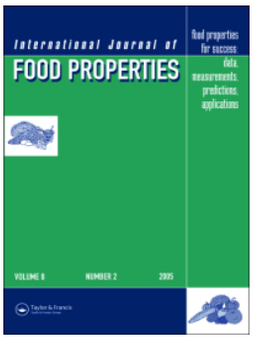

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Anthocyanin extraction methods: synthesis of morpho-anatomical knowledge for decision-making based on decision-tree

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ABSTRACT

Efficient anthocyanin extraction from emerging food matrices is essential in food technology and requires a precise, consistent, and clear extraction method. This study aimed to develop a decision-tree tool for selecting the optimal anthocyanin extraction technique. A comprehensive data synthesis covering the years 2018 to 2023 was conducted using leading academic databases, including Web of Science, Scopus, Medline, and SciELO. A combination of systematic and non-systematic approaches was employed to guide the decision-making process. The keywords used included "anthocyanin extraction methods," and studies with more than 10 citations were prioritized, along with recent and relevant publications. Thirty-six articles were analyzed according to the PRISMA 2020 guidelines for systematic reviews. While ultrasound and microwave-assisted methods were predominantly featured, accounting for 46% of the reviewed studies, other methods such as enzyme-assisted extraction, deep eutectic solvents, and ionic liquid extraction were also evaluated for their comparative efficiency and suitability across various matrices. Fruits were the primary matrix, with a focus on the pericarp. While fruits, particularly the pericarp, was the primary matrix studied, the decision-tree tool is designed to be applicable across various food matrices, demonstrating its versatility and generalizability beyond fruits. The decision-tree tool was successfully applied to matrices with different structures, showcasing its adaptability. Integration of this tool could streamline selection processes, resulting in significant time and resource savings. In conclusion, this study highlights the influence of plant morpho-anatomical structures and extraction parameters on anthocyanin yield. It demonstrates how the decision-tree approach enhances efficiency and productivity, validated through blackberry and purple sweet potato matrices.

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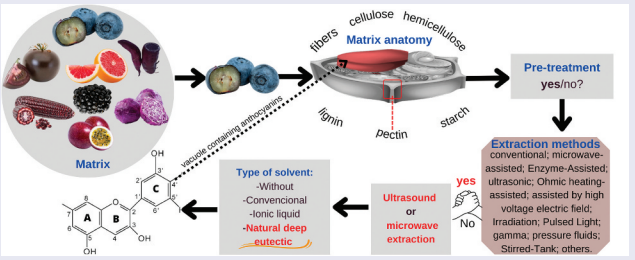

Matrix selection, accompanied by a breakdown of compositional details, processing and selection to optimize the method for high anthocyanin extraction yield.

Introduction

Anthocyanins are a type of flavonoid produced through metabolic pathways involving phenylpropanoids and the pentose phosphate pathway. [1] Moreover, the biosynthesis of anthocyanin pigments starts with dihydroflavonol reductase (DFR) and the co-factor NADPH, forming leucoanthocyanidins.[2] The second step is catalyzed by anthocyanin synthase (ANS), which produces anthocyanidins. Finally, modifications enhance stability and storability, resulting in glycosylated anthocyanins.[3] Anthocyanins are characterized by the absence of a carbonyl in the C ring and the presence of the oxonium ion (flavylium cation) (Figure 1). Among the pigments synthesized by plants, anthocyanins represent the largest group with polar characteristics. Anthocyanins can have various hues, such as blue, red, purple, and violet (Figure 1). Additionally, research across various fields, including food, cosmetics, pharmaceuticals, and other industrial applications, has been developed because of the potential of natural colorants and functional properties.[4] Therefore, anthocyanins are water-soluble pigments that provide color and biological functions.

Although there are more than 20 types of anthocyanidins, the glycosylated forms of pelargonidin, cyanidin, peonidin, delphinidin, and malvidin are among the most frequently cited (Figure 1). These

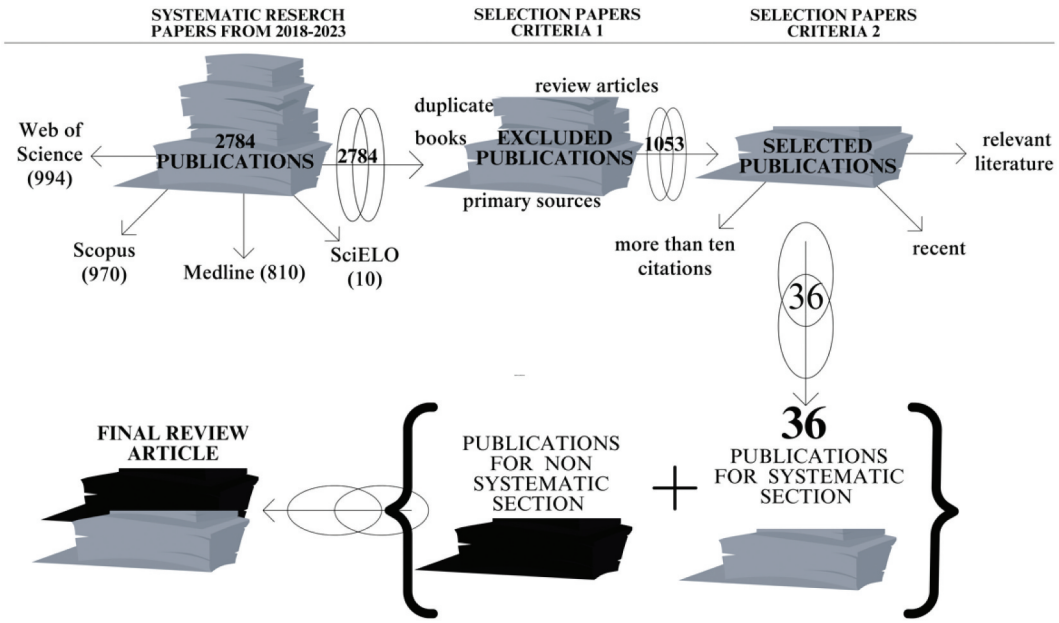

Figure 1. Review process in systematic and nonsystematic criteria for selecting the final work papers.

compounds are known for their reversible color changes, influenced by factors such as pH, substitution patterns in the B ring, and the prevalence of acids in both acylated and non-acylated groups.[2] The colors associated with the Flavylium Cation are predominantly red, Carbinol is colorless, the Anhydro base is violet, Quinoidal is blue, and Chalcone appears yellow. Therefore, anthocyanin colorants cannot identify chalcone because they are lost during the process.[1] The characteristics of anthocyanin alterations depend on several factors and their respective intensities, as shown in Figure 2.

Artificial dyes contain complex molecules that are difficult for the human digestive system to metabolize, compromising the mechanisms underlying pathogenicity in response to immune systems after ingestion.[5] Furthermore, synthetic dyes have been heavily criticized by Adeel et al.[6] for their association with allergies. For this reason, natural colorants based on anthocyanins are proposed to replace artificial colorants.

Anthocyanins are used commercially in the food industry to color products with pHs between 2.5 and 3.8, such as soft drinks, sweets, confectionery, refreshments, cake toppings, and jellies due to their attractive coloring. Additionally, anthocyanins have therapeutic properties.[4] These activities include antiproliferative,[7] anti-inflammatory,[8] antibacterial,[9] neuroprotective,[9] anti-obesity,[10] and anti-diabetic properties,[11] as well as the prevention of cardiovascular diseases,[3] among others.[12]

Extraction methods for anthocyanins involve physicochemical processes that rely on mass transfer between two phases. Thermodynamic and kinetic factors influence the mass transfer during

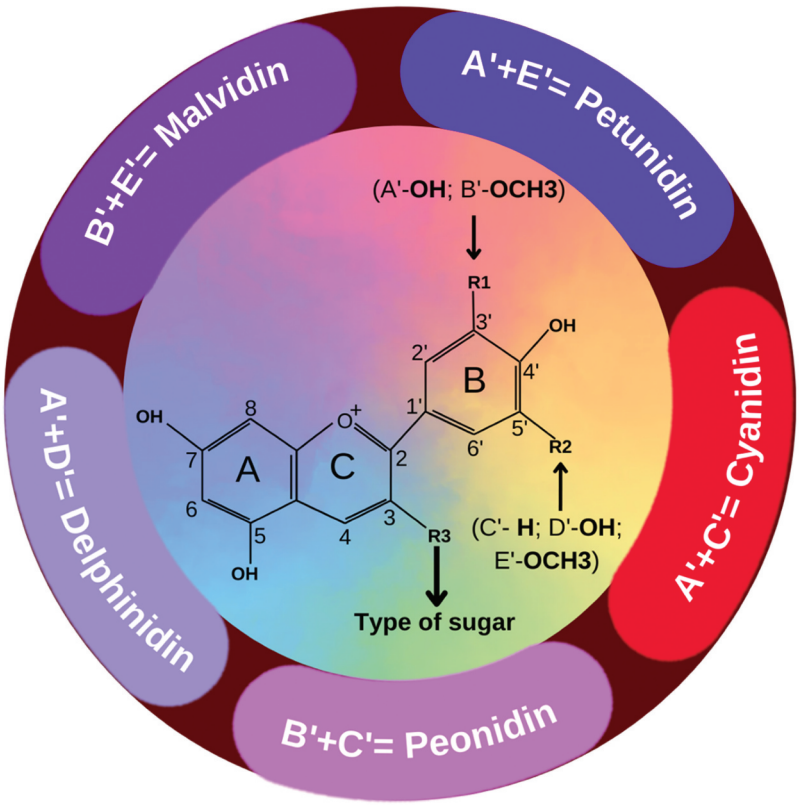

Figure 2. Five common types of anthocyanins. These structures showed the presence of A,' B,' C,' D,' and E,' which correspond to OH, OCH3, H, OH, and OCH3, respectively, in R1 and R2. Cyanidin is formed by the combination of A' and C,' while peonidin is formed by the combination of B' and C.' Delphinidin is formed by the combination of A' and D,' and malvidin is formed by the combination of B' and E.' Petunidin is formed by the combination of A' and E.' The type of sugar present in the anthocyanin molecule is defined by the position of R3.

extraction, significantly affecting the extraction yield. Thermodynamics refers to the maximum amount of analytes that can be extracted using a particular technique, while kinetics refers to the rate at which this transfer occurs. Physical structure, chemical composition, and pH must be considered to yield high extraction.[13] Therefore, to select the best anthocyanin extraction method, the type and structures in the matrix surrounding the cell vacuole should be considered (Figure 3).[14]

This study aimed to introduce a decision-tree framework to enhance the efficiency of selecting an anthocyanin extraction method based on plant structural characteristics. Integration of this decision-tree tool can streamline selection processes, resulting in significant time and resource savings. For example, in preliminary tests with blackberry and purple sweet potato matrices, the tool reduced extraction method selection time by 30% and minimized solvent consumption by 20%. These quantifiable benefits highlight the tool's practical value in optimizing extraction processes. Specifically, the study (i) examines the principles of anthocyanin extraction methods, (ii) describes how different anatomy and physiology structures respond to various anthocyanin extraction methods,

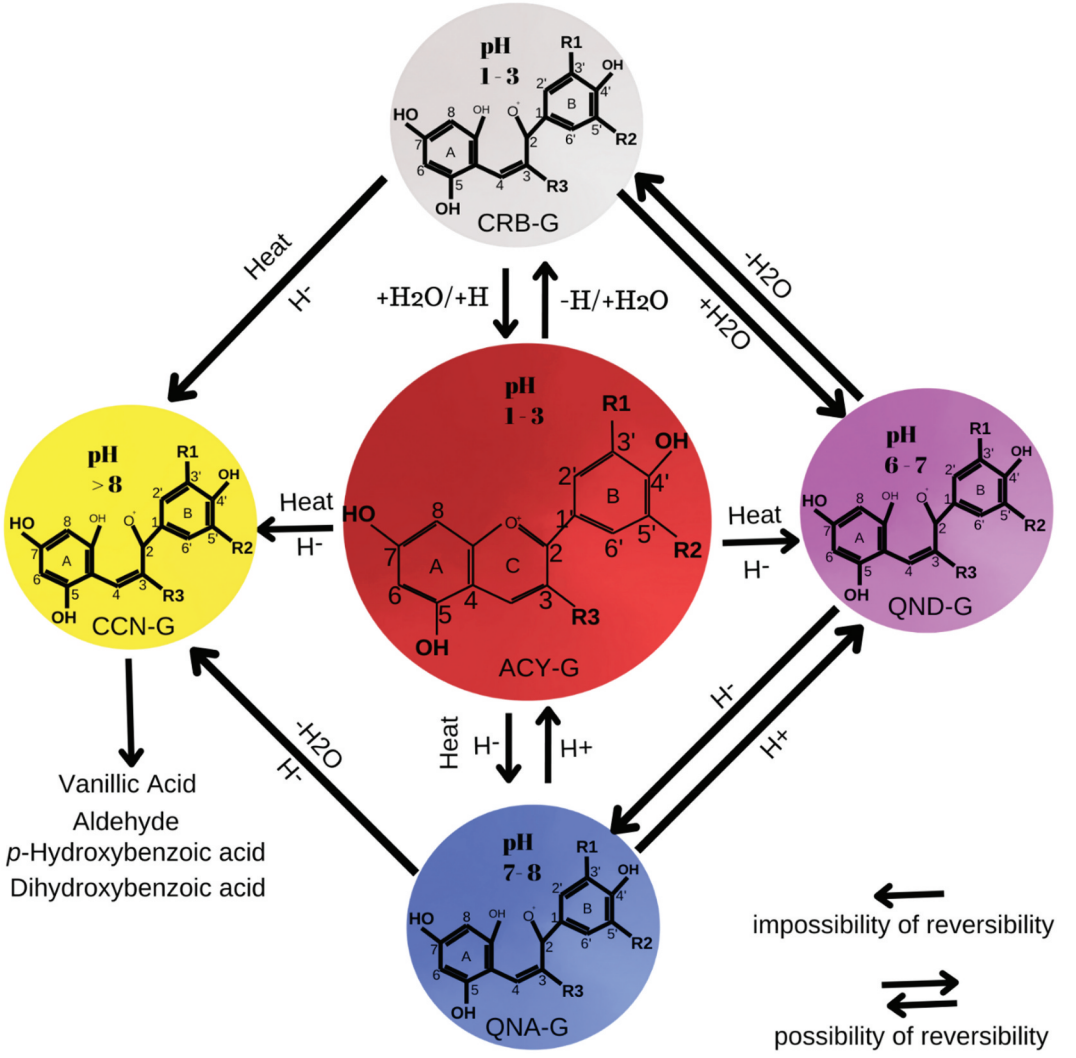

Figure 3. Changes in the characteristics of anthocyanins by temperature, pH, Hydroxyl (OH) and Water (H2O), ACY-G (anthocyanin glucoside), CRB-G (Carbidol glucoside), QND-G (Khenidal glucoside), QNA-G (Anionic kenoidal glucoside), CCN-G (chalcone glucoside).

and (iii) provides a decision-tree framework that outlines the processes to follow before starting extraction. Moreover, the influence of extraction methods on blackberries and purple sweet potatoes was evaluated.

Extraction methods overview

This review's primary objective was to investigate the fundamental principles underlying the efficacy of anthocyanin extraction methods, particularly their interaction with diverse cellular anatomical structures found in plant matrices. A comprehensive combination of systematic and non-systematic literature searches was used to conduct this review. Initially, a systematic review was performed to investigate methods for extracting anthocyanins.[15] Simultaneously, a non-systematic review was conducted to explore the anatomy and physiology of plant structures containing anthocyanins. Subsequently, the literature was organized based on citation frequency and its relevance in constructing a decision-tree.

For the systematic review, comprehensive searches were conducted covering the years 2018 to 2023. At first, many publications were identified, totaling 994, 970, 810, and 10 records: Web of Science, Scopus, Medline (via PubMed), and SciELO, respectively. In addition, duplicate publications, primary sources not relevant to the central object of study, review articles, and books were excluded, resulting in a total of 1053 publications. The most cited publications on anthocyanin extraction methods (those with more than 10 citations) were highlighted for inclusion in this study. Additionally, recent and relevant literature was used as a criterion for the search method to include articles that may have yet to achieve a high citation rate due to their recent publication date. The selection process resulted in 36 publications to be analyzed in this review.[15]

For a non-systematic review, we examined the literature on the botanical anatomy and physiological mechanisms involved in anthocyanin accumulation within plant structures. This literature provided valuable insights into how anthocyanins are stored within cellular structures and their metabolic pathways. Finally, synthesized information from systematic and non-systematic reviews was used to construct the decision-tree.

