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A systematic review and meta-analysis of extraction and identification of barberry bioactive compounds

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ABSTRACT

Barberry (Berberis spp.), a genus in the Berberidaceae family with 650 species, holds significant potential in the pharmaceutical and food industries. This review assesses the available information and carries out a meta-analysis of published research on bioactive compounds extracted from various Berberis species. PubMed, Web of Science, and Scopus databases were searched extensively for articles published between 2009 and 2023. This analysis included 38 relevant articles, including those that evaluated multiple extraction methods. Four extraction methods involving different techniques and equipment were identified in the included studies and comparatively evaluated in this systematic review and meta-analysis. According to our meta-analysis of the published data, the frequency of use of the methods was as follows: Press Extraction (PE) (22.72%), Maceration Extraction (ME) (20.45%), Ultrasound-Assisted Extraction (UAE) (18.18%), and Subcritical Water Extraction (SWE) (6.82%). The most common solvents used in the selected studies were water (42.86%) and methanol (22.86%). In addition, this review investigated, based on the reported data, the effects of the extraction method on antioxidant activity (DPPH), Total Phenolic Content (TPC), and Total Anthocyanin Content (TAC). The results showed that, among the reported techniques, SWE was generally associated with the highest DPPH values. Moreover, UAE was most frequently used for determining TPC and TAC on a dry-weight basis, whereas ME and SWE were more commonly applied when data were expressed on a solution basis.

1. Introduction

The *Berberis* genus is distributed geographically throughout Asia, Europe, East Africa, North America and South America. A wide range of conditions—including pain, bacterial infections, fever, diabetes, and skin irritations—have traditionally been treated using the roots, stems, leaves, flowers, and fruits of this plant. In recent studies, barberry extract has been found to have beneficial effects on the vascular and nervous systems [1]. Furthermore, barberry fruits have been used as medicinal remedies for acute and chronic inflammation, antihistaminic and anticholinergic effects, antioxidant properties, and influence on heart function [2,3]. *Berberis* species contain various anthocyanins, flavonoids, proteins, terpenoids, antioxidants, lignans, vitamins, carotenoids, tannins, organic acids, and phenolic acids. Additionally, barberry fruits are considered the main source of antioxidants, since they contain phenolic compounds, such as apigenin, rutin, quercetin, chlorogenic acid, caffeic acid, and anthocyanins [4-6].

Generally, qualitative and quantitative studies of bioactive compounds extracted from plant materials depend on the proper extraction methods [7]. As bioactive compounds play a significant role in functional foods and health care, increasing attention has been paid to the extraction of active components using green extraction techniques [8]. Several methods have been developed to extract bioactive compounds from plants. Based on the extraction techniques employed, these methods can be broadly classified into traditional approaches (including maceration, percolation, decoction, reflux, and Soxhlet extraction) and modern or novel approaches (such as ultrasound-assisted and microwave-assisted extraction). A number of environmentally friendly and efficient extraction methods, including supercritical fluid extraction and pressurized liquid extraction, are also available [9].

Traditional extraction methods such as maceration, Soxhlet extraction, and hydrodistillation are commonly used to extract bioactive compounds from fruit residues [10]. Barberry extracts using ultrasound assisted extraction (UAE), subcritical water extraction (SWE), maceration extraction (ME) and press extraction (PE) are more commonly studied than others [11]. In comparison to conventional extraction methods, the UAE method reduces extraction time and energy requirements [12]. Low-frequency ultrasound propagates through liquids and causes cavitation. During cavitation, bubbles form, grow, and implode, creating localized increases in pressure and temperature. In addition to disrupting cell membranes and walls, UAE facilitates the extraction of

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intracellular compounds [3]. Moreover, besides offering an environmentally friendly approach for extracting bioactive compounds from natural sources, SWE represents a promising engineering method [13,14]. Generally, SWE systems require a temperature range between 100 and 374 °C (the critical point of water is 374 °C and 22 MPa) along with a pressure high enough to maintain the liquid state of the water. Hydrogen bonds between molecules of water break down under subcritical conditions and their dielectric constants decrease [13]. ME can be used to extract bioactive components from plants. The solvent used will determine which bioactive components are derived. Maceration is a method of extraction that has both positive and negative aspects. An advantage of a simple experimental design is that it can be applied easily. The long extraction time and low productivity are disadvantages. Furthermore, maceration can generally be applied to samples containing heat-resistant components [15]. PE is utilized to compress or extract solids or liquids by applying enormous force [16].

The present systematic review and meta-analysis aimed to identify studies that assessed bioactive compounds of barberry using various extraction techniques and, in particular, to highlight their effects on extraction efficiency, total phenolic compounds (TPC), total anthocyanin compounds (TAC), total flavonoid compounds (TFC), ascorbic acid content, and antioxidant activity (DPPH).

2. Methods

2.1. Searching process to find the relevant papers

A systematic review of published studies has examined barberry bioactive compounds for their potential applications in the food industry. Between 2009 and 2023, a comprehensive literature search was conducted using the PubMed, Web of Science, and Scopus databases. This process involved collaborative group work. Several keywords and Boolean operators were used in the search process: extraction method + anthocyanin; phenolic compounds + extraction of compounds from barberry or novel extraction methods; anthocyanin + ultrasound; antioxidant capacity + anthocyanin + extraction + phenolic compounds + flavonoids + ascorbic acid and food industry. It was not limited in terms of the type of publication, the study design, or the method of outcome measurement.

