bionanocomposite films based on sago starch reinforced with a combination of TiO2 nanoparticles and penganum harmala extract for preserving chicken fillets, Polymers (Basel) 15 (2023) 2889.
[237] U. Siripatrawan, B.R. Harte, Physical properties and antioxidant activity of an active film from chitosan incorporated with green tea extract, Food Hydrocoll. 24 (2010) 770–775.
[238] C.C. Bastante, N.H.C.S. Silva, L.C. Cardoso, C.M. Serrano, E.J.M. de la Ossa, C.S. R. Freire, C. Vilela, Biobased films of nanocellulose and mango leaf extract for active food packaging: supercritical impregnation versus solvent casting, Food Hydrocoll. 117 (2021) 106709.
[239] M.-R. Chia, I. Ahmad, S.-W. Phang, Starch/polyaniline biopolymer film as potential intelligent food packaging with colourimetric ammonia sensor, Polymers (Basel) 14 (2022) 1122.
[240] F. Garavand, M. Rouhi, S. Jafarzadeh, D. Khodaei, I. Cacciotti, M. Zargar, S. H. Razavi, Tuning the physicochemical, structural, and antimicrobial attributes of whey-based Poly (L-Lactic Acid) (PLLA) films by chitosan nanoparticles, Front. Nutr. 9 (2022) 880520.
[241] P. Müller, M. Schmid, Intelligent packaging in the food sector: a brief overview, Foods 8 (2019) 16.
[242] A. Brandelli, L.F.W. Brum, J.H.Z. dos Santos, Nanobiotechnology methods to incorporate bioactive compounds in food packaging, in: E.L.S. Ranjan, N. Dasgupta (Eds.), Nanoscience in Food and Agriculture 2, Springer, 2016, pp. 27–58.
[243] N.A. Azlim, A. Mohammadi Nafchi, N. Oladzadabbasabadi, F. Ariffin, P. Ghalambor, S. Jafarzadeh, A.A. Al-Hassan, Fabrication and characterization of a pH-sensitive intelligent film incorporating dragon fruit skin extract, Food Sci. Nutr. 10 (2022) 597–608.
[244] S. Chen, M. Wu, P. Lu, L. Gao, S. Yan, S. Wang, Development of pH indicator and antimicrobial cellulose nanofibre packaging film based on purple sweet potato anthocyanin and oregano essential oil, Int. J. Biol. Macromol. 149 (2020) 271–280.
[245] L.X. Mei, A.M. Nafchi, F. Ghasemipour, A.M. Easa, S. Jafarzadeh, A.A. Al-Hassan, Characterization of pH sensitive sago starch films enriched with anthocyanin-rich torch ginger extract, Int. J. Biol. Macromol. 164 (2020) 4603–4612.
[246] Z. Guo, X. Wu, X. Zhao, J. Fan, X. Lu, L. Wang, An edible antioxidant film of Artemisia sphaerocephala Krasch. gum with sophora japonica extract for oil packaging, Food Packag Shelf, Life 24 (2020) 100460.
[247] M. Fajri, E. Julianti, J. Silalahi, Porang glucomannan based edible film with the addition of mangosteen peel extract, in: IOP Conf Ser Earth Environ Sci, IOP Publishing, 2021: p. 32103.
[248] X. Wang, H. Yong, L. Gao, L. Li, M. Jin, J. Liu, Preparation and characterization of antioxidant and pH-sensitive films based on chitosan and black soybean seed coat extract, Food Hydrocoll. 89 (2019) 56–66.
[249] V.D.M. Silva, M.C.C. Macedo, C.G. Rodrigues, A.N. dos Santos, A.C. de F e Loyola, C.A. Fante, Biodegradable edible films of ripe banana peel and starch enriched with extract of Eriobotrya japonica leaves, Food Biosci. 38 (2020) 100750.
[250] L.I. Lim, H.L. Tan, L.P. Pui, Development and characterization of alginate-based edible film incorporated with hawthorn berry (Crataegus pinnatifida) extract, J. Food Meas. Charact. 15 (2021) 2540–2548.
[251] S. Jancikova, E. Jamróz, P. Kulawik, J. Tkaczewska, D. Dordevic, Furcellaran/gelatin hydrolysate/rosemary extract composite films as active and intelligent packaging materials, Int. J. Biol. Macromol. 131 (2019) 19–28.
[252] F. Wang, C. Xie, H. Tang, H. Li, J. Hou, R. Zhang, Y. Liu, L. Jiang, Intelligent packaging based on chitosan/fucoidan incorporated with coleus grass (Plectranthus scutellarioides) leaves anthocyanins and its application in monitoring the spoilage of salmon (Salmo salar L.), Int. J. Biol. Macromol. 252 (2023) 126423.