Discussion of results

Anthocyanin extraction methods

Anthocyanin extraction methods can be classified as conventional and innovative (Figure 3).[16] Among the 36 articles selected for the systematic review, five reviews used conventional methods, 29 publications referred to innovative extraction, and two used a combination of both (Table 1). The following description details the categorization and operating principles of these methods.

Conventional extraction method (CME)

The CME used conventionally follows procedures commonly employed for anthocyanin extraction (Figure 3). It can be categorized based on the process, techniques, and type of solvent employed. The most widely recognized conventional methods are:

(1) Maceration: mixing the raw sample, whether fresh or dry, directly with a solvent after disrupting the cell processes using tools such as a crusher and pestle.[17]
(2) Infusion: Like maceration, water is used as a solvent instead of other liquids.[51]
(3) Digestion: The sample undergoes maceration, and the temperature is also increased, typically above the environmental condition (25 °C).[17]
(4) Decoction: This method involves preparing an infusion with water heated above its boiling point.[3]

Table 1. Classification of anthocyanin extraction methods according to the selected studies.

Extraction method	Manuscript title	Vegetal structure	Plant organ	Pre-treatment application	Results in Anthocyanin content	Advantages	Disadvantages	Author
Conventional	Extraction methods and food uses of a natural red colorant from dye sorghum	Pericarp	Seed	Soaking in water with rock salt (alkaline)	27.1 mg/g of dry sample	Suitable for most plant structures, the extraction process is straightforward and easily replicable.	High consumption of solvents and energy.	[17]
	Anthocyanin-rich extract of jabuticaba epicarp as a natural colorant: Optimization of heat – and ultrasound-assisted extractions and application in a bakery product	Epicarp	Fruit	Acidified ethanol solvent (pH 3)	55.82 mg/g of fresh sample			[12]
	Optimization and comparison of heat and ultrasound assisted extraction techniques to obtain anthocyanin compounds from *Arbutus unedo* L. fruits	Pericarp	Fruit	None explicitly mentioned	382.4 µg/g of dry sample			[18]
	Rapid analysis of anthocyanin and its structural modifications in fresh tomato fruit	Exocarp	Peel	None explicitly mentioned	3977.93 mg/kg of fresh sample			[19]
Enzymatic	Ultrasound-assisted enzymatic extraction of anthocyanins from raspberry wine residues: process optimization, isolation, purification, and bioactivity determination	Pericarp	Peel	Enzymatic pre-treatment with pectinase	0.723 ± 0.004 mg/100 g of fresh sample	High selectivity and efficiency while being environmentally friendly	Incompatibility among enzymes, physical and chemical instability.	[20]
	Ultrasonic-assisted enzymatic extraction and identification of anthocyanin components from mulberry wine residues	Mesocarp	Fruit	Enzymes (pectinase and cellulase) in combination with ultrasound	5.98 mg/g of fresh sample			[21]
	Robust and recyclable magnetic nano biocatalysts for extraction of anthocyanin from black rice	Pericarp	Seed	None explicitly mentioned	266 mg cyanidin-3-glucoside/100 g of fresh sample			[22]

(*Continued*)

Table 1. (Continued).

Extraction method	Manuscript title	Vegetal structure	Plant organ	Pre-treatment application	Results in Anthocyanin content	Advantages	Disadvantages	Author
Microwave assisted	Deep eutectic solvents and nonconventional technologies for blueberry-peel extraction: kinetics, anthocyanin stability, and antiproliferative activity	Exocarp	Fruit	None explicitly mentioned	25.83 mg/g of fresh sample	Low time and energy consumption.	Higher thermal degradation; Heterogeneity in solubilization.	[23]
	Improvement of Anthocyanins Rate of Blueberry Powder under Variable Power of Microwave Extraction	Exocarp	Fruit	None explicitly mentioned	186.79 mg/100 g of fresh sample			[24]
	Evaluation of enzyme and microwave-assisted conditions on extraction of anthocyanins and total phenolics from black soybean (*Glycine max* L.) seed coat	Pericarp	Seed	Enzymatic pre-treatment with cellulase	5094.9 mg/l of fresh sample			[25]
Ultrasound and ultrasonication	Extraction and identification of anthocyanins in corn cob and corn husk from Cacahuacintle Maize	Exocarp and endocarp	Cob and husk	None explicitly mentioned	24.47 mg/g of fresh sample	Reduced solvent usage, low cost, high contact angle.	Complex, tedious processes, heat required, high degradation during extraction.	[26]
	Ultrasound as a rapid and low-cost extraction procedure to obtain anthocyanin-based colorants from *Prunus spinosa* L. fruit epicarp: Comparative study with conventional heat-based extraction	Epicarp	Fruit	None explicitly mentioned	11.76 mg/g of fresh sample			[27]
	Conventional and ultrasound-assisted methods for extraction of bioactive compounds from red araçá peel (*Psidium cattleianum* Sabine)	Pericarp	Fruit	None explicitly mentioned	121.85 mg/g of fresh sample			[28]
	Ultrasound assisted extraction of anthocyanins and total phenolic compounds from dried cob of purple waxy corn using response surface methodology	Endocarp	Cob	None explicitly mentioned	240.161 mg cyanidin-3-glucoside/g dry sample			[29]
	Camu-camu bioactive compounds extraction by ecofriendly sequential processes (ultrasound assisted extraction and reverse osmosis)	Pericarp	Fruit	None explicitly mentioned	66.169 mg of cyanidin-3-glucoside/100 g of fresh sample			[30]

(*Continued*)

Table 1. (Continued).

Extraction method	Manuscript title	Vegetal structure	Plant organ	Pre-treatment application	Results in Anthocyanin content	Advantages	Disadvantages	Author
Ohmic heating	Application of innovative processing methods for the extraction of bioactive compounds from saffron (*Crocus sativus*) petals	Petals	Flower	Ohmic heating	238 mg/100 g of fresh sample	Low energy and solvent consumption.	Application, the matrices and solvents must have electrical properties, and a high degree of heat dissipation is also required.	[31]
	Extraction of phenolic compounds from Cornelian Cherry (*Cornus mas* L.) using microwave and ohmic heating assisted microwave methods	Pericarp	Fruit	None explicitly mentioned	0.65 mg cya-3-glu/g dry sample			[32]
	Ohmic heating for processing of whey-raspberry flavored beverage	Pericarp	Fruit	None explicitly mentioned	2.91 ± 0.23 mg/g of fresh sample			[33]
	Using Ohmic Heating effect on grape skins as a pretreatment for anthocyanins extraction	Exocarp	Fruit	Ohmic heating (40°C for 20 minutes)	1349 mg/g of fresh sample			[34]
Electric field	Green extraction methods for extraction of polyphenolic compounds from Blueberry Pomace	Pericarp	Fruit	None explicitly mentioned	1757.32 mg/g of dry sample	Low energy consumption; Bonding preserves; Environmentally friendly.	The extraction process is too slow.	[35]
	Comparison of different extraction methods of antioxidant anthocyanins in Zuoyouhong (*Vitis Amurensis*)	Exocarp	Fruit	None explicitly mentioned	163.15 mg/100 g of fresh sample			[36]
Irradiation	Gamma radiation and pasteurization on anthocyanin stability and antioxidant capacity of jussara pulp (*Euterpe edulis*) during storage	Exocarp	Fruit	None explicitly mentioned	948.77 mg/100 g of dry sample	This system reduces compound degradation caused by soft light and is environmentally friendly.	Requires the integration of additional methods to disrupt the cell wall.	[37]
	Effect of extraction and processing conditions on anthocyanins of barberry	Pericarp	Fruit	Adjusting solvent type (water, ethanol), pH, and temperature	863.26 6 1.37 mg/100 g of fresh sample			[38]

(*Continued*)

Table 1. (Continued).

Extraction method	Manuscript title	Vegetal structure	Plant organ	Pre-treatment application	Results in Anthocyanin content	Advantages	Disadvantages	Author
Pressurized	Optimization of pressurized liquid extraction and ultrasound methods for recovery of anthocyanins present in jambolan fruit (*Syzygium cumini* L.)	Pericarp	Fruit	None explicitly mentioned	47.05 mg c3g.g of dry sample	The enzyme is inactivated by inert atmospheric pressure and the absence of light, allowing for mild temperature conditions and short processing times.	Low affinity between CO2 and anthocyanins because of their nonpolar nature.	[39]
	Modeling and optimization of supercritical fluid extraction of anthocyanin and phenolic compounds from *Syzygium cumini* fruit pulp	Pericarp	Fruit	None explicitly mentioned	231.13 mg/100 g of fresh sample			[40]
	Ultrasound and supercritical fluid extraction of phytochemicals from purple tamarillo: Optimization, comparison, kinetics, and thermodynamics studies	Pericarp	Fruit	None explicitly mentioned	0.62 mg Cyanidin 3-galactoside/g of fresh sample			[41]
	The effect of different pressurized fluids on the extraction of anthocyanins and total phenolics from cranberry pomace	Pericarp	Fruit	None explicitly mentioned	3.7 ± 0.962 mg Cyanidin 3-galactoside/100 g of fresh sample			[42]
	An eco-friendly pressure liquid extraction method to recover anthocyanins from broken black bean hulls	Pericarp	Seed	None explicitly mentioned	5.88 mg/g of fresh sample			[43]
	Capacity of solutions involving organic acids in the extraction of the anthocyanins present in jabuticaba skins (*Myrciaria cauliflora*) and red cabbage leaves (*Brassica oleracea*).	Epidermis and exocarp	Leaves and fruit	None explicitly mentioned	71.34 mg/L of fresh sample			[44]
Hydrostatic pressure	Effects of high hydrostatic pressure and thermal processing on anthocyanin content, polyphenol oxidase and β-glucosidase activities, color, and antioxidant activities of blueberry (*Vaccinium* Spp.) puree	Pericarp	Fruit	Thermal Processing	503.5 µg cyanidin-3-O-glucoside/mL of fresh sample	The treatment process results in minimal degradation: the extraction process reduces the pH value of the solvent.	High cost; Reduction in anthocyanin bioaccessibility.	[45]
	Effect of high hydrostatic pressure processing on the anthocyanins content, antioxidant activity, sensorial acceptance and stability of Jussara (*Euterpe edulis*) juice	Exocarp	Fruit	None explicitly mentioned	51.98 mg/100 mL of cyanidin-3-O-glucoside and cyanidin-3-O-rutinoside of fresh sample			[11]

(*Continued*)

Table 1. (Continued).

Extraction method	Manuscript title	Vegetal structure	Plant organ	Pre-treatment application	Results in Anthocyanin content	Advantages	Disadvantages	Author
Radio frequency	Radio frequency-assisted enzymatic extraction of anthocyanins from *Akebia trifoliata* (Thunb.) Koidz. flowers: Process optimization, structure, and bioactivity determination	Epiderm	Floral calyx	Radio frequency heating at 40°C for 10 minutes	50.87 mg cyanidin-3-O-glucoside equivalents/100 g of fresh sample	Deep contact into the matrix; low chemical residues; Environmentally friendly.	Anthocyanins denature due exposed to heat; require combination with other extraction methods.	[46]
Stirred tank	Pressurized liquid extraction of polyphenols and anthocyanins from saffron processing waste with aqueous organic acid solutions: Comparison with stirred-tank and ultrasound-assisted techniques	Endocarp	Seed	Stirred-tank with ultrasonication using 1% lactic acid	3.25 mg/g of fresh sample	The extract exhibits a high degree of external homogenization.	Assistance from other methods is required.	[47]
	Natural food colorants derived from onion wastes: Application in a yogurt product	Exocarp	Peel	Eco-friendly solvents (water, glycerol) with the aid of cyclodextrins	3.13 mg cyanidin-3-O-glucoside/g of dried sample			[48]
Combined	Ultrasound-assisted pressurized liquid extraction of anthocyanins from *Aronia melanocarpa* pomace	Pericarp	Fruit	None explicitly mentioned	48.6 ± 0.4 mg cyanidin-3-O-glucoside of dried sample	Reduced solvent usage, low cost, and high contact angle offer	Employing intricate and time-consuming processes, with a notable risk of heightened degradation of anthocyanins during the extraction	[49]
	Enabling technologies for the extraction of grape-pomace anthocyanins using natural deep eutectic solvents in up-to-half-liter batches extraction of grape-pomace anthocyanins using NADES	Pericarp	Fruit	None explicitly mentioned	1.77 mg/g of dried sample			[50]

(5) Percolation and Filtration: The sample is mixed continuously in a solvent-dried state. Thus, the renewal processes occur in a percolator and then filtration.[52]
(6) Soxhlet: This method involves cyclic and continuous mixing of a solid-state sample with a solvent within a Soxhlet system over a controlled period.[16]

The solvent selection for anthocyanin extraction follows the "like dissolves like" principle. Anthocyanins, inherently polar compounds, tend to dissolve in solvents of similar polarity. Water, ethanol, methanol, acetone, or other solvents can also be used. However, methanol and ethanol, both polar solvents[53] are commonly used for anthocyanin extraction due to their practical ability to dissolve anthocyanins from the extracts.[43,54] Water, a polar solvent, is frequently used instead of organic solvents due to environmental and health concerns. Although less polar than methanol and ethanol, acetone is still effective for anthocyanin extraction. Therefore, the solvent mixtures are often used to improve extraction efficiency by taking advantage of the complementary solubility properties of different solvents.[55] These mixtures can enhance the efficiency in anthocyanin extraction by providing a more comprehensive range of solubility, maximizing yield and specificity in anthocyanin isolation from vegetal sources.[56]

Non-conventional extraction methods

These techniques involve the green process and use of safe solvents to improve the yield of anthocyanins extraction.

Enzyme-assisted aqueous extraction (EAE)

The enzymatic method is a structural biological manipulation approach used in plants to expose anthocyanins by employing individual or combined enzymes.[57] This method is widely used in various scientific fields, particularly for extracting bioactive compounds. Anthocyanin extraction involves breaking down cell walls and facilitating the release using enzymes. EAE procedures can also be simple to complex.[57] Depending on the desired objectives, enzymatic extraction can be combined with other extraction techniques.[58] This strategy allows access to anthocyanin compounds retained within cell organelles by using the basic principle of cellular degradation in the extracellular and intracellular walls. Thus, the method enables the extraction of anthocyanins trapped in cellular structures.[16]

According to Lotfi et al.[57] enzymes can be classified into two main groups: carbohydrases (1A) and polysaccharides (1B) or proteases (2A) and proteinases (2B). Therefore, group 1 breaks down complex carbohydrates like cellulose, hemicellulose, and pectin. This group includes cellulases, hemicellulases, and pectinases. Group 2 can break down proteins into amino acids. Cellulases, hemicellulases, and pectinases can be used individually or in combination.[57] However, group 2 should be utilized separately to avoid hydrolyzing enzymatic proteins.[59]

Enzymatic efficiency depends on several factors, including cell structure,[16] enzymatic structure,[57] enzymatic composition,[60] and pH. Generally, the pH range for enzymatic hydrolysis in anthocyanin extraction is between 3.0 and 5.0, as enzymes involved in anthocyanin extraction often exhibit optimal activity in this acidic pH range.[61] However, the temperature range for extracting anthocyanins varies depending on the enzyme and source material, typically between 25°C and 50°C. Thus, removing the anthocyanins at moderate temperatures is preferable to prevent degradation. Additionally, the ratio between the enzyme and treated sample can also vary. Still, it is often expressed as a percentage or ratio of enzyme weight to the weight of the treated sample, with a typical range of 1–5% (w/w). The solid-liquid ratio for anthocyanin extraction typically ranges from 1:5 to 1:20 (w/v).[61] Contact time, which indicates the duration of enzyme treatment, can vary widely, ranging from 30 minutes to 24 hours for anthocyanin extraction, depending on the enzyme and other extraction conditions.[57]

Microwave-assisted extraction

Microwave extraction is a process that can extract anthocyanins by introducing electromagnetic waves into the polar molecules. Then, the energy can be absorbed and cause ions to migrate, then start to move around.[62] The process can create vibrations in the molecules and polarize the water present, possibly increasing pressure and temperature.[63] The Microwave extraction method can break down plant cell structures sensitive to heat, allowing anthocyanins to move out of the cells.[64] The effectiveness of this method depends on various factors, such as the strength of the microwaves, the duration of exposure, the type of solvent used, and the characteristics of the plant material.[25,63]

Furthermore, due to the heightened thermal effects caused by microwave operation, several adjustments have been made to reduce temperature elevation during extraction procedures. These modifications include microwave extraction under atmospheric pressure,[65] oxygen flow-assisted microwave extraction,[66] and nitrogen-protected microwave-assisted extraction (NPMAE).[56] Nevertheless, various methods of extraction have been explored, including vacuum microwave-assisted extraction (VMAE),[67] Soxhlet extraction combined with microwave-assisted extraction (FMASE),[68] ultrasonic-assisted microwave extraction (UMAE),[69] microwave hydro-distillation (MWHD or MAHD) and microwave steam distillation (MSD),[16] solvent-free microwave extraction (SFME),[70] and microwave vacuum hydrodistillation (VMHD).[71] Furthermore, in 2022, methods for optimizing extraction efficiency while minimizing the impact of heat on sample integrity were proposed, including microwave-assisted extraction techniques such as microwave gravity hydrodiffusion (MHG)[72] solvent-free pressurized microwave extraction (PSFME),[16] and microwave-assisted two-phase aqueous extraction (MA-ATPE).[73] These techniques have been developed to ensure that the extracted samples remain intact and undamaged.