2.2. Qualification

The following criteria were met for eligibility: (1) design of the experiment; (2) application to the food industry; (3) measurement of one or more of the specified parameters (antioxidant capacity, phenolic content, anthocyanin content, flavonoid content, ascorbic acid); and (4) publication in English. Alternatively, in vivo and ex vivo model studies, letters, conference abstracts, patient studies, review articles, and abstracts without details were excluded. This study examined the reported bioactive compounds obtained by various extraction methods, in order to provide future directions on the most suitable extraction techniques for specific target compounds.

2.3. Data collection, evaluation and screening

In the first stage of the research process, the articles were screened according to their titles, abstracts, and keywords. In the second stage, the relevance of the full-text articles was evaluated according to the inclusion and exclusion criteria (section 2.2). A discussion was held to resolve any disagreements. A data extraction form (Table 1) was used to extract data on species, method, solvent, processing condition, application, antioxidant capacity, total phenolic content (TPC), total anthocyanin content (TAC), Ascorbic acid, and total flavonoid content (TFC).

A total of 210 records were retrieved through database searching (PubMed, Web of Science, and Scopus) for the period 2009–2023. After removal of duplicates, 163 articles remained for title and abstract screening. Of these, 108 records were excluded because they were not relevant to barberry bioactive compounds or did not meet the inclusion criteria.

A total of 55 full-text articles were assessed for eligibility. Among them, 17 full-texts were excluded due to reasons such as: in vivo or ex vivo studies, insufficient quantitative data on DPPH, TPC, or TAC, non-food applications, review articles, or not written in English. At last, 38 studies met all the eligibility criteria and were included in both the qualitative synthesis and the descriptive meta-analysis (Fig. 1).

2.4. Statistical analysis

A descriptive meta-analysis approach was applied due to the substantial heterogeneity among the included studies. A comparative evaluation of antioxidant activity (DPPH), total phenolic content (TPC), and total anthocyanin content (TAC) was conducted. Because these variables were reported using different analytical standards and non-comparable units (e.g., DPPH expressed as %, IC_{50}, or Trolox equivalents; TPC expressed in mg GAE/g, mg GAE/mL, or mg GAE/100 g; TAC expressed in mg/L, mg/100 g, or mg/mL), the extracted numerical values were first harmonized into comparable units whenever possible to enable graphical comparison across studies.

However, despite this harmonization, the degree of methodological and analytical variability prevented the calculation of standardized effect sizes required for classical pooled meta-analysis models (e.g., MD, SMD, or Hedges g). Therefore, fixed-effect and random-effects models were not applicable. In accordance with previously published meta-analyses in this field [17,18], the present study employed a descriptive meta-analytical framework consisting of aggregated data extraction, frequency analysis, and comparative statistical evaluation.

A one-way analysis of variance (ANOVA) was

performed on the harmonized pooled values to compare extraction methods, followed by Fisher's post hoc test to detect statistically significant differences *($p < 0.05$)*. All statistical analyses were performed using SPSS (version 25.0).

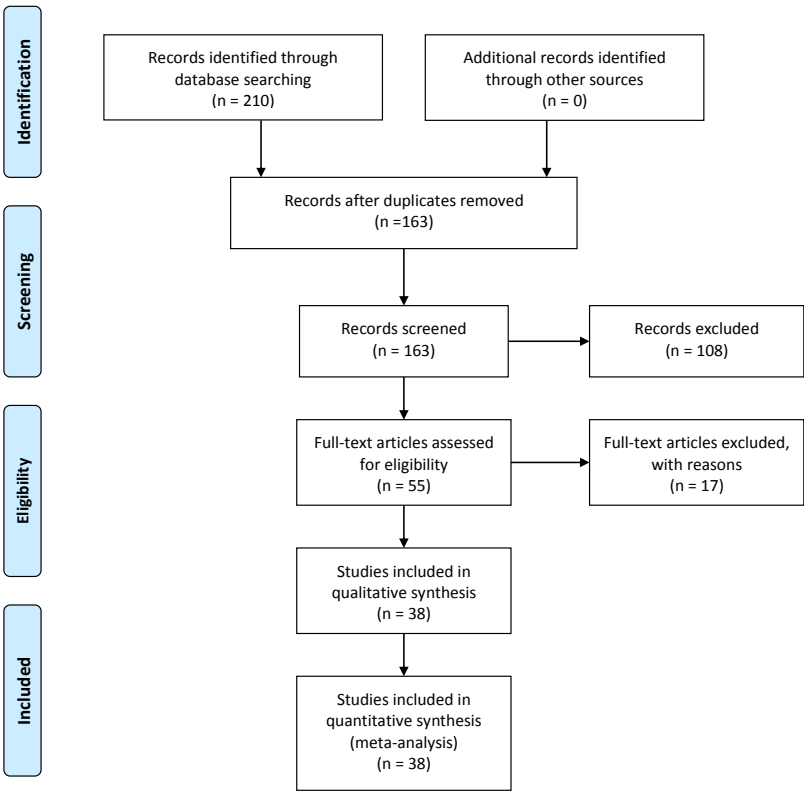

Fig. 1. PRISMA flow diagram of the identification, screening, eligibility, and inclusion of studies. In total, 210 records were identified and 38 studies were included in the final analysis.