[253] S. Naghdi, M. Rezaei, M. Abdollahi, A starch-based pH-sensing and ammonia detector film containing betacyanin of paperflower for application in intelligent packaging of fish, Int. J. Biol. Macromol. 191 (2021) 161–170.
[254] H.-L. Huang, I.-L. Tsai, C. Lin, Y.-H. Hang, Y.-C. Ho, M.-L. Tsai, F.-L. Mi, Intelligent films of marine polysaccharides and purple cauliflower extract for food packaging and spoilage monitoring, Carbohydr. Polym. 299 (2023) 120133.
[255] H. Hosseini, E.Y. Hamgini, S.M. Jafari, S. Bolourian, Improving the oxidative stability of sunflower seed kernels by edible biopolymeric coatings loaded with rosemary extract, J. Stored Prod. Res. 89 (2020) 101729.
[256] A. Farhan, N.M. Hani, Active edible films based on semi-refined κ-carrageenan: antioxidant and color properties and application in chicken breast packaging, Food Packag. Shelf Life 24 (2020) 100476.
[257] O.L. Vidal, A. Tsukui, R. Garrett, M.H.M. Rocha-Leão, C.W.P. Carvalho, S. P. Freitas, C.M. de Rezende, M.S.L. Ferreira, Production of bioactive films of carboxymethyl cellulose enriched with green coffee oil and its residues, Int. J. Biol. Macromol. 146 (2020) 730–738.
[258] N.M. Malherbi, A.C. Schmitz, R.C. Grando, A.P. Bilck, F. Yamashita, L. Tormen, F. M. Fakhouri, J.I. Velasco, L.C. Bertan, Corn starch and gelatin-based films added with guabiroba pulp for application in food packaging, Food Packag Shelf, Life 19 (2019) 140–146.
[259] I. Albertos, A.B. Martin-Diana, M. Burón, D. Rico, Development of functional bio-based seaweed (Himanthalia elongata and Palmaria palmata) edible films for extending the shelflife of fresh fish burgers, Food Packag. Shelf Life 22 (2019) 100382.
[260] L. Sun, J. Sun, L. Chen, P. Niu, X. Yang, Y. Guo, Preparation and characterization of chitosan film incorporated with thinned young apple polyphenols as an active packaging material, Carbohydr. Polym. 163 (2017) 81–91.
[261] R. Balti, M. Ben Mansour, N. Sayari, L. Yacoubi, L. Rabaoui, N. Brodu, A. Massé, Development and characterization of bioactive edible films from spider crab (Maja crispata) chitosan incorporated with Spirulina extract, Int. J. Biol. Macromol. 105 (2017) 1464–1472.
[262] S. Karača, A. Bušić, V. Đorđević, A. Belščak-Cvitanović, A.V. Cebin, B. Bugarski, D. Komes, The functional potential of immortelle (Helichrysum italicum) based edible films reinforced with proteins and hydrogel particles, LWT 99 (2019) 387–395.
[263] S.A. Mir, B.N. Dar, A.A. Wani, M.A. Shah, Effect of plant extracts on the techno-functional properties of biodegradable packaging films, Trends Food Sci. Technol. 80 (2018) 141–154.
[264] F. Yi, F. Hou, S. Zhan, L. Song, R. Zhang, X. Han, X. Sun, Z. Liu, Preparation, characterization and application of pH-responsive smart film based on chitosan/zein and red radish anthocyanin, Int. J. Biol. Macromol. 253 (2023) 127037.
[265] P. Mustafa, M.B.K. Niazi, Z. Jahan, S. Rafiq, T. Ahmad, U. Sikander, F. Javaid, Improving functional properties of PVA/starch-based films as active and intelligent food packaging by incorporating propolis and anthocyanin, Polym. Polym. Compos. 29 (2021) 1472–1484.
[266] Q. Zhang, W. Zhai, L. Cui, Y. Liu, W. Xie, Q. Yu, H. Luo, Physicochemical properties and antibacterial activity of polylactic acid/starch acetate films incorporated with chitosan and tea polyphenols, Polym. Bull. 80 (2023) 13319–13341.
[267] R. Thakur, V. Gupta, T. Ghosh, A.B. Das, Effect of anthocyanin-natural deep eutectic solvent (lactic acid/fructose) on mechanical, thermal, barrier, and pH-sensitive properties of polyvinyl alcohol based edible films, Food Packag. Shelf Life 33 (2022) 100914.