Ultrasound-assisted extraction (UAE)

UAE method uses compression and expansion generated by acoustic cavitation to induce shear forces, resulting in cell rupture and anthocyanin extraction.[74] The ultrasound can be divided into ultrasonic and ultrasound processes. The ultrasonic waves are at either low frequency (100–1000 kHz) at low power and amplitude or high frequency (20–100 kHz) with high power and amplitude, the latter being commonly used for anthocyanin extraction.[75] Extraction can be performed directly through sonication. The device, connected to a transducer, is immersed in the extraction vessel and directly contacts the sample.[76] Ultrasounds are generally more cost-effective and accessible but may lead to uneven energy distribution and lower extraction efficiency than the direct method.[77] Ultrasound techniques can be adapted to optimize extraction outcomes across various technologies.[78] In general, the efficiency in ultrasonic and ultrasound extraction is influenced by power, temperature, solid-liquid ratio, and extraction and pre-processing time.[79]

Ohmic heating-assisted extraction (electroconductive heating)

Ohmic heating extraction (OH) is a method that involves the transfer of electricity through a system consisting of a power supply, isolation transformer, treatment chamber, frequency generator, and microprocessor board.[80] This method works based on the ionic components present in plant tissues, such as salts and acids, that conduct electricity.[81] The electricity passing through the components of a glass ohmic heating cell is converted into heat energy. An increase in temperature can damage cell structures, which can lead to the exposure of anthocyanins due to increased diffusion.[81] In addition, the extraction efficiency of anthocyanins through electric conductivity heating is influenced by various factors, such as the sample's moisture content, the electric field's intensity, the presence of electrons and salts in the raw material, the duration of exposure in the extraction system, and how the system is combined or adapted with other extraction methods.[32]

High voltage electric field assisted extraction

The method of the high-voltage electric field involves applying loads, sometimes with pulses predominating, using variable time and intensity, either in continuous or static mode.[82,83] However, the

extraction technique described in this study relies on external electrical forces to permeate cell membranes in plant tissues.[84] These forces cause the formation of hydrophilic pores in the cell membranes, which opens them and causes them to lose their protective function. This exposes anthocyanins to the surrounding environment.[55] The protective membrane is typically lost when the transmembrane potential exceeds a critical value of about 1 V.[82] This reduces the thickness of charge-carrying molecules and the permeabilization of smaller molecules.[85] High-voltage electric field extraction can be classified into two primary categories. Jafari and Saien[83] discuss High Electrostatic Field (HEF) and High Voltage Electrical Discharges (HVED).

The High Electrostatic Field (HEF) system maintains a constant current or voltage throughout the experiment. This technique utilizes parallel plate electrodes to ensure uniform electric field distribution during operation. In contrast, High Voltage Electrical Discharges (HVED) involve chemical reactions and physical processes. This method injects energy directly into an aqueous solution through a plasma channel created by a high-current electrical discharge (>40 kV; >10 kA) between two submerged electrodes.[86] The process of HVED operates in two phases: the pre-break phase and the break phase. In the pre-break phase, relatively weak shock waves are generated, forming tiny bubbles that disrupt cell structures and accelerate the extraction of intracellular compounds.[83]

During the intensified electrohydraulic phase, which occurs during the transition from pre-breaking to the breaking phase, various effects take place. These include strong shock waves, intense UV radiation (200–400 nm), production of highly concentrated free radicals, bubbles containing plasma, and vigorous liquid turbulence. These phenomena lead to the mechanical destruction of cellular tissues and oxidation, which may impact the antioxidant activity of bioactive compounds.[55] Overall, this extraction method provides a more effective mechanical disintegration of cell walls, leading to a more efficient extraction. Therefore, this technique has been utilized for extracting bioactive compounds from various raw materials.[55]

The efficiency of anthocyanin extraction via pulsed electric fields (PEF) depends on several factors, including the strength of the applied electric field (ranging from 0.1 to 20 kV/cm), type of raw material, exposure time, electric field intensity, specific energy input pulse, chamber size, initial temperature, and combination with other extraction methods.[55,83] Pulsed electric fields (PEF) are an innovative technique for enhancing anthocyanin extraction efficiency by disrupting plant cell structures. This involves applying short pulses of high electric field strength to a sample. The principle behind anthocyanin extraction using PEF is to induce permeabilization of cell membranes, thereby facilitating the release of intracellular compounds, including anthocyanins.[55] However, PEF has not been used to extract anthocyanins from plant cells. The process starts with membrane permeabilization, which leads to electroporation or electropermeabilization. This procedure results in rearranging the lipid bilayer in the cell membrane and forming nanopores. These nanopores facilitate the passage of ions, water, and other small molecules across the membrane, ultimately increasing diffusion and leaching, thus improving the extraction efficiency of anthocyanins.[83]

Irradiation extraction

Anthocyanins can be extracted through irradiation, a physical and non-thermal process. This process exposes cell structure to high-energy ions that chemically break down protective substances surrounding the anthocyanins into vacuoles.[87] Nonetheless, the degree of modification depends on factors such as the type of raw materials, amount of radiation, and radiation source.[88] Food irradiation treatment involves exposing food to either ionizing or non-ionizing radiation. Ionizing radiation sources include gamma rays, X-rays, and high-energy electrons, while non-ionizing radiation sources include electromagnetic radiation, such as UV rays, visible light, and infrared radiation.[89]

Gamma radiation extraction is a continuous process involving the flow of high-energy photons capable of energizing electrons within atoms in the food matrix. This energization process causes the transition of atoms to higher energy levels.[90] Atoms with unpaired electrons in their outer shell can react with the outer shell electrons of atoms that comprise cell components, producing free radicals in hydrogen and hydroxyl bonds from water molecules.[91] This process triggers the hydrolysis of pectins

after depolymerizing carbohydrate polymers, which softens the cell components and exposes anthocyanins.[92]

Pulsed light extraction

The extraction of anthocyanins using pulsed light is an emerging method that can be described according to different procedures.[93] This method includes intense pulsed light, high-intensity pulsed UV light, pulsed white light, or pulsed UV light. The technique involves applying very short pulses of light (ranging from 1 μs to 0.1 s) using a xenon lamp to supply the high-intensity pulse generation device on the extraction matrix. The process can be conducted with contact or non-contact, using a range of wavelengths from 100 nm to 1100 nm.[93] Additionally, the extraction of anthocyanins through pulsed light involves two fundamental mechanisms: the photochemical effect and the photothermal effect.[94] The photochemical effect is associated with the UV portion of the pulsed light spectrum, depending on the direct interaction between photon energy and matrix molecules. During the pulsed light process, chemical compounds absorb optical energy, causing photoionization, decomposition of chemical bonds, and changes in the structural conformation of the applied matrix.[95] Additionally, some photons can transfer their energy to the material thermally, increasing the temperature of the applied matrix. This mechanism primarily affects the infrared and visible portions of the pulsed light spectrum, resulting in physical changes to cells and cellular structures. These changes include loss of cell membrane permeability, expanded vacuoles, shape alteration, and lack of cell walls.[96] The effectiveness of pulsed light technology depends on the pulses emitted, lamp types used and their combinations, emission time, optical properties, and matrix species used.[97]

Supercritical fluids extraction

The transfer of mass from plant cells can be achieved using pressurized fluid techniques through three main methods: supercritical fluid extraction (SFE), pressurized liquid extraction, and high-pressure liquid extraction.[53,55] SFE involves carbon dioxide and co-solvents.[54] This process occurs at temperatures and pressures well above the critical points (7.4 MPa and 31.1 °C) and carbon dioxide, which modifies its properties to improve mass transfer during anthocyanin extraction.[98] The selectivity in SFE is a current research focus, and parameters can be optimized to suit specific compounds and matrix characteristics. SFE is a valuable technique in various fields, including food, pharmaceuticals, and natural products.[53] The extraction process typically involves a static period during which the solvent remains in contact with the sample and a dynamic period during which the solvent continuously passes through the sample.[99] The extraction efficiency relies on various factors, including temperature, pressure, particle size, type and quantity of co-solvent, sample moisture content, extraction duration, CO2 flow rate, and liquid-to-solid ratio.[100]

Pressurized and high-pressure liquids extraction

Pressurized Liquid Extraction (PLE) and High-Pressure Liquid Extraction (HPLP) are analytical chemistry techniques that isolate anthocyanin compounds from specific matrices. Although they share similar operating principles, they differ only in the methods employed.[17,39] PLE, also known as accelerated solvent extraction (ASE), involves using liquid solvents at temperatures above their boiling points (around 200°C) from medium to high extraction pressures (3.5 to 20 MPa). The PLE anthocyanins extraction kept the solvent liquid at temperatures above its boiling point to enhance the solubility of the analytes.[39] The extraction yield depends on various factors (i.e., temperature, pressure, static time, and the number of cycles to which the matrices are subjected). Efficient extraction of analytes from a sample into a solvent can be achieved by increasing pressure and temperature.

High-pressure liquid extraction is a technique for extracting anthocyanins. The term "high pressure" can refer to different methods, but extraction typically involves using elevated pressure in liquid systems to enhance extraction efficiency. One subgroup comprises discontinuous high hydrostatic pressure (HHP). In contrast, the other subset comprises continuous techniques such as high-pressure

homogenization (HPH), microfluidization (MF), and ultra-high-pressure homogenization (UHPH).[101]

The critical difference from other pressurized liquid extraction techniques is that high pressure keeps the solvent above its boiling point.[102] This method simplifies extraction, reducing the amount of solvent used and the time required. High-pressure methods, such as those using pressures exceeding 100 MPa (HP), 300 MPa (UHP), or 400 MPa (UHPH), provide better solvent penetration into cell membranes and improve bioaccessibility.[103]

The efficiency of compound extraction depends on factors including solvent composition, pressure, temperature, particle size, moisture content of the material, extraction time, and solvent-to-solid ratio.[43] In brief, pressurized liquid extraction (PLE) is a technique that utilizes pressure. In contrast, high-pressure liquid extraction (HPLP) can encompass a broader range of strategies for compound extraction.

Radiofrequency heating-assisted extraction

Radio frequency-assisted anthocyanin extraction is a technology that uses radio electromagnetic waves (3 kHz-300 MHz) to interact with target matrix molecules. This interaction induces heating within the plant tissue, causing protective structures to break down.[46] As a result, anthocyanins become more accessible, facilitating their extraction during the process.[46]

The principle of the system consists of a densified bed of conductive particles positioned between two electrodes that are cyclically charged by a radio frequency transducer. This setup causes the ions of the matrix components or the solvents used to migrate toward the oppositely charged electrodes. In addition, polar molecules align with the established electric field's polarity, resulting in molecular and ionic friction. Friction during the extraction process generates heat within the matrix, as described by Izadifar and Baik.[104] This process can be conducted at room temperature, with less amount of solvent. The process works well with plant structures that contain high pectin content.[105]

Stirred-tank extraction

By improving the kinetic conditions within the target matrix, extraction of anthocyanins using stirred tanks enhances mass transfer.[106] This method relies on a mechanical apparatus that includes a containment tank for matrices, inert stirring, mechanical agitators, a thermometer, a heating system, a rotor, and other essential components.[106] In addition, the element in this system has a crucial role in facilitating anthocyanin extraction by adjusting and functioning according to predefined parameters. This optimization improves operational efficiency by breaking down protective elements surrounding anthocyanins, thereby exposing them for extraction.[47]

The performance of agitated bath extraction includes temperature, solvent ratio, stirring speed, extraction time, and integration with other extraction techniques or sample processing.[47,106] These parameters contribute to the efficiency and yield of the extraction process. Optimization and control are essential to achieve desired outcomes.

Combined extraction method

Technological advancements have led to proposals that combine two or more extraction methods to enhance the extraction of anthocyanins from natural sources.[107] The extraction of anthocyanin is influenced by both kinetic and thermodynamic factors, which significantly impact extraction yield.[30] Although the efficacy of an anthocyanin extraction procedure can be observed, it is essential to understand the extent of extraction to prevent excessive degradation during the process.[108]

Combining two or more methods aims to improve extraction efficiency and speed.[20,25,107] These combinations may involve conventional or innovative extraction systems depending on the desired objectives.[109] The efficiency of combined extractions relies on synergies between the coupled systems, which may vary depending on the raw material being extracted.[107]

Conventional and non-conventional solvents for anthocyanin extraction

Solvents are the main component that directly interacts with the method. The specific names are based on the principles used to obtain them and their method during anthocyanin extraction.[110] In comparison, many solvents are considered conventional.[111] Therefore, the growing trend of non-conventional solvents is toward using natural, environmentally friendly solvents with sustainable operating principles, often called green solvents as depicted in Figure 3.

Conventional solvents

A suitable extraction solvent must have access to plant tissues and be able to dissolve anthocyanins and other bioactive compounds in their cell organelles.[112] However, conventional solvents that are commonly used include water (H_2O), ethanol (C_2H_5OH), acetone (CH_3COCH_3), methanol (CH_3OH), diethyl ether $(C_2H_5)_2O$, chloroform ($CHCl_3$), hexane (C_6H_{14}), petroleum ether, toluene ($C_6H_5CH_3$), xylene ($C_6H_4(CH_3)2$), dichloromethane (CH_2C_{l2}), acetonitrile (CH_3CN), ethyl acetate ($CH_3COOC_2H_5$), butanol (C_4H_9OH), cyclohexane (C_6H_{12}) and others.[25,46,111,113]

When selecting an extraction solvent, the following factors should be considered: Selectivity: The solvent must target the specific compound in the plant, whether it's polar or nonpolar[53,55]; Boiling point: Choose a solvent with a low boiling point to facilitate removal after anthocyanin extraction and purification. Reactivity: The solvent should not chemically react with the compounds in the extract to avoid degrading the compounds of interest. Viscosity: Generally, a low viscosity is preferred, but it shouldn't be too low to interfere with the diffusion and solubility of the compounds. Safety: Choose a nonflammable, nontoxic, and non-corrosive solvent to prevent environmental and health hazards. Cost: The solvent should be cost-effective to make the extraction method viable. Vapor pressure: Low vapor pressure helps avoid solvent loss during extraction, allowing for easy evaporation and solvent recovery afterward. Recovery: The solvent should be easily separated from the extract using simple methods. Considering these factors will help select the most appropriate solvent for anthocyanin extraction to ensure efficiency, safety, and cost-effectiveness.

Non-conventional solvents

Ionic liquids (ILs) are a class of solvents used for "green extraction" that can aid in the separation of polar and nonpolar compounds.[114] Furthermore, ILs are organic salts in a liquid state and consist of an organic cation paired with an organic or inorganic anion. These solvents exhibit several unique properties: they have low electrical conductivity, are nonionic (nonpolar), have high viscosity, low vapor pressure, low flammability, good thermal stability, and a wide liquid phase range, making them ideal for dissolving a wide range of polar and nonpolar compounds.[115]

Due to their distinctive chemical functional groups, ILs facilitate matrix-solvent interactions when used for anthocyanin extraction. Many ILs are readily available commercially or can be synthesized by reaction of appropriate cationic and anionic components.[116] Although ILs have received increasing attention for their excellent extraction properties, they also have drawbacks. These include the toxicity of specific components, their stimulating properties, and their high cost, which limits their widespread use despite their considerable utility.[117]

Natural deep eutectic extraction solvent (NADEES)

Extraction using deep eutectic natural solvents is a technique that maximizes the physicochemical affinity between the solvent and the cellular organelles that protect anthocyanins.[50] These solvents are typically made by mixing two or more components, each containing at least one hydrogen bond donor and one hydrogen bond acceptor, forming liquid salts.[118] The resulting green solvent is often composed of naturally occurring sugars and acids, following the principles of green chemistry.[109] After preparation, these solvents exhibit lower melting points than their components, which is attributed to the formation of intermolecular hydrogen bonds.[50] The efficiency of extraction using

deep eutectic solvents depends on various factors, including the solvent composition, the extraction technique used, the contact time with the raw material,[119] the solvent concentration, and the solid/liquid ratio.[118,120]

Basic decision-tree design considerations

Several approaches were emphasized in establishing criteria for understanding how anthocyanin extraction methods work for different vegetal matrices.[77,113,121] These include the relationship between anthocyanin storage organs and extraction methods, common research on anthocyanin extraction, the difficulty of comparing extraction methods in raw materials with different structures, and anatomical structures and physical-chemical composition in anthocyanin Extraction.