3. Results and discussion

An extraction involves the separation of compounds from solids or liquids using chemical, physical, and/or mechanical methods [19]. There are several critical factors involved in an extraction process, including the type of solvent, the process conditions (temperature, pH, and the ratio of solvent to matrix), as well as the properties of the plant material (composition and particle size) [20]. Solvents and their polarity can influence the transfer of electrons and hydrogen atoms. In the extraction of polyphenols, this is an important factor that may have an impact on the extraction yield as well as the antioxidant activity [21].

Based on articles published from 2009 to 2023, the present review classified the reported methods and equipment used for the extraction of bioactive compounds from barberry into four categories. The four groups included: (a) press extraction (PE); (b) maceration extraction (ME); (c) ultrasound-assisted extraction (UAE) and (d) subcritical water extraction (SWE). Fig. 2. illustrates the relative frequency of PE (22.72%), ME (20.45%), UAE (18.18%), and SWE (6.82%) as reported in the included studies. There was also an equal percentage of 4.54% for methods such as water bath, solid-liquid, accelerated solvent extraction (ASE) and high-pressure carbon dioxide (HPCD). The frequency percentage is calculated by counting how many times a specific value occurs in a data set, and expressing this repetition as a percentage. The purpose of this calculation is to determine what proportion of the entire data set is comprised of a particular value. It is commonly used to analyze statistical data and generate frequency distribution charts [22]. The relevant section below discusses the rationale and analysis supporting these methods.

Table 1 provides an overview of research conducted on bioactive compounds from various *Berberis* species from 2009 to 2023. This table provides an overview of several critical aspects of the studies. These include the different *Berberis* species examined, the extraction methods employed, the solvents used, and the specific extraction conditions applied. Further, the article discusses the potential uses of the extracted compounds in the pharmaceutical, nutraceutical, and cosmetic industries. The table also includes a detailed analysis of key bioactive components, such as antioxidant activity (DPPH), total phenolic content (TPC), total anthocyanin content (TAC), ascorbic acid, and total flavonoid content (TFC), which are commonly used as indicators of the biological activity and therapeutic potential of the extracts.

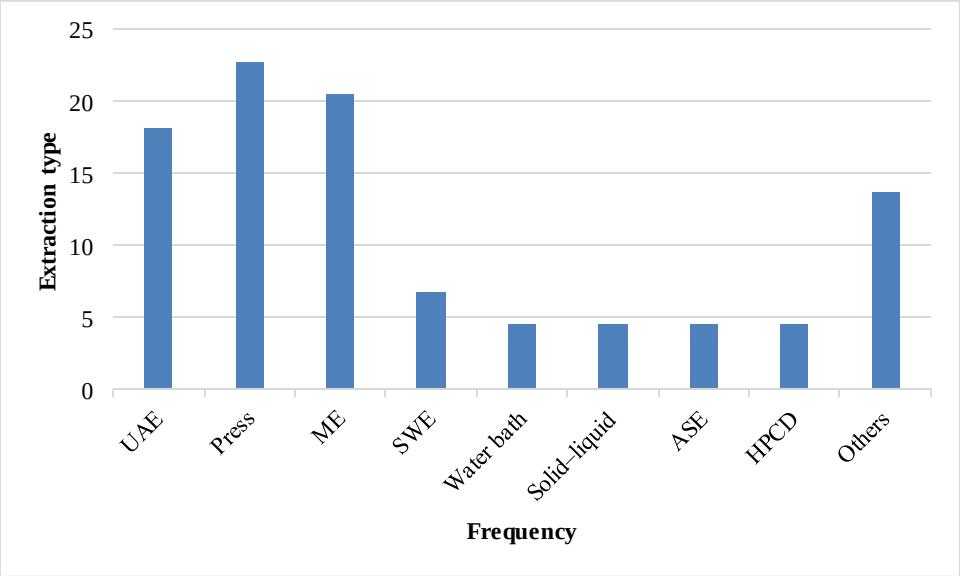

Fig. 2. Frequency distribution of extraction methods used for isolating bioactive compounds from *Berberis* species in studies published between 2009 and 2023.

All of the factors listed above are considered essential in the reviewed studies, as they have a direct impact on the efficacy and quality of the extracted bioactive compounds. This table serves as a useful reference for researchers by compiling such valuable data. It provides insight into the most effective extraction methods and conditions for maximizing yields and bioactive compounds. Future studies can be guided by this information, which will assist researchers in identifying the most promising methods and compounds for a particular application. Furthermore, it can be used to facilitate the comparison of different studies in order to develop standardized protocols for extracting and utilizing bioactive compounds from *Berberis* species.