[268] Z.N. Correa-Pacheco, S. Bautista-Baños, M. de Lorena Ramos-García, M. del Carmen Martínez-González, J. Hernández-Romano, Physicochemical characterization and antimicrobial activity of edible propolis-chitosan nanoparticle films, Prog. Org. Coat. 137 (2019) 105326.
[269] B. Rukmanikrishnan, S.K. Rajasekharan, J. Lee, S. Ramalingam, J. Lee, K-carrageenan/lignin composite films: biofilm inhibition, antioxidant activity, cytocompatibility, UV and water barrier properties, Mater Today Commun 24 (2020) 101346.
[270] W.N. Lau, A.M. Nafchi, M. Zargar, N.H.M. Rozalli, A.M. Easa, Development and evaluation of Bauhinia Kockiana extract-incorporated sago starch intelligent film strips for real-time freshness monitoring of coconut milk, Int. J. Biol. Macromol. 260 (2024) 129589.
[271] X. Wu, X. Yan, J. Zhang, X. Wu, M. Luan, Q. Zhang, Preparation and characterization of pH-sensitive intelligent packaging films based on cassava starch/polyvinyl alcohol matrices containing Aronia melanocarpa anthocyanins, LWT 194 (2024) 115818.
[272] W.A. Wan Yahaya, N.A. Mohd Azman, P.M. Krishnnan, F. Adam, M.P. Almajano, Thermo-mechanical and antioxidant properties of eugenol-loaded carrageenan-cellulose nanofiber films for sustainable packaging applications, J. Appl. Polym. Sci. 141 (2024) e54943.
[273] O. Mileti, D. Mammolenti, N. Baldino, F.R. Lupi, D. Gabriele, Starch films loaded with tannin: the study of rheological and physical properties, Int. J. Biol. Macromol. 254 (2024) 127973.
[274] C. Pérez-Santaescolástica, P.E.S. Munekata, X. Feng, Y. Liu, P.C. Bastianello Campagnol, J.M. Lorenzo, Active edible coatings and films with Mediterranean herbs to improve food shelf-life, Crit. Rev. Food Sci. Nutr. 62 (2022) 2391–2403.
[275] Y. Estrada-Girón, E. Cabrera-Díaz, R.M. Esparza-Merino, A. Martín-del-Campo, A. J. Valencia-Botín, Innovative edible films and coatings based on red color pectin obtained from the byproducts of Hibiscus sabdariffa L. for strawberry preservation, J. Food Meas. Charact. 14 (2020) 3371–3380.
[276] S. Jafarzadeh, M. Hadidi, M. Forough, A.M. Nafchi, A. Mousavi Khaneghah, The control of fungi and mycotoxins by food active packaging: a review, Crit. Rev. Food Sci. Nutr. 63 (2023) 6393–6411.

[277] S. Volpe, M. Valentino, R. Muhammad, E. Torrieri, Application of releasing systems in active packaging for dairy products, in: Releasing Systems in Active Food Packaging: Preparation and Applications, Springer, 2022, pp. 353–372.
[278] M. Gavahian, Y.-H. Chu, J.M. Lorenzo, A. Mousavi Khaneghah, F.J. Barba, Essential oils as natural preservatives for bakery products: understanding the mechanisms of action, recent findings, and applications, Crit. Rev. Food Sci. Nutr. 60 (2020) 310–321.
[279] K.I.B. Moro, A.B.B. Bender, L.P. da Silva, N.G. Penna, Green extraction methods and microencapsulation technologies of phenolic compounds from grape pomace: a review, Food Bioprocess Technol. 14 (2021) 1407–1431.
[280] F. Chemat, M.A. Vian, A.-S. Fabiano-Tixier, M. Nutrizio, A.R. Jambrak, P.E. S. Munekata, J.M. Lorenzo, F.J. Barba, A. Binello, G. Cravotto, A review of sustainable and intensified techniques for extraction of food and natural products, Green Chem. 22 (2020) 2325–2353.
[281] S. Xiu, A. Shahbazi, Bio-oil production and upgrading research: a review, Renew. Sust. Energ. Rev. 16 (2012) 4406–4414.
[282] H. Ben Salah, N. Allouche, Plant-based chemicals extraction and isolation, in: Plant Based "Green Chemistry 2.0" Moving From Evolutionary to Revolutionary, 2019, pp. 89–117.
[283] F. Chemat, M. Abert-Vian, A.S. Fabiano-Tixier, J. Strube, L. Uhlenbrock, V. Gunjevic, G. Cravotto, Green extraction of natural products, Origins, current status, and future challenges, TrAC Trends in Analytical Chemistry 118 (2019) 248–263.