Relationship between anthocyanin storage organs and extraction methods

Anthocyanins are pigments in plant cells found in vacuoles.[18,71] Anthocyanins are mainly present in different plant organs, including flowers or inflorescences, leaves, roots or underground organs, fruits, and seeds are shown in Figure 4.[46] Therefore, to get high-yield anthocyanin extraction on this matrix source, specific procedures are necessary due to the complex and diverse compositions of their structure composition. Additionally, techniques that enhance mass transfer are necessary.[111] The process involves selecting the appropriate method, which guarantees the adequate rupture of structural barriers and preserving compound stability at the same time.[25] The procedures reduce particle size, break down interfering structures such as pectin, cellulose, hemicellulose, lignin, or other cell wall components, and separate compounds that can limit anthocyanin extraction, such as lipids and proteins. Additionally, solubilizing certain materials like starch and utilizing appropriate solvents such as ethanol, methanol, water, and soluble sugars play crucial roles.[18,25] During material preparation, it is essential to understand the specifics of the tissue fraction where anthocyanins are protected. For example, in fruits such as jabuticaba and grapes (most cultivars), over 90% of anthocyanins are in

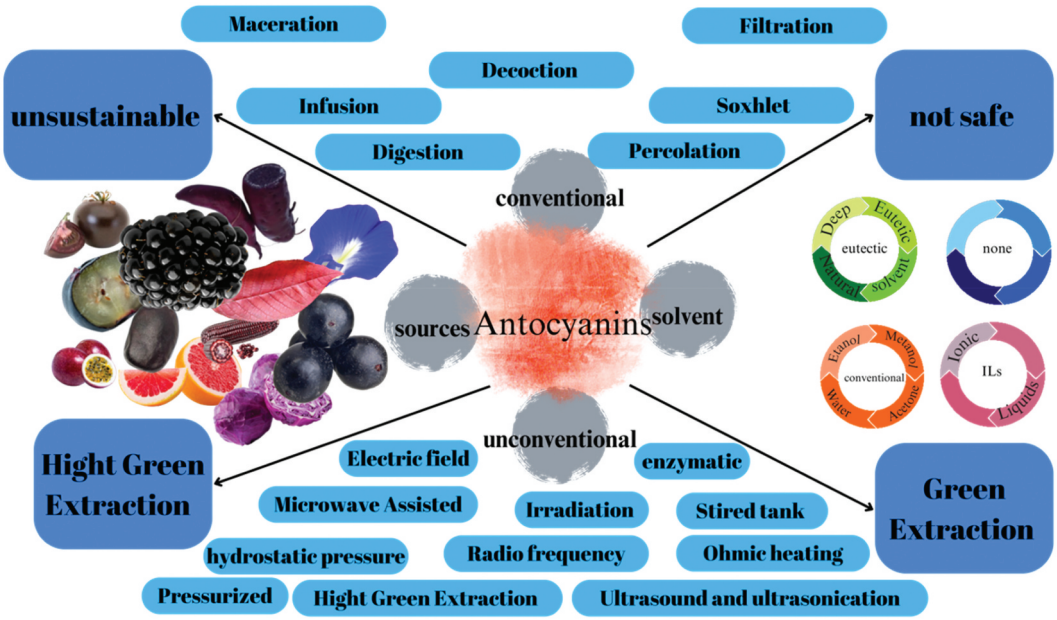

Figure 4. Comprehensive illustrative system describing the sources of anthocyanin extraction, the solvents used for extraction, the extraction methods used, the similarity characteristics between methods, and the raw material, along with their respective health, environmental, and extraction process impacts.

the skin, protected by pectin and fibers. Therefore, using a unit operation to separate this composition from anthocyanins can greatly help to improve the best anthocyanins extraction from the skins.[77,113]

Common research for anthocyanin on extraction

The analyzed set of studies shares several common experimental characteristics:

(1) Comparison of conventional and unconventional extraction methods.[16,18]
(2) Designs applied to optimize factors and achieve optimal points.[122,123]
(3) Simulation of extraction methods for large-scale application.[50,62,124]
(4) Evaluation of the performance of extraction methods based on pre-treatment to modify the physical state of raw materials, including dry and fresh matter. The studies referenced for this section are[125–127]:
(5) Comparison of combined extraction methods, with references to studies by Jiang et al.[46] and González et al..[128]
(6) this section compares raw materials processed in organic and conventional solvents, with references to studies by Fernández et al.[129] and Alrugaibah, Yagiz, and Gu.[4]
(7) This section compares modified extraction methods from Wathon et al.[130] and Wu et al..[131]
(8) In the studies conducted by Porto and Natolino[132] and Parra-Campos and Ordonez-Santos,[133] modeling systems combined with multivariate optimization were utilized to determine optimal points.

The works significantly contribute to the extraction of anthocyanins from the specific raw materials studied. Additionally, the authors describe the food matrices and preparation procedures used. This information enables the construction of a deductive strategy to propose methods for untested materials.

Difficulty of comparing extraction methods in raw materials with different structures

Matos, Mota, and Carmo[113] compared conventional extraction methods, high hydrostatic pressure, and ultrasound-assisted extraction. The results showed that ultrasound extraction was the most effective method, producing 407.15 mg of cyanidin-3-glucoside per 100 g of fresh sample. However, scalability concerns led to the recognition of the resilience of conventional methods. Similarly, Syrpas et al.[134] found that enzyme-assisted extraction yielded the highest anthocyanin and antioxidant capacity from blueberry pomace. In contrast, Ryu and Koh's[122] optimization studies for anthocyanin extraction in black soybeans favored conventional extraction. The studies examined factors such as HCl concentration (0.3–0.5%), solid-liquid ratio (1/30 g/mL-1/50 g/mL), and extraction temperature (30–50°C). Similarly, Liu et al.[123] emphasized using conventional purple passion fruit peel extraction. The optimal conditions for achieving the best results were determined to be a solution-solid ratio of 20:30 mL/g, power ranging from 500–900 W, delay time of 1:3 s, extraction time of 20–60 min, and cavitation time of 1:3. These conditions resulted in a yield of 0.826 mg/g of cyanidin-3-glucoside. In a comparable study on jambolan (*Syzygium cumini* L.) extracts, dos Santos et al.[135] found conventional extraction optimal, emphasizing the importance of optimizing temperature and extraction time. These findings highlight the variability of extraction factors affected by the physiological structures in plant matrices.

Although each study identified at least one optimal extraction method or factor, as described in the previous paragraph, discrepancies arise when comparing the yields obtained, such as 407.15 mg of cyanidin-3-glucoside per 100 g of fresh sample in jabuticaba peel[113] and 136.68 mg/100 g of fresh sample in black soybean.[122] The difference in anthocyanin extraction can be attributed to variations in raw materials and pretreatment methods that alter the material's physical state. According to Ávila-Hernández et al.,[125] who evaluated anthocyanin extraction from strawberries pre-treated by lyophilization, the yield of total anthocyanins was approximately 0.428 g/100 g, which was higher than the yield from non-lyophilized treatment. Studies on extraction from two blackberry cultivars have found

higher amounts of monomeric anthocyanins in lyophilized raw materials. They explicitly yielded approximately 436.48 mg/100 g of dry matter of cyanidin-3-o-glucoside.[126] However, outcomes may vary in some cases.[127]

The difference in results can be attributed to the variation in the simple and combined extraction methods. This causes one matrix to be extracted extensively at the expense of another. Jiang et al.[46] studied the extraction of anthocyanins in *Akebia trifoliata* (Thunb.) Koidz flowers. They compared a combined system (radio-frequency-assisted enzymatic extraction) with conventional and enzymatic extraction. The results showed that radiofrequency-assisted enzymatic extraction had the highest crude yields (26.55%) and anthocyanin content (50.87 mg cyanidin-3-O-glycoside equivalents/100 g). Fernández et al.[129] demonstrate the functionality of kinetics and mathematical modeling in the ultrasound-assisted extraction of anthocyanins from jaboticaba bark (*Myrciaria cauliflora*). Experimental designs based on multivariate analysis models are increasingly common, and the obtained results are primarily from laboratory-scale studies.[133] However, a question always arises as to whether extraction methods can be applied on a large scale using only residual biomass from the industry. According to Wathon et al.[130] who extracted anthocyanins from bark residues of *Aronia melanocarpa* (Michx.) after juice extraction, the system can be replicated on a large scale. However, Wu et al.[131] found that it is possible to extract 281.56 ± 3.02 mg/100 g of cyanidin-3-glucoside from the residues of *Euryale ferox* Salisb. Moraes et al.[62] investigated the extraction of anthocyanins from blackberries using microwave hydrodiffusion. They concluded that while the methodology can be operationalized on an industrial scale, the application costs are too high.

Yi et al.[3] demonstrated that solvent extraction of black rice resulted in an anthocyanin content of 266 mg/100 g of fresh sample. In contrast, Pedro, Granato, and Rosso[136] reported a yield of 117 mg/100 g, 79% lower than the result of Yi et al.[3] using enzymes. Furthermore, Jha et al.[137] reported even lower yields of 3.36 mg/100 g when extracting anthocyanins from black rice husks using ultrasound and microwave-assisted methods. Ju, Grego, and Zhang[138] highlighted the significance of comprehending the composition of plant structures before compound extraction, as cells have inherent resistance to various degradation mechanisms. In general, the approach for anthocyanin extraction methods presented in the work above makes it very difficult to select the best method when intending to apply to different matrix sources.

Main anthocyanin storage structures: plant organs

Anthocyanins are widely distributed in various plant parts, including fruits, roots, tubers, leaves, flowers, and seeds Figure 4a.[25] A thorough understanding of the anatomy of plant organs is critical for selecting appropriate extraction methods.[12]

Roots. Roots are classified as primary or secondary based on structural characteristics. The piliferous zone marks the beginning of adventitious root development and typically consists of a single layer of thin-walled cells. The innermost layer, called the endodermis, is specialized, while the vascular cylinder or stele can take the form of a radial protostele or a medullary protostele.[139] Anthocyanins are typically found in the cortical region, which is the outermost layer of the root. However, the concentration of anthocyanins can vary among different species and cultivars of tuber roots and in other parts of the root.

Tubers. Tubers originate from root systems, and specific cultivars exhibit a reddish or purple coloration due to the accumulation of anthocyanins in plant tissues. Examples of such tubers include purple sweet potato and purple yam.[113]

Leafs. The leaf is a fundamental plant organ consisting primarily of a protective epidermis, parenchymal mesophyll, and vascular system. Variations in epidermal cell structure, stomatal distribution, and epidermal trichomes are commonly observed among different leaf types. The mesophyll, which serves

as the main site of reserve storage in plants, can also store anthocyanins, with concentrations often higher in the mesophyll than in other leaf tissues.[139]

Flowers. The floral stem or pedicel exhibits distinct structures, such as bracts with a reduced calyx and a corolla that often resembles leaf-like structures. Various elements such as epidermal cells, epithelial and covering hairs, mesophyll cells, sebaceous glands, and crystals contribute to the intricate composition of flower parts. Anthocyanins are commonly found in flower petals and impart red, purple, or blue colors.[140]

Fruits. Fruits are diverse and can be categorized as dry or fleshy, each corresponding to a specific fruit type. These include berries, drupes, legumes, capsules, and achenes, each with unique characteristics such as seed dispersal mechanisms and pericarp composition. Anthocyanins are often concentrated in fleshy fruits' skin or outer layers, contributing to their coloration and antioxidant properties.[139–142]

Seeds possess a sclerenchymatous layer and exhibit characteristic variations in the number of cell layers, structure, arrangement, color, and content. The seed epidermis typically consists of thick-walled cells, often lignified, associated with storage tissues known as perisperm and endosperm. While anthocyanins are less abundant in seeds than other plant organs, they may still be in trace amounts in the seed coat or outer layers[141,143]

Anatomical structures and physical-chemical composition in anthocyanin extraction

Since plant structures are primarily composed of various polysaccharides, understanding their composition is crucial for selecting appropriate extraction methods for anthocyanins, as illustrated in Figure 4. Cellulose, which forms the main structure of plant cell walls, provides strength and rigidity and influences the efficiency of extraction techniques by affecting tissue permeability.[56] Hemicellulose Figure 5b. Another component of cell walls contributes to tissue flexibility and elasticity, potentially affecting the potential permeability of extraction solvents into plant tissues.[144] Lignin, while providing stiffness and resistance to degradation, can hinder the extraction process due to its dense structure, requiring specialized methods to overcome its barrier effects.[139] Starch, an energy reserve stored in plastids, can affect extraction efficiency depending on its distribution in plant tissues and accessibility to extraction solvents.[56] Pectens in the middle lamella and cell walls can influence extraction by affecting tissue consistency and adhesion, potentially altering the release of anthocyanins during the extraction process.[144] Therefore, consideration of the composition and distribution of these polysaccharides is essential to optimize anthocyanin extraction from plant matrices.

Criteria for decision-tree in the selection of the appropriate method for extracting anthocyanins

Despite the extensive evaluation of several innovative methods for anthocyanin extraction, selecting an appropriate method remains a significant challenge due predominantly to the specific properties of the raw material.[29,34,38,145] This challenge is compounded by a fundamental understanding of the plant matrix's morpho-anatomical characteristics and the operational principles underlying these methods.[18,26,114]

Description of the decision-tree for selecting anthocyanin extraction methods

The decision tree in Figure 5 is useful for selecting anthocyanin extraction methods that promote accurate, streamlined, and sustainable approaches.[6,33,98,130] Our proposed decision tree design facilitates selecting the most suitable method based on the specific characteristics of the chosen plant material.

The decision-tree, as shown in Figure 5 assists in selecting an anthocyanin extraction method based on the predominant plant matrix and its structural characteristics.[19,21,23,24,27,35,37,40,42,44,45,48,57,146] These characteristics include porosity (PRS), which indicates whether the structure allows easy passage

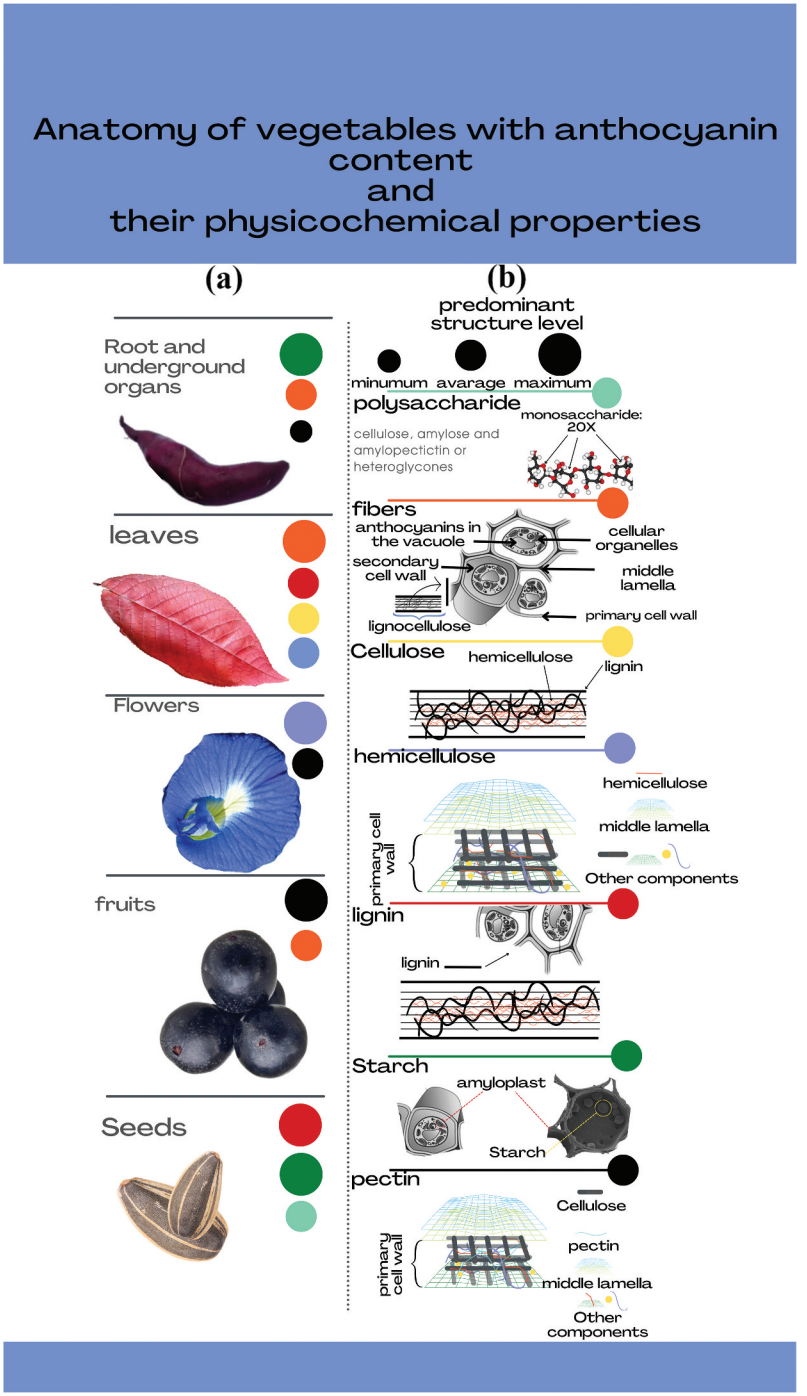

Figure 5. Accumulation of anthocyanins in the main plant organs (A) and their predominant physicochemical structures (B).