3.1. Press extraction (PE)

For the extraction of barberry bioactive compounds, PE is the most commonly used method. According to the results of extraction type studies, 22.27% were conducted using press extraction (Figure 2). It is a highly efficient and cost-effective method for extracting bioactive compounds from barberry. Due to its minimal equipment requirements and operational costs, this method is economically viable for both research and industrial applications. The method utilizes only mechanical pressure, preventing the use of chemical solvents, resulting in extracts that are natural, safe, and suitable for use in pharmaceuticals, foods, and cosmetics. A low-temperature process allows for the preservation of sensitive bioactive compounds such as anthocyanins and flavonoids, which are susceptible to degradation under other extraction methods [23]. A further benefit of this method is its ease of scalability, which provides efficiency and versatility on a wide range of production scales. As a sustainable extraction method, it has a reduced environmental impact because it eliminates chemical solvents [24]. In general, this method provides a balanced approach in the extraction of bioactive compounds from barberries, combining cost-effectiveness, safety, and environmental sustainability. Numerous researchers have utilized the PE method to extract bioactive compounds from *Berberis* species, as shown in Table 1. Generally, no solvent was used [25-29]. This method is used to extract compounds that can be used as food additives and fruit juices [3, 30-32].

Ozgen *et al.* [29] examined six purple-black barberry accessions by using the PE method, by analyzing the levels of phenolics, monomeric anthocyanins, and antioxidant activity. The results showed variability in antioxidant levels and chemical composition among the accessions [29].

Akbulut *et al.* [25] carried out the chemical properties of wild barberry (*Berberis vulgaris*) fruits grown in Turkey, with mineral content extracted using PE. The chemical composition includes reduced sugars, ascorbic acid, phenolics, and anthocyanins. The findings provide valuable information for processing, transportation, storage, and human nutrition [25].

3.2. Maceration extraction (ME)

During the ME process, plant material is soaked in an appropriate solvent, where it is agitated to enhance compound diffusion and heated to enhance dissolution. During this process, plant cell walls are broken, releasing soluble phytoconstituents, which are then filtered or pressed following a period of soaking [24]. Even though ME is an efficient and widely used method, it requires a large quantity of plant material and solvents, which results in relatively low yields [23].

ME is the second most commonly used method for extracting bioactive compounds from barberry, valued for its simplicity and accessibility. This technique involves soaking plant material in a solvent for an extended period of time, which makes it a cost-effective solution for both small- and large-scale applications [23]. As compared to more advanced techniques, maceration usually requires

fewer resources and uses readily available solvents, such as ethanol, methanol, or water. It is important to note that the extraction process is slower, but it is gentle, as a result of which compounds like flavonoids and phenolics that are vital for their antioxidant and anti-inflammatory effects can be preserved [24]. Maceration also offers flexibility in terms of solvent choice and extraction conditions, enabling compound-specific customization. It is widely used in both traditional herbal medicine and in modern industrial settings. It is used extensively in the production of natural extracts for food, cosmetic, and pharmaceutical applications. Due to these advantages, maceration remains a widely employed and effective method for extracting bioactive compounds from barberry [33].

According to Table 1, numerous researchers have utilized the ME method to extract bioactive compounds from *Berberis* species [1, 33-36]. For the purpose of achieving optimal extraction conditions, they employed a variety of solvents (acetone, ethanol, methanol, and water), different solid-to-solvent ratios (1:10, 1:20, 1:70, 1:4), different extraction times (overnight, 24 h, 15 min, 2 h, 1 hour, 18 h, 72 h), as well as varying temperatures (100 °C, room temperature, 70 °C, 30 °C). Furthermore, the process of obtaining bioactive compounds by using this method has shown promising applications in the food industry as additives, indicator films, nutraceuticals, food packaging, food colorants, antioxidants, and antibacterial agents [37-39].

Belwal *et al.* [40] investigated the extraction of phenolic compounds and antioxidant activity from *Berberis asiatica* fruits using ME and response surface methodology. The extraction procedure was performed under the following optimal conditions: 80 °C, 30 min, a sample-to-solvent ratio of 1:50, pH 3, and a methanol concentration of 80%. The results showed that extraction temperature, sample-to-solvent ratio, and solvent concentration were key factors influencing the yield, with these conditions providing an effective method for obtaining high concentrations of bioactive phenolics [40].

The purpose of the study by Hosseini *et al.* [36] was to utilize ME. Anthocyanins were extracted from barberry, eggplant peel, and red cabbage using various organic solvents. The impact of different acids (hydrochloric, citric, and acetic) on the extraction of anthocyanins and total phenols was evaluated by preparing acidified aqueous solutions of water and ethanol. The results demonstrated that citric acid was the most effective solvent, yielding the highest DPPH radical scavenging activity. Furthermore, the stability of anthocyanins in the solution was found to be dependent on temperature and the presence of other components in the medium [36].

Jaberi *et al.* [38] investigated on *Berberis vulgaris* fruit and the optimal conditions for anthocyanin extraction were determined using ME. The focus was on key variables such as solvent type (ethanol, 2% hydrochloric, acetic, and citric acids), ethanol concentration (20-80%), acid concentration (1-4%), extraction temperature (30-60 °C), extraction time (60-240 min), and fruit-to-solvent ratio (1:5–1:20). The optimal extraction conditions were 80% ethanol with 2% citric acid, an extraction temperature of 30 °C, 120 min of extraction, and a fruit/solvent ratio of 1:20. Under these conditions, the highest levels of anthocyanins, phenolics, and antioxidant capacity were achieved [38].