of water (hydrophilic) or not (hydrophobic), and polarity affinity (AFNT) in water (polar) or alcohols (nonpolar).[31,53,55,114] However, plant extract anthocyanins are sensitive to harsh conditions and may exhibit acidic or basic properties depending on their affinity in water (AFNT).[22,44] Acidic conditions are present when the pH value is below 4.5, while primary conditions occur above pH 4.5. Furthermore,

plant structures may have protective components such as coatings (MCC) in films or fibers.[41,55,87] Films and fibers can be disrupted through heat or high pressures that exceed their elastic limit.[6,36]

Vegetables possess diverse anatomical textures, which vary from species to species. These textures may be juicy, fleshy, or dry, sometimes featuring mixed structures.[15,28,43,102,119] These structures are composed of different polysaccharides, which determine the suitable disruption mechanism. Polysaccharides may be stored in different structural sections depending on the plant organ (ENE).[57]

After selecting a matrix for anthocyanin extraction, researchers must conduct fundamental analyses. Firstly, they must identify the type of plant structure they are working with, such as leaves, floral organs, roots or tubers, root system developments, or fruits.[44,49,57,76,113,132] Secondly, they should determine the characteristics of the plant structure, identifying the fraction or tissue where anthocyanins are concentrated. Researchers should analyze the components that make up the structure, particularly those that contribute to anthocyanin coloration, and understand their physical and chemical properties.[95] This information can be used to identify appropriate mechanisms for extraction, including pre-treatments, extraction techniques, and solvent selection. Finally, researchers can select one or more extraction methods that align with the principles established through their analysis.[143]

Decision-tree applicability criterion an example of its use

Our laboratory research focused on developing natural dyes from two distinct matrices: blackberry and purple sweet potato. We optimized the extraction conditions for these matrices, which typically take about six months. However, questions about the optimal extraction method for less-studied matrices are common in the research environment. This underscores the importance of a decision-tree. For instance, consider the decision logic applied to Blackberry. Blackberries are a type of drupe fruit with specific attributes, including porosity (PRS)-1, affinity (AFNT)-4, state of matter (STM)-5, coating component (CCM)-7, PS-10, anatomical texture (ATXT)-12, polysaccharide type (PSCT)-16, 18, and 19, and anatomical structure (ANE)-20, 23. To ensure the preservation of mesocarp anthocyanins while breaking down macro surface structures, a suitable method must be selected based on Figure 6 and the principles

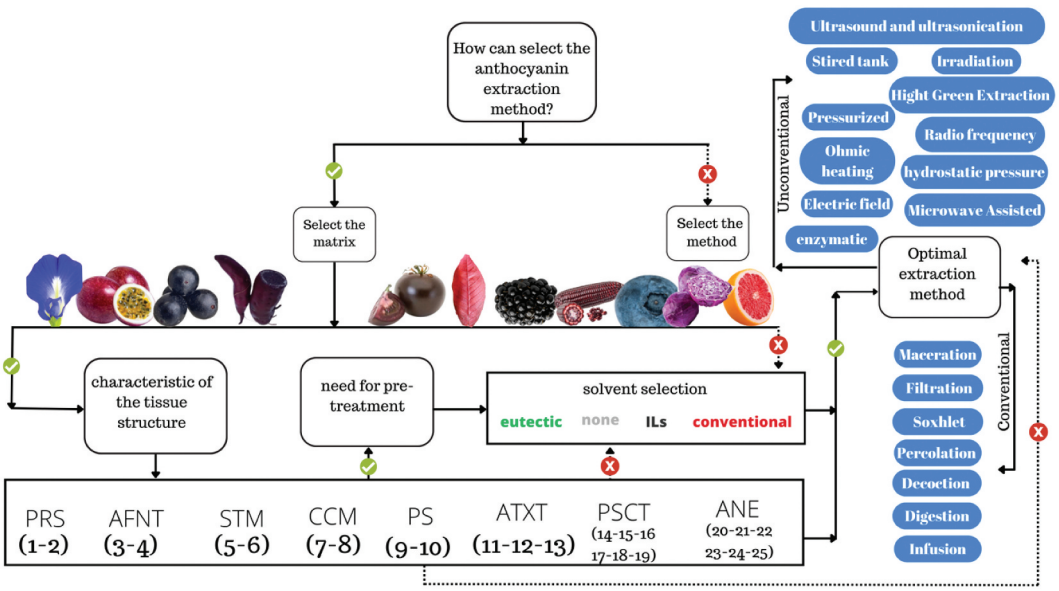

Figure 6. Decision- tree for selecting anthocyanin extraction methods based on intrinsic characteristics and response to solvents. **RS** – Porosity; **AFNT** – Affinity; **STM** – State of Matter; **CCM** – Coating Component; PS – Particle Size; **ATXT** – Anatomical Texture; **PSCT** –Polysaccharide Type; **ANE** – Anatomical Structure; (1) Hydrophilic; (2) Hydrophobic; (3) Water; (4) Alcohol; (5) Acid; (6)Basic; (7) Film; (8) fiber; (9) Micro; (10) Macro; (11) FLS – Fleshy; (12) JCY – Juicy; (13) DRY – Dry; (14) LGN – Lignin; (15) STC – Starch; (16) PCN – Pectin; (17) Gel; (18) CLS – Cellulose; (19) HCL – Hemicellulose; (20) MC – Mesocarp; (21) PR – Pericarp; (22) CPR – Receptacle; (23) EXP -Exocarp; (24)EC -Endocarp; (25) EP – Epidermis.

of anthocyanin extraction methods. Conventional methods, such as maceration, may be appropriate, but prolonged exposure could lead to degradation. Alternatively, traditional percolation could be used if blackberry is lyophilized. However, methods such as decoction, Soxhlet extraction, infusion, and digestion could be more practical due to the need for continuous heating.

Regarding emerging methods, microwave, ohmic heating, and high-voltage electric fields are considered unsuitable due to the heat they generate during operation. On the other hand, pressurized fluid, high hydrostatic pressure, and ultrasonication methods can be used without difficulty. The Purple Sweet Potato is a tuberous root-type matrix with specific attributes (PRS-1; AFNT-4; STM-6; CCM-8; PS-10; ATXT-13; PSCT-15; ANE-22). Conventional methods such as maceration, infusion, and digestion can be applied. Percolation is viable with pre-treatment like freeze-drying, although it may reduce the yield.

Conversely, methods like Soxhlet and decoction are considered unsuitable. Among the emerging techniques, microwave, enzymatic, ohmic heating, and high voltage electric fields (HVEF) are considered the most suitable. Conversely, high hydrostatic pressure and pressurized fluids can be used with matrix pre-treatment. However, tank agitation, radio frequency, irradiation, ultrasonic bath, and ultrasonication methods may need to be more efficient due to the relationship between their operating principle and the need to induce mass diffusion in the matrix.

Laboratory tests confirmed the effectiveness of these recommendations (data not shown). For blackberries, the best results were obtained using conventional extraction with 50% ethanol, regardless of the acidification level, at room temperature. In the case of purple sweet potatoes, the best results were obtained using 50% ethanol acidified to pH 2, especially when subjected to agitation in a shaking bath for one hour at 40°C (data not shown). The anthocyanin extraction behavior was similar across three different cultivars of both raw materials.

Conclusion

In conclusion, this study provides a comprehensive evaluation of various methodologies used for anthocyanin extraction, ranging from conventional techniques to more innovative, non-conventional methods. Each technique leverages fundamental chemical and physical principles, with their efficacy largely dependent on key variables such as solvent selection, temperature control, solvent-to-matrix ratio, contact time, and the pre-treatment of plant matrices. These factors significantly optimize the yield and purity of anthocyanins, influencing both laboratory research and industrial applications.

The morpho-anatomical structures of plant tissues – whether roots, tubers, leaves, flowers, fruits, or seeds – present unique challenges and opportunities for anthocyanin extraction. Each plant organ contains specialized cells and varying distributions of key substances like cellulose, hemicellulose, lignin, amylose, amylopectin, and pectin, which must be carefully considered when selecting an extraction method. The presence of these structural components can significantly impact the interaction between the extraction solvent and the matrix, as well as the efficiency of cell wall disruption, which is a critical step in the extraction process.

By implementing a decision-tree approach, this study offers a practical tool to help researchers and industry professionals systematically select the most appropriate extraction method based on the specific characteristics of the plant matrix. This framework considers the morpho-anatomical structure, extraction parameters, and solvent systems to streamline the decision-making process. As a result, this approach can optimize resource use, reduce experimental trial and error, and enhance the overall efficiency of anthocyanin extraction.

The decision-tree model was validated using blackberry and purple sweet potato matrices, demonstrating its applicability across different plant structures. The results show that this tool can not only improve the selection process but also significantly contribute to reducing time and time and resource investment. This methodology provides a valuable contribution to anthocyanin research by facilitating more more targeted and efficient extraction methods, which are critical for both scientific inquiry and commercial applications in the food and nutraceutical industries.

In the broader context, this study underscores the importance of considering plant matrix variability and extraction method characteristics in anthocyanin research. It also opens avenues for further development of decision-support tools that can be adapted to other bioactive compound extractions, enhancing productivity in natural product research. Ultimately, this decision-tree framework represents a significant step forward in optimizing extraction protocols and contributing to more sustainable and efficient food science and technology practices.

Advancements and certain limitations

Scalability: Current research has focused mainly on laboratory-scale extraction methods, leaving their industrial applicability largely unexplored. Environmental Concerns: The reliance on organic solvents calls for the development of greener and more sustainable extraction methods.Matrix-Specific Optimization: Variations in plant cell structures necessitate further research on a broader range of plant matrices to optimize extraction across diverse sources.

Future research

Scaling up extraction techniques for industrial applications. Developing sustainable, environmentally friendly extraction processes. Exploring underutilized plant matrices to expand the potential for anthocyanin extraction.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Author contributions

GB and CR conceptualized the work and were responsible for the primary investigation. FTSS, RT, and JGW collected data and generated visualizations (figures and tables) used in the manuscript. All authors (GB, FT, RT, JGW, MV, CR, AU, and LN) contributed to the first draft and edited the manuscript.

Ethical statements

This work did not include any human subjects or animal experiments.

References

[1] Sánchez-López, Á. M.; Bahaji, A.; Gámez-Arcas, S.; De Diego, N.; Vrobel, O.; Tarkowski, P.; Baroja-Fernández, E.; Muñoz, F. J.; Almagro, G.; Seguí-Simarro, J. M., et al. PGI1-Mediated Vascular Oxidative Pentose Phosphate Pathway Modulates Photosynthesis via Long-Distance Cytokinin Signaling. *Plant. Physiol. Biochem.* **2024**, *209*, 108520. DOI: 10.1016/j.plaphy.2024.108520.

[2] Quan, W.; He, W.; Lu, M.; Yuan, B.; Zeng, M.; Gao, D.; Qin, F.; Chen, J.; He, Z. Anthocyanin Composition and Storage Degradation Kinetics of Anthocyanins-Based Natural Food Colourant from Purple-Fleshed Sweet Potato. *Int. J. Food Sci. Technol.* **2019**, *54*(8), 2529–2539. DOI: 10.1111/ijfs.14163.

[3] Yin, M.; Xie, J. C.; Xie, M. L.; Yang, X. E. Extration, Identification and Stability Ananlysis of Anthocyanins from Organic Guizhou Blueberries in China. *Food Sci. Technol.* **2021**, *42*, 42. DOI: 10.1590/fst.33520.
[4] Murthy, H. N.; Joseph, K. S.; Paek, K. Y.; Park, S. Y. Anthocyanin Production from Plant Cell and Organ Cultures *In Vitro*. *Plants*. **2023**, *13*(1), 117. DOI: 10.3390/plants13010117.
[5] Antela, K. U.; Sáez-Hernández, R.; Morales-Rubio, Á.; Cervera, M. L.; Luque, M. J. Smartphone-Based Procedure to Determine Content of Single Synthetic Dyes in Food Using the Arata-Possetto Extraction Method. *Talanta*. **2024**, *270*, 125537. DOI: 10.1016/j.talanta.2023.125537.
[6] Adeel, S.; Azeem, M.; Habib, N.; Hussaan, M.; Kiran, A.; Haji, A.; Haddar, W. Sustainable Application of Microwave-Assisted Extracted Tea-Based Tannin Natural Dye for Chemical and Bio-Mordanted Wool Fabric. *J. Nat. Fiber* **2023**, *20*(1), 1–9. DOI: 10.1080/15440478.2022.2136322.
[7] Li, X.; Chen, L.; Gao, Y.; Zhang, Q.; Chang, A. K.; Yang, Z.; Bi, X. Black Raspberry Anthocyanins Increased the Antiproliferative Effects of 5-Fluorouracil and Celecoxib in Colorectal Cancer Cells and Mouse Model. *J. Funct. Foods*. **2021**, *87*, 104801. DOI: 10.1016/j.jff.2021.104801.
[8] Kanpipit, N.; Nualkaew, N.; Kiatponglarp, W.; Priprem, A.; Thapphasaraphong, S. Development of a Sericin Hydrogel to Deliver Anthocyanins from Purple Waxy Corn Cob (*Zea Mays* L.) Extract and in vitro Evaluation of Anti-Inflammatory Effects. *Pharmaceutics* **2022**, *14*(3), 577. DOI: 10.3390/pharmaceutics14030577.
[9] Filaferro, M.; Codeluppi, A.; Brighenti, V.; Cimurri, F.; González-Paramás, A. M.; Santos-Buelga, C.; Bertelli, D.; Pellati, F.; Vitale, G. Disclosing the Antioxidant and Neuroprotective Activity of an Anthocyanin-Rich Extract from Sweet Cherry (*Prunus Avium* L.) Using in vitro and in vivo Models. *Antioxidants* **2022**, *11*(2), 211. DOI: 10.3390/antiox11020211.
[10] Zhang, M.; Hou, X. D.; Liu, W.; Wang, L.; Jiang, M. F.; Hou, J.; Tang, H.; Ge, G. B. Uncovering the Anti-Obesity Constituents in *Ginkgo Biloba* Extract and Deciphering Their Synergistic Effects. *Fitoterapia*. **2023**, *171*, 105669. DOI: 10.1016/j.fitote.2023.105669.
[11] Oliveira, A. A.; Torres, A. G.; Perrone, D.; Monteiro, M. Effect of High Hydrostatic Pressure Processing on the Anthocyanins Content, Antioxidant Activity, Sensorial Acceptance and Stability of Jussara (*Euterpe edulis*) Juice. *Foods* **2021**, *10*(10), 2246. DOI: 10.3390/foods10102246.
[12] Albuquerque, B. R.; Pinela, J.; Barros, L.; Oliveira, M. B. P. P.; Ferreira, I. C. F. R. Anthocyanin-Rich Extract of Jabuticaba Epicarp as a Natural Colorant: Optimization of Heat and Ultrasound-Assisted Extractions and Application in a Bakery Product. *Food Chem.* **2020**, *316*, 126364. DOI: 10.1016/j.foodchem.2020.126364.
[13] Hou, F.; Song, S.; Yang, S.; Wang, Y.; Jia, F.; Wang, W. Study on the Optimization, Extraction Kinetics, and Thermodynamics of the Ultrasound-Assisted Enzymatic Extraction of *Tremella Fuciformis* Polysaccharides. *Foods* **2024**, *13*(9), 1408. DOI: 10.3390/foods13091408.
[14] Boulet, J. C.; Abi-Habib, E.; Carrillo, S.; Roi, S.; Veran, F.; Verbaere, A.; Meudec, E.; Rattier, A.; Ducasse, M. A.; Jørgensen, B., et al. Focus on the Relationships Between the Cell Wall Composition in the Extraction of Anthocyanins and Tannins from Grape Berries. *Food Chem.* **2023**, *406*, 135023. DOI: 10.1016/j.foodchem.2022.135023.
[15] Page, M. J.; McKenzie, J.; Bossuyt, E.; Boutron, P. M.; Hoffmann, I.; Mulrow, T. C.; Shamseer, C. D.; Tetzlaff, L.; Akl, J. M.; Brennan, E. A., et al. The PRISMA 2020 Statement: an Updated Guideline for Reporting Systematic Reviews. *BMJ* **2021**, n71. DOI: 10.1136/bmj.n71.
[16] Wang, J.; Liu, Z.; Li, X.; Liu, G.; Zhao, J. Elucidating Structure of Pectin in Ramie Fiber to Customize Enzyme Cocktail for High-Efficiency Enzymatic Degumming. *Carbohydr. Polym*. **2023**, *314*, 120954. DOI: 10.1016/j.carbpol.2023.120954.
[17] Akogou, F. U. G.; Kayodé, A. P. P.; Besten, H. M. W.; Linnemann, A. R. Extraction Methods and Food Uses of a Natural Red Colorant from Dye Sorghum. *J. Sci. Food Agric*. **2018**, *98*(1), 361–368. DOI: 10.1002/jsfa.8479.
[18] López, C. J.; Caleja, C.; Prieto, M. A.; Barreiro, M. F.; Barros, L.; Ferreira, I. C. F. R. Optimization and Comparison of Heat and Ultrasound Assisted Extraction Techniques to Obtain Anthocyanin Compounds from *Arbutus Unedo* L. Fruits. *Food Chem.* **2018**, *264*, 81–91. DOI: 10.1016/j.foodchem.2018.04.103.
[19] Wang, H.; Sun, S.; Zhou, Z.; Qiu, Z.; Cui, X. Rapid Analysis of Anthocyanin and Its Structural Modifications in Fresh Tomato Fruit. *Food Chem*. **2020**, *333*, 35. DOI: 10.1016/j.foodchem.2020.127439.
[20] Xue, H. K.; Tan, J. Q.; Li, Q.; Tang, J.; Cai, X. Ultrasound-Assisted Enzymatic Extraction of Anthocyanins from Raspberry Wine Residues: Process Optimization, Isolation, Purification, and Bioactivity Determination. *Food Analytical Methods* **2021**, *14*(7), 1369–1386. DOI: 10.1007/s12161-021-01976-8.
[21] Zhang, L.; Gongjian, F.; Muhammad, A. K.; Zheng, Y.; Beta, T. Ultrasonic-Assisted Enzymatic Extraction and Identification of Anthocyanin Components from Mulberry Wine Residues. *Food Chem.* **2020**, *323*(1), 126714. DOI: 10.1016/j.foodchem.2020.126714.
[22] Yi, J.; Qiu, M.; Zhu, Z.; Dong, X.; Decker, E. A.; McClements, D. J. Robust and Recyclable Magnetic Nanobiocatalysts for Extraction of Anthocyanin from Black Rice. *Food Chem*. **2021**, *364*, 130447. DOI: 10.1016/j.foodchem.2021.130447.
[23] Grillo, G.; Gunjevic, V.; Radosevic, K.; Redovnikovic, I. R.; Cravotto, G. Deep Eutectic Solvents and Nonconventional Technologies for Blue-Berry-Peel Extraction: Kinetics, Anthocyanin Stability, and Antiproliferative Activity. *Antioxidants* **2020**, *9*(11), 1069. DOI: 10.3390/antiox9111069.

[24] Liu, C.; Xue, H.; Shen, L.; Liu, C.; Zheng, X.; Shi, J.; Xue, S. Improvement of Anthocyanins Rate of Blueberry Powder Under Variable Power of Microwave Extraction. *Sep. Purif. Technol.* **2019**, *226*, 286–298. DOI: 10.1016/j.seppur.2019.05.096.
[25] Kumar, M.; Dahuja, A.; Sachdev, A.; Kaur, C.; Varghese, E.; Saha, S.; Sairam, K. Evaluation of Enzyme and Microwave-Assisted Conditions on Extraction of Anthocyanins and Total Phenolics from Black Soybean (*Glycine Max* L.) Seed Coat. *Int. J. Biol. Macromol.* **2019**, *135*, 1070–1081. DOI: 10.1016/j.ijbiomac.2019.06.034.
[26] Fernandez-Aulis, F.; Hernandez-Vasquez, L.; Aguilar-Osorio, G.; Arrieta-Baez, D.; Navarro-Ocana, A. Extraction and Identification of Anthocyanins in Corn Cob and Corn Husk from Cacahuacintle Maize. *J. Food Sci.* **2019**, *84* (5), 954–962. DOI: 10.1111/1750-3841.14589.
[27] Leichtweis, M. G.; Pereira, C.; Prieto, M. A.; Barreiro, M. F.; Baraldi, I. J.; Barros, L.; Ferreira, I. C. F. R. Ultrasound as a Rapid and Low-Cost Extraction Procedure to Obtain Anthocyanin-Based Colorants from *Prunus Spinosa* L. Fruit Epicarp: Comparative Study with Conventional Heat-Based Extraction. *Molecules* **2019**, *24*(3), 573. DOI: 10.3390/molecules24030573.
[28] Meregalli, M. M. ;.; Puton, B. M. S.; Camera, F. D.; Amaral, A. U.; Zeni, J.; Cansian, R. L.; Mignoni, M. L.; Backes, G. T. Conventional and Ultrasound-Assisted Methods for Extraction of Bioactive Compounds from Red Araçá Peel (*Psidium Cattleianum* Sabine). *Arabian J. Chem.* **2020**, *13*(6), 5800–58009. DOI: 10.1016/j.arabjc.2020.04.017.
[29] Muangrat, R.; Pongsirikul, I.; Blanco, P. H. Ultrasound Assisted Extraction of Anthocyanins and Total Phenolic Compounds from Dried Cob of Purple Waxy Corn Using Response Surface Methodology. *Food Process. And Preserv.* **2018**, *42*(2), e13447. DOI: 10.1111/jfpp.13447.
[30] Rodrigues, L. M.; Romanini, E. B.; Silva, E.; Pilau, E. J.; Costa, S. C. D.; Madrona, G. S. Camu-Camu Bioactive Compounds Extraction by Ecofriendly Sequential Processes (Ultrasound Assisted Extraction and Reverse Osmosis). *Ultrason. Sonochem.* **2020**, *64*, 105017. DOI: 10.1016/j.ultsonch.2020.105017.
[31] Hashemi-Gahruie, H.; Parastouei, K.; Mokhtarian, M.; Rostami, H.; Niakousari, M.; Mohsenpour, Z. Application of Innovative Processing Methods for the Extraction of Bioactive Compounds from Saffron (*Crocus sativus*) Petals. *J. Appl. Res. On Med. And Aromatic Plants.* **2020**, *19*, 100264. DOI: 10.1016/j.jarmap.2020.100264.
[32] Kutlu, N.; Isci, A.; Sakiyan, O.; Yilmaz, A. E. Extraction of Phenolic Compounds from Cornelian Cherry (*Cornus Mas* L.) Using Microwave and Ohmic Heating Assisted Microwave Methods. *Food Bioprocess Technol.* **2021**, *14* (4), 650–664. DOI: 10.1007/s11947-021-02588-0.
[33] Ferreira, M. V. S.; Cappato, L. P.; Silva, R.; Rocha, R. S.; Guimaraes, J. T.; Balthazar, C. F.; Esmerino, E. A.; Freitas, M. Q.; Rodrigues, F. N.; Granato, D., et al. Ohmic Heating for Processing of Whey-Raspberry Flavored Beverage. *Food Chem.* **2019**, *297*, 125018. DOI: 10.1016/j.foodchem.2019.125018.
[34] Pereira, R. N.; Coelho, M. I.; Genisheva, Z.; Fernandes, J. M.; Vicente, A. A.; Pintado, M. E.; Teixeira, J. A. Using Ohmic Heating Effect on Grape Skins as a Pretreatment for Anthocyanins Extraction. *Food Bioprod. Process.* **2020**, *124*, 320–328. DOI: 10.1016/j.fbp.2020.09.009.
[35] Loncaric, A.; Celeiro, M.; Jozinovic, A.; Jelinic, J.; Kovac, T.; Jokic, S.; Babic, J.; Moslavac, T.; Zavadlav, S.; Lores, M. Green Extraction Methods for Extraction of Polyphenolic Compounds from Blueberry Pomace. *Foods.* **2020**, *9*(11), 1521. DOI: 10.3390/foods9111521.
[36] He, Y.; Wen, L. K.; Du, Y. J.; Wang, Z. T.; Lin, K. Comparison of Different Extraction Methods of Antioxidant Anthocyanins in Zuoyouhong Vitis Amurensis. *Oxid. Commun.* **2016**, *39*(4–I), 2928–2937.
[37] Rocha, C. T.; Silva, E. C. P.; Stringheta, P. C.; Paula, D. A.; Fernandes, S. A.; Pinto, M. R. M. R.; Ramos, A. M. Gamma Irradiation and Pasteurization on Anthocyanin Stability and Antioxidant Capacity of Jussara Pulp (*Euterpe edulis*) During Storage. *Ciência Rural* **2023**, *53*(6). DOI: 10.1590/0103-8478cr20210912.
[38] Ardestani, S. B.; Sahari, M. A.; Barzegar, M. Effect of Extraction and Processing Conditions on Anthocyanins of Barberry. *J. Food Process. And Preserv.* **2016**, *40*(6), 1407–1420. DOI: 10.1111/jfpp.12726.
[39] Sabino, L. B. D.; Alves, E. G.; Fernandes, F. A. N.; Brito, E. S. D.; Silva, I. J. Optimization of Pressurized Liquid Extraction and Ultrasound Methods for Recovery of Anthocyanins Present in Jambolan Fruit (*Syzygium Cumini* L.). *Food Bioprod. Process.* **2021**, *127*, 77–89. DOI: 10.1016/j.fbp.2021.02.012.
[40] Maran, J. P.; Priya, B.; Manikandan, S. Modeling and Optimization of Supercritical Fluid Extraction of Anthocyanin and Phenolic Compounds from *Syzygium Cumini* Fruit Pulp. *J. Food Sci. Technol.* **2014**, *51*(9), 1938–1946. DOI: 10.1007/s13197-013-1237-y.
[41] Rohilla, S.; Chutia, H.; Marboh, V.; Mahanta, C. L. Ultrasound and Supercritical Fluid Extraction of Phytochemicals from Purple Tamarillo: Optimization, Comparison, Kinetics, and Thermodynamics Studies. *Appl. Food Res.* **2022**, *2*(2), 100210. DOI: 10.1016/j.afres.2022.100210.
[42] Saldaña, M. D.; Martine, E. R.; Sekhon, J. K.; Vo, H. The Effect of Different Pressurized Fluids on the Extraction of Anthocyanins and Total Phenolics from Cranberry Pomace. *J. Supercrit. Fluids* **2021**, *175*, 105279. DOI: 10.1016/j.supflu.2021.105279.
[43] Teixeira, R. F.; Benvenutti, L.; Burin, V. M.; Gomes, T. M.; Ferreira, S. R. S.; Zielinski, A. A. F. An Eco-Friendly Pressure Liquid Extraction Method to Recover Anthocyanins from Broken Black Bean Hulls. *Innovative Food Sci. & Emerging Technol.* **2021**, *67*, 102587. DOI: 10.1016/j.ifset.2020.102587.

[44] Galvão, A. C.; Souza, P. P.; Robazza, W. S.; França, C. A. L. Capacity of Solutions Involving Organic Acids in the Extraction of the Anthocyanins Present in Jabuticaba Skins (*Myrciaria cauliflora*) and Red Cabbage Leaves (*Brassica oleracea*). *J. Food Sci.Amp; Technol.* **2020**, *57*(11), 3995–4002. DOI: 10.1007/s13197-020-04430-5.
[45] Zhang, W.; Shen, Y.; Li, Z.; Xie, X.; Gong, E. S.; Tian, J.; Si, X.; Wang, Y.; Gao, N.; Shu, C., et al. Effects of High Hydrostatic Pressure and Thermal Processing on Anthocyanin Content, Polyphenol Oxidase and B-Glucosidase Activities, Color, and Antioxidant Activities of Blueberry (*Vaccinium* Spp.) Puree. *Food Chem.* **2021**, *342*, 128564. DOI: 10.1016/j.foodchem.2020.128564.
[46] Jiang, Y.; Ding, Y.; Wang, D.; Deng, Y.; Zhao, Y. Radio Frequency-Assisted Enzymatic Extraction of Anthocyanins from *Akebia Trifoliata* (Thunb.) Koidz. Flowers: Process Optimization, Structure, and Bioactivity Determination. *Ind. Crops Products*. **2020**, *149*, 112327. DOI: 10.1016/j.indcrop.2020.112327.
[47] Pappas, V. M.; Athanasiadis, V.; Palaiogiannis, D.; Poulianiti, K.; Bozinou, E.; Lalas, S. I.; Makris, D. P. Pressurized Liquid Extraction of Polyphenols and Anthocyanins from Saffron Processing Waste with Aqueous Organic Acid Solutions: Comparison with Stirred-Tank and Ultrasound-Assisted Techniques. *Sustainability*. **2021**, *13*(22), 12578. DOI: 10.3390/su132212578.
[48] Mourtzinos, I.; Prodromidis, P.; Grigorakis, S.; Makris, D. P.; Biliaderis, C. G.; Moschakis, T. Natural Food Colourants Derived from Onion Wastes: Application in a Yoghurt Product. *Electrophoresis* **2018**, *39*(15), 1975–1983. DOI: 10.1002/elps.201800073.
[49] Andrade, T. A.; Hamerski, F.; López-Fetzer, D. E.; Roda-Serrat, M. C.; Corazza, M. L.; Norddahl, B.; Errico, M. Ultrasound-Assisted Pressurized Liquid Extraction of Anthocyanins from *Aronia Melanocarpa* Pomace. *Sep. Purif. Technol.* **2021**, *276*, 119290. DOI: 10.1016/j.seppur.2021.119290.
[50] Panic, M.; Gunjevic, V.; Cravotto, G.; Redovnikovic, I. R. Enabling Technologies for the Extraction of Grape-Pomace Anthocyanins Using Natural Deep Eutectic Solvents in Up-To-Half-Litre Batches Extraction of Grape-Pomace Anthocyanins Using NADES. *Food Chem.* **2019**, *300*, 125185. DOI: 10.1016/j.foodchem.2019.125185.
[51] Heinonen, J.; Farahmandazad, H.; Vuorinen, A.; Kallio, H.; Yang, B. R.; Sainio, T. Extraction and Purification of Anthocyanins from Purple-Fleshed Potato. *Food Bioprod. Process*. **2016**, *99*, 136–146. DOI: 10.1016/j.fbp.2016.05.004.
[52] Dia, V. P.; Wang, Z. Q.; West, M.; Singh, V.; West, L.; Mejia, E. G. Processing Method and Corn Cultivar Affected Anthocyanin Concentration from Dried Distillers Grains with Solubles. *J. Agric. Food Chem.* **2015**, *63*(12), 3205–3218. DOI: 10.1021/acs.jafc.5b00128.
[53] Tuhanioglu, A.; Ubeyitogullari, A. High-Value Lipids and Phenolic Compounds from Sorghum Bran are E via a Sequential Supercritical Carbon Dioxide Approach. *ACS Food Sci. & Technol. 2* **2022**, *2*(12), 1879–1887. DOI: 10.1021/acsfoodscitech.2c00266.
[54] Supanivatin, P.; Thipayarat, A.; Siriwattanayotin, S.; Ekkaphan, P.; Deepatana, A.; Wongwiwat, J. A Comparative Analysis of Phenolic Content, Antioxidant Activity, Antimicrobial Activity, and Chemical Profile of *Coffea Robusta* Extracts Using Subcritical Fluid Extraction and Supercritical Carbon Dioxide Extraction. *Foods* **2023**, *12*(18), 3443. DOI: 10.3390/foods12183443.
[55] Szot, I.; Łysiak, G. P.; Sosnowska, B.; Chojdak-Łukasiewicz, J. Health-Promoting Properties of Anthocyanins from Cornelian Cherry (*Cornus Mas* L.) Fruits. *Molecules* **2024**, *29*(2), 449. DOI: 10.3390/molecules29020449.
[56] Rizwan, M.; Gilani, S. R.; Durrani, A. I.; Naseem, S. Low Temperature Green Extraction of Acer Platanoides Cellulose Using Nitrogen Protected Microwave Assisted Extraction (NPMAE) Technique. *Carbohydr. Polym.* **2021**, *272*, 118465. DOI: 10.1016/j.carbpol.2021.118465.
[57] Lotfi, L.; Kalbasi-Ashtari, A.; Hamedi, M.; Ghorbani, F. Effects of Enzymatic Extraction on Anthocyanins Yield of Saffron Tepals (*Crocos sativus*) Along with Its Color Properties and Structural Stability. *J. Food Drug. Analyses* **2015**, *23*(2), 210–218. DOI: 10.1016/j.jfda.2014.10.011.
[58] Vardakas, A. T.; Shikov, V. T.; Dinkova, R. H.; Mihalev, K. M. Optimisation of the Enzyme-Assisted Extraction of Polyphenols from Saffron (*Crocus Sativus* L.) Petals [Pdf]. *Acta scientiarum. Polonorum Technol. Aliment.* **2021**, *20*(3), 359–367. DOI: 10.17306/J.AFS.0954.
[59] Tagami, T. Structural Insights into Starch-Metabolizing Enzymes and Their Applications. *Biosci. Biotechnol. Biochem.* **2024**, *88*(8), 864–871. DOI: 10.1093/bbb/zbae069.
[60] Meini, M. R.; Cabezudo, I.; Boschetti, C. E.; Romanini, D. Recovery of Phenolic Antioxidants from Syrah Grape Pomace Through the Optimization of an Enzymatic Extraction Process. *Food Chem.* **2019**, *283*, 257–264. DOI: 10.1016/j.foodchem.2019.01.037.
[61] Tan, J.; Xue, H.; Li, Q.; Tang, J. T. Ultrasound-Assisted Enzymatic Extraction of Anthocyanins from Grape Skins: Optimization, Identification, and Antitumor Activity. *J. Food Sci.* **2020**, *85*(11), 3731–3744. DOI: 10.1111/1750-3841.15497.
[62] Moraes, D. P.; Lozano-Sa´nchez, J.; Machado, M. L.; Vizzotto, M.; Lazzaretti, M.; Leyva-Jimenez, F. J. J.; Silveira, T.; Ries, E. F.; Barcia, M. Characterization of a New Blackberry Cultivar Brs Xingu: Chemical

Composition, Phenolic Compounds, and Antioxidant Capacity in vitro and in vivo. *Food Chem.* **2020**, *322*, 126783. DOI: 10.1016/j.Foodchem.2020.126783.