3.3. Ultrasound-assisted extraction (UAE)

The ultrasound-assisted extraction (UAE) method is a highly effective method for obtaining bioactive compounds from barberry, ranking third in popularity due to its significant advantages. UAE enhances extraction efficiency by generating low-frequency sound waves that create cavitation bubbles that disrupt plant cell walls and release bioactive compounds such as anthocyanins, flavonoids, and phenolic compounds [41]. Compared to traditional methods such as maceration, this method produces higher yields and faster extraction times. Moreover, UAE reduces extraction times from several hours to minutes, saving lab technicians and industrial workers both time and energy. Furthermore, the method is environmentally friendly and cost-effective, as it requires lower solvent volumes and reduces chemical waste [42]. UAE minimizes thermal degradation risk by operating at moderate temperatures, preserving the stability of heat-sensitive compounds. A wide range of bioactive compounds can be analyzed using UAE under various solvents and conditions as a result of its versatility. Additionally, studies have shown that UAE extracts from barberry exhibit higher antioxidant activity than conventional methods. Therefore, it has enhanced value in the food, nutraceutical, and cosmetic industries [23,43].

The extraction of bioactive compounds from *Berberis* with UAE has been investigated with different concentrations of ethanol and methanol as solvents [2,12,37,44,45]. Some of these studies have specified the type of ultrasonic device and ultrasonic bath model used. An important variable in these studies is the extraction time (ranging from 15 min to 2 h), the temperature (room temperature, 30 °C, 50 °C, 57 °C, 70 °C, and 25 °C), and the solid-to-solvent ratio (1:10, 1:70, 1:6, 0.1:10, 1:30) (Table 1). Among other factors, these factors have been studied to optimize extraction conditions. Additionally, this method has demonstrated significant potential for extracting bioactive compounds for use in various applications, including food additives, nutraceuticals, food colorants, antioxidants, and antibiotics [46-48].
Radziejewska-Kubzdela *et al.* [3] conducted a study to explore the effects of UAE (frequency 20 kHz, amplitude 70%, power 140 W for 10 min), heating (80 °C for 5 min), and enzymatic pre-treatment (50 °C, 0.23 g/1000 g Rohapect 10 L, maceration for 60 min) on the yield and bioactive compound content in *Berberis amurensis* juice. Ultrasound treatment, in particular, significantly improved extraction efficiency. The fruit contained 636 mg of phenolics, 217 mg of anthocyanins, and 16.60 mg of ascorbic acid/ 100 g of fresh weight [3].

Another study investigated the potential of *Berberis*

crataegina anthocyanins as a natural food coloring agent. UAE was used to extract anthocyanins, with the effects of ultrasound power (20-100%), extraction temperature (20-60 °C), and extraction time (10-20 min) on TPC and TAC being evaluated. The optimal conditions were an extraction temperature of 57.41 °C and a time of 13.86 min [12].

Cakir and Karabulut [44] investigated UAE to analyze the physicochemical properties, antioxidant activity, total phenolic content, mineral content, and phenolic profiles of *B. vulgaris* and *B. crataegina* wild-grown in Bayburt. The total phenolic content in *B. crataegina* was higher than in *B. vulgaris*. Additionally, *B. crataegina* exhibited superior antioxidant activity, as measured by β-carotene and DPPH methods [44].

Homayoonfal *et al.* [49] developed a method based on inverse parameter estimation of a finite volume model to estimate process coefficients for UAE of anthocyanin compounds from barberry. The study showed that UAE enhanced the extraction rate, although degradation of the anthocyanins occurred, with significant agreement between experimental and predicted data [49].

3.4. Subcritical water extraction (SWE)

SWE is an effective technique for extracting bioactive compounds from barberry, but it is less commonly used than techniques such as ME, UAE, and PE. SWE uses water as a solvent, which is non-toxic and environmentally friendly, and eliminates the risk of solvent contamination in the final product. As a result, SWE is suitable for food, nutraceutical, and pharmaceutical applications. In this method, moderate temperatures (100 to 200 °C) and high pressures (up to 200 bar) are used to enhance the solubility of bioactive compounds such as phenolics and anthocyanins while maintaining their stability [50].

SWE provides several advantages, including a shorter extraction time, greater yield, and an ability to extract thermally sensitive compounds without degradation. Despite this, its adoption is limited by the high initial cost of equipment, the specialized setup requirements, and the need for technical expertise. These factors make SWE less accessible for small-scale operations and result in its lower utilization than other extraction methods. The complexity and high cost of the method inhibit its widespread use despite its potential efficiency and environmental benefits [51].

In studies on the extraction of bioactive compounds from barberry using SWE, the applications have mostly been associated with antioxidants and food additives [39]. The effect of variables such as the solid-to-solvent ratio (1:30), temperature (60 °C, 140 °C, and 180 °C), and extraction time (30 min) has been investigated (Table 1). The use of water as a solvent under controlled temperatures has proven efficient in extracting bioactive compounds from barberries, which makes it a promising option for the health and nutrition industries [9,50].

The study by Mohamadi *et al.* [39] investigated the antioxidant properties of juice extracted from *Berberis vulgaris* using ME and SWE (10 bars, 120-180 °C), comparing these methods with conventional extraction techniques. The total phenolic content and antioxidant activity of the extracts were determined. Results indicated an increase in phenolic compounds as temperature and pressure were elevated. The reduction power of the SWE extract was significantly different from that of BHA (synthetic antioxidant) and ascorbic acid (natural antioxidant) [39].