[63] Cassol, L.; Rodrigues, E.; Noreña, C. P. Z. Extracting Phenolic Compounds from *Hibiscus Sabdariffa* L. Calyx Using Microwave Assisted Extraction. *Ind. Crops Products* **2018**, *133*, 168–177. DOI: 10.1016/j.indcrop.2019.03.023.

[64] Yang, W.; Chen, Y.; Li, K.; Jin, W.; Zhang, Y.; Liu, Y.; Ren, Z.; Li, Y.; Chen, P. Optimization of Microwave-Expanding Pretreatment and Microwave-Assisted Extraction of Hemicellulose from Bagasse Cells with the Exploration of the Extracting Mechanism. *Carbohydr. Polym.* **2024**, *330*, 121814. DOI: 10.1016/j.carbpol.2024.121814.

[65] Araujo, A. R. T. S.; Périno, S.; Fernandez, X.; Cunha, C.; Rodrigues, M.; Ribeiro, M. P.; Jordao, L.; Silva, L. A.; Rodilla, J.; Coutinho, P., et al. Solvent-Free Microwave Extraction of *Thymus Mastichina* Essential Oil: Influence on Their Chemical Composition and on the Antioxidant and Antimicrobial Activities. *Pharmaceuticals* **2021**, *14* (8), 709. DOI: 10.3390/ph14080709.

[66] Bagade, S. B.; Patil, M. Recent Advances in Microwave Assisted Extraction of Bioactive Compounds from Complex Herbal Samples: A Review. *Crit. Rev. Anal. Chem.* **2021**, *51*(2), 138–149. DOI: 10.1080/10408347.2019.1686966.

[67] Skenderidis, P.; Leontopoulos, S.; Petrotos, K.; Giavasis, I. Optimization of Vacuum Microwave-Assisted Extraction of Pomegranate Fruits Peels by the Evaluation of Extracts' Phenolic Content and Antioxidant Activity. *Foods* **2020**, *9*(11), 1655. DOI: 10.3390/foods9111655.

[68] Oualcadi, Y.; Sebban, M. F.; Berrekhis, F. Improvement of Microwave-Assisted Soxhlet Extraction of Bioactive Compounds Applied to Pomegranate Peels. *J. Food Process. Preserv* **2020**, *44*(5), e14409. DOI: 10.1111/jfpp.14409.

[69] Chamutpong, S.; Chen, C. J.; Chaiprateep, E. O. Optimization Ultrasonic-Microwave-Assisted Extraction of Phenolic Compounds from *Clinacanthus Nutans* Using Response Surface Methodology. *J. Adv. Pharm. Technol. Res.* **2021**, *12*(2), 190–195. DOI: 10.4103/japtr.JAPTR_344_20.

[70] Othman, S. N. S.; Ana, N. M.; Ku, H. K. H. Extraction of Polyphenols from *Clinacanthus Nutans* Lindau (*C. nutans*) by Vacuum Solvent-Free Microwave Extraction (V-SFME). *Chem. Eng. Commun.* **2021**, *208*(5), 727–740. DOI: 10.1080/00986445.2020.1727452.

[71] Tena, N.; Asuero, A. G. Up-To-Date Analysis of the Extraction Methods for Anthocyanins: Principles of the Techniques, Optimization, Technical Progress, and Industrial Application. *Antioxidants*. **2022**, *11*(2), 286. DOI: 10.3390/antiox11020286.

[72] Moraes, D. P.; Machado, M. L.; Farias, C. A. A.; Barin, J. S.; Zabot, G. L.; Lozano-Sánchez, J.; Ferreira, D. F.; Vizzotto, M.; Leyva, J.; Silveira, T. Effect of Microwave Hydrodiffusion and Gravity on the Extraction of Phenolic Compounds and Antioxidant Properties of Blackberries (*Rubus* Spp.): Scale-Up Extraction. *Food Bioprocess Technol.* **2022**, *13*(12), 2200–2216. DOI: 10.1007/s11947-020-02557-z.

[73] Mokgehle, T. M.; Madala, N.; Gitari, W. M.; Tavengwa, N. T. Effect of Microwave-Assisted Aqueous Two-Phase Extraction of A-Solanine from *S. Retroflexum* and Analysis on UHPLC-qTOF-MS. *Food Analytical Methods* **2022**, *15*(5), 1256–1268. DOI: 10.1007/s12161-021-02224-9.

[74] Teixeira, B. A.; Gutiérrez, E. A.; de Souza, M. S. D. S.; Rigolon, T. C. B.; Martins, E.; Pessoa, F. L. P.; Vidigal, M. C. T. R.; Stringheta, P. C. Design, Optimization, and Modeling Study of Ultrasound-Assisted Extraction of Bioactive Compounds from Purple-Fleshed Sweet Potatoes. *Foods (Basel, Switz.)* **2024**, *13*(10), 1497. DOI: 10.3390/foods13101497.

[75] Ivane, N. M. A.; Wang, W.; Ma, Q.; Wang, J.; Sun, J. Harnessing the Health Benefits of Purple and Yellow-Fleshed Sweet Potatoes: Phytochemical Composition, Stabilization Methods, and Industrial Utilization—A Review. *Food Chem.: 10* **2024**, *23*, 101462. DOI: 10.1016/j.fochx.2024.101462.

[76] Chakraborty, S.; Uppaluri, R.; Das, C. Optimization of Ultrasound-Assisted Extraction (UAE) Process for the Recovery of Bioactive Compounds from Bitter Gourd Using Response Surface Methodology (RSM). *Food Bioprod. Process.* **2020**, *120*, 114–122. DOI: 10.1016/j.fbp.2020.01.003.

[77] Mazza, K. E. L.; Santiago, M.; Nascimento, L. S. M. D.; Godoy, R. L. O.; Souza, E. F.; Brigida, A. I. S.; Borguini, R. G.; Tonon, R. V. Syrah Grape Skin Valorization Using Ultrasound-Assisted Extraction: Phenolic Compounds Recovery, Antioxidant Capacity and Phenolic Profile. *Int. J. Food Sci. Technol.* **2019**, *54*(3), 641–650. DOI: 10.1111/ijfs.13883.

[78] Peredo, A. V. G.; Vazquez-Espinosa, M.; Espada-Bellido, E.; Ferreiro-Gonzalez, M.; Amores-Arrocha, A.; Palma, M.; Barbero, G. F.; Jimenez-Cantizano, A. Alternative Ultrasound-Assisted Method for the Extraction of the Bioactive Compounds Present in Myrtle (*Myrtus Communis* L.). *Molecules*. **2019**, *24*(5), 882. DOI: 10.3390/molecules24050882.

[79] Arruda, T. R.; Vieira, P.; Silva, B. M.; Freitas, T. D.; Amaral, A. J. B.; Vieira, E. N. R.; Leite, J. B. R. C. What are the Prospects for Ultrasound Technology in Food Processing? An Update on the Main Effects on Different Food Matrices, Drawbacks, and Applications. *J. Food Process Eng.* **2021**, *44*(11), e13872. DOI: 10.1111/jfpe.13872.

[80] Wan, J.; Coventry, J.; Swiergon, P.; Sanguansri, P.; Versteeg, C. Advances in Innovative Processing Technologies for Microbial Inactivation and Enhancement of Food Safety – Pulsed Electric Field and Low-Temperature Plasma. *Trends Food Sci. & Technol.* **2009**, *20*(9). DOI: 10.1016/j.tifs.2009.01.050.

[81] Loypimai, P.; Moongngarm, A.; Chottanom, P.; Moontree, T. Ohmic Heating-Assisted Extraction of Anthocyanins from Black Rice Bran to Prepare a Natural Food Colourant. *Innovative Food Sci. & Emerging Technol.* **2015**, *27*, 102–110. DOI: 10.1016/j.ifset.2014.12.009.
[82] Buniowska, M.; Carbonell-Capella, J. M.; Frigola, A.; Esteve, M. J. Bioaccessibility of Bioactive Compounds After Non-Thermal Processing of an Exotic Fruit Juice Blend Sweetened with *Stevia Rebaudiana*. *Food Chem.* **2017**, *221*, 1834–1842. DOI: 10.1016/j.foodchem.2016.10.093.
[83] Jafari, F.; Saien, J. Experimental and Model Study for Liquid–Liquid Extraction of Conductive Nanofluid Drops Under Low Voltage Pulsed Electric Fields. *Chem. Eng. Sci.* **2022**, *258*, 117762. DOI: 10.1016/j.ces.2022.117762.
[84] Peiro, S.; Luengo, E.; Segovia, F.; Raso, J.; Almajano, M. P. Improving Polyphenol Extraction from Lemon Residues by Pulsed Electric Fields. *Waste Biomass Valorization* **2019**, *10*(4), 889–897. DOI: 10.1007/s12649-017-0116-6.
[85] Naliyadhara, N.; Kumar, A.; Girisa, S.; Daimary, U. D.; Hegde, M.; Kunnumakkara, A. B. Pulsed Electric Field (PEF): Avant-Garde Extraction Escalation Technology in Food Industry. *Trends Food Sci. & Technol.* **2022**, *122*, 238–255. DOI: 10.1016/j.tifs.2022.02.019.
[86] Dalvi-Isfahan, M.; Hamdami, N.; Le-Bail, A.; Xanthakis, E. The Principles of High Voltage Electric Field and Its Application in Food Processing: A Review. *Food Res. Int.* **2016**, *89*, 48–62. DOI: 10.1016/j.foodres.2016.09.002.
[87] Bian, M.; Tang, X.; Xu, Z.; Hou, Z.; Yuan, Z.; Liu, K. A Novel Monitoring Method for Gamma Irradiation Facility Based on Radio-Voltaic and Photovoltaic Effects. *Appl. Radiat. Isot.* **2021**, *173*, 109703. DOI: 10.1016/j.apradiso.2021.109703.
[88] Bednarik, M.; Pata, V.; Ovsik, M.; Mizera, A.; Husar, J.; Manas, M.; Hanzlik, J.; Karhankova, M. The Modification of Useful Injection-Molded Parts' Properties Induced Using High-Energy Radiation. *Polymers.* **2024**, *16*(4), 450. DOI: 10.3390/polym16040450.
[89] Zin, M. M.; Anucha, C. B.; Bánvölgyi, S. Recovery of Phytochemicals via Electromagnetic Irradiation (Microwave-Assisted-Extraction): Betalain and Phenolic Compounds in Perspective. *Foods.* **2020**, *9*(7), 918. DOI: 10.3390/foods9070918.
[90] Naresh, K.; Varakumar, S.; Variyar, P. S.; Sharma, A. R.; S, O. V. Effect of γ-Irradiation on Physico-Chemical and Microbiological Properties of Mango (*Mangifera Indica* L.) Juice from Eight Indian Cultivars. *Food Biosci.* **2015**, *12*, 1–9. DOI: 10.1016/j.fbio.2015.06.003.
[91] Salta, Z.; Schaefer, T.; Tasinato, N.; Kieninger, M.; Katz, A.; Herrmann, H.; Ventura, O. N. Energetics of the OH Radical H-Abstraction Reactions from Simple Aldehydes and Their Geminal Diol Forms. *J. Mol. modeling* **2024**, *30*(8), 253. DOI: 10.1007/s00894-024-06058-0.
[92] Kalaiselvan, R. R.; Sugumar, A.; Radhakrishnan, M. Gamma Irradiation Usage in Fruit Juice Extraction. In.). *Fruit Juices* **2018**, 423–435. DOI: 10.1016/B978-0-12-802230-6.00021-7.
[93] Mandal, R.; Mohammadi, X.; Wiktor, A.; Singh, A.; Singh, A. Applications of Pulsed Light Decontamination Technology in Food Processing: An Overview. *Appl. Sci.* **2020**, *10*(10), 3606. DOI: 10.3390/app10103606.
[94] Santamera, A.; Escott, C.; Loira, I.; Del-Fresno, J. M.; González, C.; Morata, A. Pulsed Light: Challenges of a Non-Thermal Sanitation Technology in the Winemaking Industry. *Beverages* **2020**, *6*(3), 45. DOI: 10.3390/beverages6030045.
[95] Alhendi, A.; Yang, W.; Goodrich-Schneider, R.; Sarnoski, P. J. Total Inactivation of Lipoxygenase in Whole Soya Bean by Pulsed Light and the Effect of Pulsed Light on the Chemical Properties of Soya Milk Produced from the Treated Soya Beans. *Int. J. Food Sci. Technol.* **2017**, *53*(2), 457–466. DOI: 10.1111/ijfs.13604.
[96] Mandal, R.; Pratap-Singh, A. Characterization of Continuous-Flow Pulsed UV Light Reactors for Processing of Liquid Foods in Annular Tube and Coiled Tube Configurations Using Actinometry and Computational Fluid Dynamics. *J. Food Eng.* **2021**, *304*, 110590. DOI: 10.1016/j.jfoodeng.2021.110590.
[97] Nowacka, M.; Dadan, M.; Janowicz, M.; Wiktor, A.; Witrowa-Rajchert, D.; Mandal, R.; Prapat-Singh, A.; Janiszewka-Turak, E. Effect of Nonthermal Treatments on Selected Natural Food Pigments and Color Changes in Plant Material. *Compr. Rev. Food Sci. Food Saf.* **2021**, *20*(5), 5097–5144. DOI: 10.1111/1541-4337.12824.
[98] Loarce, L.; Oliver-Simancas, R.; Marchante, L.; Diaz-Maroto, M. C.; Alanon, M. E. Implementation of Subcritical Water Extraction with Natural Deep Eutectic Solvents for Sustainable Extraction of Phenolic Compounds from Winemaking By-Products. *Food Res. Int.* **2020**, *137*, 109728. DOI: 10.1016/j.foodres.2020.109728.
[99] Kuasnei, M.; Wojeicchowski, J. P.; Santos, N. H.; Pinto, V. Z.; Ferreira, S. R. S.; Zielinski, A. A. Modifiers Based on Deep Eutectic Mixtures: A Case Study for the Extraction of Anthocyanins from Black Bean Hulls Using High Pressure Fluid Technology. *J. Supercrit. Fluids* **2022**, *191*, 105761. DOI: 10.1016/j.supflu.2022.105761.
[100] Babova, O.; Occhipinti, A.; Capuzzo, A.; Maffei, M. E. Extraction of Bilberry (*Vaccinium myrtillus*) Antioxidants Using Supercritical/Subcritical CO2 and Ethanol as Co-Solvent. *J. Supercrit. Fluids.* **2016**, *107*, 358–363. DOI: 10.1016/j.supflu.2015.09.029.
[101] Briones-Labarca, V.; Plaza-Morales, M.; Giovagnoli-Vicuna, C.; Jamett, F. High Hydrostatic Pressure and Ultrasound Extractions of Antioxidant Compounds, Sulforaphane and Fatty Acids from Chilean Papaya (*Vasconcellea pubescens*) Seeds: Effects of Extraction Conditions and Methods. *Lwt-Food Sci. Technol.* **2015**, *60*(1), 525–534. DOI: 10.1016/j.lwt.2014.07.057.