The purpose of the study by Sharifi *et al.* [50] was to utilize Response Surface Methodology (RSM) to optimize SWE of anthocyanins and total phenolic compounds from *Berberis vulgaris* fruit. The optimal conditions were 157.50 °C and 29.64 min, resulting in maximum anthocyanin content, total phenolics, and antioxidant activity. The SWE extracts showed over 91% DPPH radical scavenging activity [50].

3.5. Others (Reflux, Solid-liquid, HPCD, Infusion, Decoction, Microwave-assisted extraction (MAE), and Accelerated solvent extraction (ASE))

These methods are less commonly used for extracting bioactive compounds from barberry (Fig. 2. and Table 1).

As reflux extraction requires high temperatures and long extraction times, heat-sensitive compounds may be degraded [52]. It is also time consuming and consumes more energy than other modern extraction methods [53]. Despite the simplicity of solid-liquid extraction, it often relies on organic solvents, which can result in solvent contamination of the final product [52]. The requirement for solvent recovery adds complexity and environmental concerns, while the extraction process itself can be relatively costly and inefficient for large-scale applications [54]. HPCD extraction is effective, however, it requires specialized equipment and precise temperature and pressure control. Along with the high operational costs, this complexity makes it less feasible for small-scale or industrial operations in search of bioactive compounds from plants like barberry [55]. The infusion method is a simple and low-cost technique; however, its extraction efficiency is low [56]. It takes a long time to complete the process and it is generally ineffective in the preparation of certain bioactive compounds, especially those that are thermally sensitive or are not readily soluble in water [52]. Decoction involves boiling plant material in water to extract water-soluble compounds. Nevertheless, high temperatures can degrade heat-sensitive compounds, and the method is also energy- and time-consuming [57]. Moreover, it is not suitable for extracting compounds that require low-temperature conditions [24,58]. The MAE process is faster than traditional methods; however, the high temperatures involved can degrade sensitive compounds, such as anthocyanins. In addition, the equipment is expensive and specialized, which limits its use in large-scale extractions [59]. ASE requires sophisticated equipment to maintain high-pressure and high-temperature conditions [60,61]. Although this method can be efficient in terms of extraction speed, it is costly for smaller operations and

requires careful control of extraction parameters, which makes it less practical for large-scale industrial operations [62]. These limitations, such as significant energy consumption, the requirement for specialized equipment, and difficulties in maintaining optimal extraction conditions, explain why these methods are less commonly used for the extraction of bioactive compounds from barberry.

Aliakbarlu *et al*. [63] used reflux to evaluate the antioxidant and antibacterial activities of water extracts from barberry (*Berberis vulgaris*) and other plants. Barberry extracts showed the highest antioxidant activity [63]. In another research, optimization of the solvent extraction method of bioactive compounds from seedless barberry (*Berberis vulgaris*) was carried out using response surface methodology and reflux. According to these results, optimal extraction conditions were identified at 50 °C for 120 min [64].

Boeri *et al*. [65] investigated the antioxidant capacity of *Berberis* ethanolic extracts using solid-liquid extraction, and the results were satisfactory [65].

Sharifi *et al*. [66] used HPCD extraction on *Berberis vulgaris* and found that both extraction time and pressure significantly affected the yields of anthocyanins, phenolic compounds, ascorbic acid, and antioxidant activity. The optimal extraction conditions were 200 bars and 44.64 min [66].

The study conducted by Aliakbarlu *et al*. [33] on antioxidant activities of *Berberis vulgaris* fruit extracts obtained by infusion and decoction highlighted that acetone and ethanol extracts showed the highest activity. In contrast, acetone and decoction extracts were the most effective. Water extract antioxidant activity increased with heating time, with decoction outperforming infusion. The acetone extract had the highest phenolic content, and both acetone and decoction were recommended as effective natural antioxidants for the food industry [33].

Belwal *et al*. [37] studied *Berberis jaeschkeana* fruits phytochemicals using MAE. They found that microwave power, methanol, and HCl concentration significantly influenced polyphenol extraction. MAE provided higher yields of phenolics, flavonoids, tannins, and antioxidant activity than UAE and maceration. The optimized MAE conditions offered faster extraction with less solvent, making it an efficient and green method for polyphenolic antioxidant extraction in the nutraceutical industry [37].

Kukula-Koch *et al*. [67] optimized green extraction methods to obtain *Berberis cretica* extracts with high antioxidant capacity. The study used Pressurized Liquid Extraction (PLE), Accelerated Solvent Extraction (ASE), and Supercritical Fluid Extraction (SFE) combined with ASE. The results showed that both the extraction method and solvents significantly influenced antioxidant activity and chemical composition, with the most effective results achieved with methanol and a 50:50 water-ethanol mixture [67]. Another study aimed to assess *Berberis jaeschkeana* fruit antioxidant potential using ASE. The methanol extract demonstrated significant levels of total phenolics and flavonoids, along with considerable antioxidant activity. These results indicate that the methanolic extract of *Berberis jaeschkeana* fruit possesses notable antioxidant properties, suggesting its potential as a chemopreventive agent for chronic diseases [68].

Table. 1. Overview of the recent studies (2009–2023) on extraction of bioactive compounds from barberry.

Species	Method	Solvent	Processing conditions	Application	Antioxidant capacity	TPC	TAC	Ascorbic acid	TFC	Ref.
B.iliensis	UAE	Ethanol 50%	Ultrasonic bath, T: 90 min, R: 1:10, Temp: RT	Antioxidant and antibacterial agent	DPPH: 620 IC_{50} µg/mL	112 mg GA/L	-	-	-	[2]
B.vulgaris	PE	-	-	Food additive	-	789.32 mg/100 g	931.05 mg/kg	256.48 mg/kg	-	[25]
B.vulgaris	Infusion	Water	R: 1:10, T: 10 min, Temp: 100 °C	Food additive	ABTS: 95.36 ± 0.25 mg/ml DPPH: 45.45 ± 2.30 mg/ml %	39.37 mg GAE/ g	-	-	-	[33]
	Decoction	Water	R: 1:10, T: 60 min, Temp: 100 °C	Food additive	ABTS: 96.54 ± 1.16 mg/ml DPPH: 60.20 ± 0.80 mg/ml %	48.89 mg GAE/ g	-	-	-	
	ME	Acetone	R: 1:10, T: Over night, Temp: 100 °C	Food additive	ABTS: 97.61 ± 0.82 mg/ml DPPH: 68.40 ± 0.75 mg/ml %	92.75 mg GAE/ g	-	-	-	
B.vulgaris	Reflux	Water	R: 1:10, T: 1 h, Temp: 100 °C	Antibacterial agent	DPPH: 87.50 mg/ml %	≈ 32 mg GAE/g	-	-	-	[63]
B.vulgaris	PE	Water	R: 5:1	Fruit juice	-	1040 ± 3.0 mg GAE/L	495.35 mg/L	-	-	[30]

Species	Method	Solvent	Processing conditions	Application	Antioxidant capacity	TPC	TAC	Ascorbic acid	TFC	Ref.
B.vulgaris	ME	Ethanol 20%	R: 1:20, T: 24 h, Temp: RT	Indicator film	-	-	0.724 ± 0.002 mg/mL	-	-	[34]
B.integerrima	ME	Ethanol 50%	R: 1:1, T: 24 h, Temp: RT	Nutraceutical industry and food packaging	DPPH ≈ 37 IC_{50} mg/L % ABST: 3.26 µM/g	-	-	-	-	[69]
B.asiatica	Water bath	Methanol 80%	R: 1:50, T: 30 min, Temp: 80 °C, pH: 3	-	ABTS 2721 ± 64 mM AAE/100 g FRAP 36,487 ± 1251 mM AAE/100 g DPPH 1685 ± 39 mM AAE/100 g	4659 ± 34 mg GAE/100 g	219 ± 18 mg CGE/100 g	-	0.63 ± 0.13 mg QE/100 g	[40]
B.jaeschkeana	MAE	Methanol 80% + 0.1 N HCl	R: 1:40, T: 5 min	Nutraceutical industry	DPPH: 6.72 ± 0.51 mM AAE/g ABTS: 2.03 ± 0.03 mM AAE/g FRAP: 1.13 ± 0.02 mM AAE/g	108.86 ± 1.13 mg GAE/g	-	-	188.43a ± 5.29 mg QE/g	[37]
	UAE	Methanol 80% + 0.2 N HCl	Ultrasonic bath, R: 1:70, T: 15 min, Temp: 70 °C, frequency 50 kHz	Nutraceutical industry	DPPH: 12.92 ± 0.87 mM AAE/g ABTS: 4.5 ± 0.14 mM AAE/g FRAP: 0.45 ± 0.02 mM AAE/g	77.45± 2.08 mg GAE/g	-	-	172.76b ± 1.40 mg QE/g	
	ME	Methanol 80% + 0.2 N HCl	R: 1:70, T: 15 min, Temp: 70 °C	Nutraceutical industry	DPPH: 7.68 ± 0.37 mM AAE/g ABTS: 3.45 ± 0.12 mM AAE/g FRAP: 0.36 ± 0.01 mM AAE/g	71.41 ± 1.78 mg GAE/g	-	-	158.80c ± 1.47 mg QE/g	
B.microphylla	Solid–liquid	Ethanol 50%	R: 1:25, T: 2 h, Temp: 60 °C	Food additive	ABTS: 116.25 ± 17 µmol TE/g DPPH: 137.80 ± 1.90 µmol TE/g	1035.03 mg GAE/100 g	40 µmol/g	-	-	[65]
B.vulgaris, *B.crataegina*	UAE	Methanol 80%	R: 1:6, Ultrasonic bath, T: 2 times 30 min	-	DPPH: 15.65 ± 0.35 IC_{50} mg/ml DPPH: 6.30 ± 0.28 IC_{50} mg/ml	71.54 ± 0.71 µg GAE/mg 73.48 ± 0.07 µg GAE/mg	-	43.5 ± 3.54 mg/L 40.5 ± 0.71 mg/L	-	[44]
B.vulgaris	PE	-	-	Fruit juice	DPPH: 83.14 ± 0.62 %	1074.12 ± 17.21 mg/100ml	718.50 ± 23.51 mg/L	-	-	[26]