[102] Zhang, L.; Liu, P. Z.; Li, L. L.; Huang, Y.; Pu, Y. F.; Hou, X. J.; Song, L. J. Identification and Antioxidant Activity of Flavonoids Extracted from Xinjiang Jujube (*Ziziphus Jujube* Mill.) Leaves with Ultra-High Pressure Extractiontechnology. *Molecules* **2019**, *24*(1), 122. DOI: https://doi.org/10.3390/molecules24010122.
[103] Morata, A.; Guamis, B. Use of UHPH to Obtain Juices with Better Nutritional Quality and Healthier Wines with Low Levels of SO2. *Front. Nutr.* **2020**, *7*, 7. DOI: 10.3389/fnut.2020.598286.
[104] Yanagisawa, J.; Aoyama, T.; Fujii, K.; Yashima, M.; Inaguma, Y.; Kuwabara, A.; Shitara, K.; Le Ouay, B.; Hayami, S.; Ohba, M., et al. Strongly Enhanced Polarization in a Ferroelectric Crystal by Conduction-Proton Flow. *J. Am. Chem. Soc.* **2024**, *146*(2), 1476–1483. DOI: 10.1021/jacs.3c10841.
[105] Naik, M.; Rawson, A.; Rangarajan, J. M. Radio Frequency-Assisted Extraction of Pectin from Jackfruit (*Artocarpus Heterophyllus*) Peel and Its Characterization. *J. Food Process Eng.* **2020**, *43*(6), e13389. DOI: 10.1111/jfpe.13389.
[106] Fardhyanti, D. S.; Tyaningsih, D.; Afifah, S. N. Mass Transfer Coefficient in Stirred Tank for Cresol Extraction Process from Coal Tar. *J. Phys.* **2017**, *824*, 012019. DOI: 10.1088/1742-6596/824/1/012019.
[107] Alifakı, Y. Ö.; Şakıyan, Ö.; Isci, A. Extraction of Phenolic Compounds from Cranberrybush (*Viburnum Opulus* L.) Fruit Using Ultrasound, Microwave, and Ultrasound-Microwave Combination Methods. *Food Measure* **2022**, *16*(5), 4009–4024. DOI: 10.1007/s11694-022-01498-9.
[108] Kumar, M.; Dahuja, A.; Sachdev, A.; Kaur, C.; Varghese, E.; Saha, S.; Sairam, K. Valorisation of Black Carrot Pomace: Microwave Assisted Extraction of Bioactive Phytoceuticals and Antioxidant Activity Using Box-Behnken Design. *J. Food Sci. Technol.-Mysore* **2019**, *56*(2), 995–1007. DOI: 10.1007/s13197-018-03566-9.
[109] Sang, J.; Li, B.; Huang, Y. Y.; Ma, Q.; Liu, K.; Li, C. Q. Deep Eutectic Solvent-Based Extraction Coupled with Green Two-Dimensional HPLC-DAD-ESI-MS/MS for the Determination of Anthocyanins from *Lycium Ruthenicum* Murr. Fruit. *Analytical Methods* **2018**, *10*(10), 1247–1257. DOI: 10.1039/c8ay00101d.
[110] Pintac, D.; Majkic, T.; Torovic, L.; Orcic, D.; Beara, I.; Simin, N.; Mimica-Dukic, N.; Lesjak, M. Solvent Selection for Efficient Extraction of Bioactive Compounds from Grape Pomace. *Ind. Crops Products* **2018**, *111*, 379–390. DOI: 10.1016/j.indcrop.2017.10.038.
[111] Farnad, N.; Farhadi, K. Simple and Complex Coacervation Methods for the Nanoencapsulation of *Rosa Damascena* Mill L. Anthocyanin in Zein/Potato Starch: A New Approach to Enhance Antioxidant and Thermal Properties. *J. Food Sci.* **2023**, *88*(3), 1019–1032. DOI: 10.1111/1750-3841.16463.
[112] Wang, S. L.; Chu, Z. H.; Ren, M. X.; Jia, R.; Zhao, C. B.; Fei, D.; Su, H.; Fan, X. Q.; Zhang, X. T.; Wang, Y., et al. Identification of Anthocyanin Composition and Functional Analysis of an Anthocyanin Activator in *Solanum Nigrum* Fruits. *Molecules* **2017**, *22*(6), 876. DOI: 10.3390/molecules22060876.
[113] Matos, Í. T. S. R.; Mota, M. L. F.; Carmo, E. J. D. Using Purple Amerindian Yam (Cará Roxo, *Dioscorea Trifida* L.) as Brewing Adjunct: Technical and Sensorial Analysis. *Ciência e Tecnologia de Alimentos* **2022**, *42*, e48521. DOI: 10.1590/fst.4852.
[114] Ćurko, N.; Tomašević, M.; Bubalo, M. C.; Gracin, L.; Redovniković, I. R.; Ganić, K. K. Extraction of Proanthocyanidins and Anthocyanins from Grape Skin by Using Ionic Liquids. *Food Technol. And Biotechnol.* **2017**, *55*(3), 429–437. DOI: 10.17113/ftb.55.03.17.5200.
[115] Manousi, N.; Rosenberg, E.; Deliyanni, E. A.; Zachariadis, G. A. Sample Preparation Using Graphene-Oxide-Derived Nanomaterials for the Extraction of Metals. *Molecules* **2020**, *25*(10), 2411. DOI: 10.3390/molecules25102411.
[116] Lima, Á. S.; Soares, C. M. F.; Paltram, R.; Halbwirth, H.; Bica, K. Extraction and Consecutive Purification of Anthocyanins from Grape Pomace Using Ionic Liquid Solutions. *Fluid Phase Equilib.* **2017**, *451*, 68–78. DOI: 10.1016/j.fluid.2017.08.006.
[117] Fernández, I. P.; Pino, V. Chapter 17 - Extraction with Ionic Liquids-Organic Compounds. In *Liquid-Phase Extraction - Handbooks in Separation Science*, Poole, C. F., Ed. Elsevier: Amsterdam, **2020**, pp. 499–537. DOI: 10.1016/B978-0-12-816911-7.00017-7.
[118] Bi, Y.; Chi, X.; Zhang, R.; Lu, Y.; Wang, Z.; Dong, Q.; Ding, C.; Yang, R.; Jiang, L. Highly Efficient Extraction of Mulberry Anthocyanins in Deep Eutectic Solvents: Insights of Degradation Kinetics and Stability Evaluation. *Innovative Food Sci. & Emerging Technol.* **2020**, *66*, 102512. DOI: 10.1016/j.ifset.2020.102512.
[119] Pal, C. B. T.; Jadeja, G. C. Deep Eutectic Solvent-Based Extraction of Polyphenolic Antioxidants from Onion (*Allium Cepa* L.) Peel. *J. Sci. Food Agric.* **2019**, *99*(4), 1969–1979. DOI: 10.1002/jsfa.9395.
[120] Zannou, O.; Koca, I. Greener Extraction of Anthocyanins and Antioxidant Activity from Blackberry (*Rubus* Spp) Using Natural Deep Eutectic Solvents. *Lwt-Food Sci. Technol.* **2022**, *158*(15), 113 184. DOI: 10.1016/j.lwt.2022.113184.
[121] Chachar, Z.; Lai, R.; Ahmed, N.; Lingling, M.; Chachar, S.; Paker, N. P.; Qi, Y. Cloned Genes and Genetic Regulation of Anthocyanin Biosynthesis in Maize, a Comparative Review. *Front. Plant. Sci.* **2024**, *15*. DOI: 10.3389/fpls.2024.1310634.
[122] Ryu, D.; Koh, E. Application of Response Surface Methodology to Acidified Water Extraction of Black Soybeans for Improving Anthocyanin Content, Total Phenols Content and Antioxidant Activity. *Food Chem.* **2018**, *261*, 260–266. DOI: 10.1016/j.foodchem.2018.04.061.

[123] Liu, M.; Su, Y. J.; Lin, Y. L.; Wang, Z. W.; Gao, H. M.; Li, F.; Wei, X. Y.; Jiang, H. L. Optimization of Green Extraction of Anthocyanins from Purple Passion Fruit Peels by Response Surface Methodology. *J. Food Process. And Preserv.* **2018**, *42*(10), e13756. DOI: 10.1111/jfpp.13756.
[124] Belwal, T.; Huang, H.; Li, L.; Duan, Z.; Zhang, X.; Aalim, H.; Luo, Z. Optimization Model for Ultrasonic-Assisted and Scale-Up Extraction of Anthocyanins from *Pyrus Communis* 'Starkrimson' Fruit Peel. *Food Chem.* **2019**, *297*, 124993. DOI: 10.1016/j.foodchem.2019.124993.
[125] Ávila-Hernández, M. A.; Pérez-Alonso, C.; Orozco-Villafuerte, J.; Barrera-Díaz, C. E.; Alpizar-Reyes, E.; Cruz-Olivares, J. Supercritical Extraction of Lyophilized Strawberry Anthocyanins with Pulsed Electric Fields Pretreatment. *Química Nova* **2022**, *45*(6), 728–733. DOI: 10.21577/0100-4042.20170849.
[126] Cuesta-Riaño, C. S.; Castro-Guascaa, M. P.; Tarazona-Díaz, M. P. Anthocyanin Extract from Blackberry Used as an Indicator of Hydrogen Potential. *Int. J. Fruit Sci.* **2022**, *22*(1), 224–234. DOI: 10.1080/15538362.2022.2037036.
[127] Migliorini, A. A.; Piroski, C. S.; Cruz, D. T. M.; Escher, G. B.; Carmo, M. A. V.; Azevedo, L.; Marques, M. B.; Granato, D.; Rosso, N. D. Red Chicory (*Cichorium intybus*) Extract Rich in Anthocyanins: Chemical Stability, Antioxidant Activity, and Antiproliferative Activity in vitro. *J. Food Sci.* **2019**, *84*(5), 990–1001. DOI: 10.1111/1750-3841.14506.
[128] González, J. A.; Carrera, M. C.; Barbero, G. F.; Palma, M. A Comparison Study Between Ultrasound–Assisted and Enzyme–Assisted Extraction of Anthocyanins from Blackcurrant (*Ribes Nigrum* L.). *Food Chem.* **2022**, *13*, 100192. DOI: 10.1016/j.fochx.2021.100192.
[129] Fernández-Barbero, G.; Pinedo, C.; Espada-Bellido, E.; Ferreiro-González, M.; Carrera, C.; Palma, M.; García-Barroso, C. Optimization of Ultrasound-Assisted Extraction of Bioactive Compounds from Jabuticaba (*Myrciaria cauliflora*) Fruit Through a Box-Behnken Experimental Design. *Food Sci. Technol.* **2019**, *39*(4), 1018–1029. DOI: 10.1590/fst.16918.
[130] Wathon, M. H.; Beaumont, N.; Benohoud, M.; Blackburn, R. S.; Rayner, C. M. Extraction of Anthocyanins from *Aronia Melanocarpa* Skin Waste as a Sustainable Source of Natural Colorants. *Color. Technol.* **2019**, *135*(1), 5–16. DOI: 10.1111/cote.12385.
[131] Wu, C. Y.; Wang, H.; Fan, X. H.; Yue, W.; Wu, Q. N. Waste *Euryale Ferox* Salisb. Leaves as a Potential Source of Anthocyanins: Extraction Optimization, Identification and Antioxidant Activities Evaluation. *Waste Biomass Valorization* **2019**, *11*(8), 4327–4340. DOI: 10.1007/s12649-019-00762-2.
[132] Porto, C.; Natolino, A. Extraction Kinetic Modelling of Total Polyphenols and Total Anthocyanins from Saffron Floral Bio-Residues: Comparison of Extraction Methods. *Food Chem.* **2018**, *258*, 137–143. DOI: 10.1016/j.foodchem.2018.03.059.
[133] Lin, Y.; Li, C.; Shi, L.; Wang, L. Anthocyanins: Modified New Technologies and Challenges. *Foods* **2023**, *12*(7), 1368. DOI: 10.3390/foods12071368.
[134] Syrpas, M.; Valanciene, E.; Augustiniene, E.; Malys, N. Valorization of Bilberry (*Vaccinium Myrtillus* L.) Pomace by Enzyme-Assisted Extraction: Process Optimization and Comparison with Conventional Solid-Liquid Extraction. *Antioxidants* **2021**, *10*(5), 773. DOI: 10.3390/antiox10050773.
[135] Santos, F. N. D.; Souza, E. J. D. D.; Jéssica, S.; Buchveitz, P. T.; Hüttner Kringel, J.; Dillenburg, M. D. A.; Dias, R. G. A.; Zavareze, R. E. D. Multivariate Analysis as Tool for Optimization of Anthocyanins Extraction from Jambolan (*Syzygium Cumini* L.). *Food Anal. Methods* **2022**, *15*(9), 2524–2536. DOI: 10.1007/s12161-022-02313-3.
[136] Pedro, A. C.; Granato, D.; Rosso, N. D. Extraction of Anthocyanins and Polyphenols from Black Rice (*Oryza Sativa* L.) by Modeling and Assessing Their Reversibility and Stability. *Food Chem.* **2016**, *191*, 12–20. DOI: 10.1016/j.foodchem.2015.02.045.
[137] Jha, P.; Das, A. J.; Deka, S. C. Optimization of Ultrasound and Microwave Assisted Extractions of Polyphenols from Black Rice (*Oryza Sativa* Cv. Poireton) Husk. *J. Food Sci. Technol.* **2017**, *54*(12), 3847–3858. DOI: 10.1007/s13197-017-2832-0.
[138] Ju, X.; Grego, C.; Zhang, X. Specific Effects of Fiber Size and Fiber Swelling on Biomass Substrate Surface Area and Enzymatic Digestibility. *Bioresour. Technol.* **2013**, *144*, 232–239. DOI: 10.1016/j.biortech.2013.06.100.
[139] Evans, W. C.; Evans, D. Plant Description, Morphology and Anatomy. In *Trease and Evans' Pharmacognosy*, Evans, W. C., Evans, D., Eds. W.B. Saunders: Edinburgh, **2009**; pp. 541–550.
[140] Caser, M.; Demasi, S.; Stelluti, S.; Donno, D.; Scariot, V. *Crocus Sativus* L. Cultivation in Alpine Environments: Stigmas and Tepals as Source of Bioactive Compounds. *Agronomy-Basel* **2020**, *10*(10), 1473. DOI: 10.3390/agronomy10101473.
[141] Hiranrangsee, L.; Kumaree, K. K.; Sadiq, M. B.; Anal, A. K. Extraction of Anthocyanins from Pericarp and Lipids from Seeds of Mangosteen (*Garcinia Mangostana* L.) by Ultrasound-Assisted Extraction (UAE) and Evaluation of Pericarp Extract Enriched Functional Ice-Cream. *J. Food Sci. Technol.-Mysore* **2016**, *53*(10), 3806–3813. DOI: 10.1007/s13197-016-2368-8.
[142] Barros, G. L. D.; Pio, R.; Ribeiro, C. H. M.; Fazenda, L. H. V.; Silva, A. D.; Peche, P. M. Management of Blackberry Pruning to Extend Harvest Seasonality. *Pesqui. Agropecuária Brasileira* **2023**, *58*, e03197. DOI: 10.1590/S1678-3921.pab2023.v58.03197.

[143] Sang, J.; Ma, Q.; Hou, X. F.; Li, C. Q. Extraction Optimization and Identification of Anthocyanins from *Nitraria Tangutorun* Bobr. Seed Meal and Establishment of a Green Analytical Method of Anthocyanins. *Food Chem.* **2017**, *218*, 386–395. DOI: 10.1016/J.Foodchem.2016.09.093.

[144] Bae, R.; Kim, K.; Kim, T.; Lee, S. Anatomical Observations of Anthocyanin Rich Cells in Apple Skins. *HortScience HortSci.* **2006**, *41*(3), 733–736. DOI: 10.21273/HORTSCI.41.3.733.

[145] Zavala-Lopez, M.; Garcia-Lara, S. An Improved Microscale Method for Extraction of Phenolic Acids from Maize. *Plant. Methods* **2017**, *13*(1), 81. DOI: https://doi.org/10.1186/s13007-017-0235-x.

[146] He, S. D.; Lou, Q. Y.; Shi, J.; Sun, H. J.; Zhang, M. L.; Li, Q. Water Extraction of Anthocyanins from Black Rice and Purification Using Membrane Separation and Resin Adsorption. *J. Food Process. And Preserv*. **2017**, *41*(4), e13091. DOI: 10.1111/jfpp.13091.