Species	Method	Solvent	Processing conditions	Application	Antioxidant capacity	TPC	TAC	Ascorbic acid	TFC	Ref.
B.vulgaris	ME	Ethanol solution + HCl (15:85 v/v)	R: 1:4, T: 2 h, Temp: 30 °C	-	DPPH: 16.78 ± 0.21 IC_{50} mg/Ml %	416.51 ± 10.27 mg/L	223.97 ± 19.36 mg/L	-	-	[35]
B.crataegina	UAE	Methanol 80%	Ultrasonic bath, R: 0.1:10, T: 13.86 min, Temp: 57.41 °C	Food colorant	-	62.95 mg/100 g	2659.297 mg/L	-	-	[12]
B.vulgaris	UAE	Methanol	Ultrasonic bath, R: 1:10, T: 15 min, Temp: 25 °C, Then 24 h maceration	Antioxidant agent	FRAP: 1039 ± 3 µg TE/mg DPPH: 295 ± 1 µg TE/mg ABTS: 118.8 ± 0.9 µg TE/mg	494±2 µg GAE/mg dry extract weight	-	-	2170±4 mg RE/ mg	[45]
B.vulgaris	PE	-	-	Fruit juice	-	1598.246 ± 0.873 mg GAE/100 m	265.756 ± 0.432 mg/100 mL	-	-	[27]
B.vulgaris	PE	-	-	Fruit juice	DPPH: 42.89 ± 3.37 µg AAE /mL	992.18 ± 8.95 mg GAE/100 mL	6662.92 ± 8.54 mg/L	-	-	[31]
B.vulgaris	Solid-liquid	Ethanol 96%	T: 0.5 h	-	DPPH: 30%	-	-	-	-	[70]
B.vulgaris	ME	Water	R: 1.5:10, T: 60 min, Temp: RT	Food colorant	DPPH: 96.60 ± 1.03 %	2636.16 ± 11.86 mg GAE /100 g	47.69 ± 1.39 mg/100 g	-	-	[36]
B.vulgaris	ME	Ethanol 80% + 2% citric acid	R: 1:20, T: 120 min, Temp: 30 °C	Food additive	DPPH: 92.41 ± 0.25%	3269.05 ± 111.11 mg GAE/ kg	101.03 ± 1.89 mg /100g	-	-	[38]
B.vulgaris	Reflux	Acidified ethanol and distilled water (1:3)	T: 2 h, Temp: 50 °C	Food additive	-	-	609.25 ± 2.18 mg/100 mL	-	-	[71]
B.vulgaris	PE	-	-	Fruit juice	DPPH: IC_{50} 0.0152 ± 0.003 ml/mg	10.00 ± 1.82 mg GAE/100 ml	0.525 ± 0.001 mg/g	-	-	[32]
B.vulgaris	ME	Water	R: 1:20, T: 18 h	Antioxidant agent	DPPH: IC_{50}:3200	≈ 2200 mg GAE /100 gr	-	-	-	[39]
	SWE	Water	R: 1:30, T: 30 min, Temp: 180 °C, Pressure: 10 bar	Antioxidant agent	DPPH: IC_{50}: ≈ 2800	≈ 2650 mg GAE /100 gr	-	-	-	
B.vulgaris	UAE	Ethanol 70%	Ultrasound bath, T: 30 min, Temp: 50 °C	-	DPPH: 50.853 ± 0.246 mg TE/g FRAP: 302.458 ± 15.257 mg TE/g	100.862 ± 1.967 mg GAE/g	-	-	8.306 ± 0.509 mg QE/g	[46]
B.vulgaris	Reflux	Water	R: 2:5, T: 120 min, Temp: 50 °C	Food additive	DPPH: 84.260%	585.725 mg GAE/100 mL	208.392 mg/L	1292.56 mg/L	-	[64]
B.vulgaris	PE	-	-	Nutraceutical industry	DPPH: 80.53 ± 2.32%	221.45 ± 3.61 mg GAE/100 g	-	-	-	[28]
B.vulgaris	-	-	-	-	DPPH: 40.31 ± 2.15% FRAP: 0.45 ± 0.01 µmol Fe^{+2}/100 g	65.33 ± 1.98 mg GAE/100 g	3298.00 ± 93.61 mg CGE/100 g	1219.89 ± 10.64 µg/g	-	[72]
B.jaeschkeana	ASE	Methanol 80%	3 cycles, T: 10 min, Temp: 80 °C	Antioxidant agent	ABTS: 31.15 mg TE/g	43.52 ± 2.37 mg GAE/g	-	-	6.08 ± 0.48 mg QE/g	[68]

Species	Method	Solvent	Processing conditions	Application	Antioxidant capacity	TPC	TAC	Ascorbic acid	TFC	Ref.
B.vulgaris	ASE	Methanol 80%	3 cycles, T: 10 min , Temp: 80 ℃	Antioxidant agent	ABTS: 117.93 ± 0.01 mg TE/g DPPH: 64.73 ± 0.008 mg TE/g	52.77 ± 0.01 mg GAE/g	-	-	6.11 ± 0.02 mg QE/g	[73]
B.vulgaris	Press	-	-	Food additive	TEAC: 44.2 ± 7.13 mmol TE/ L FRAP: 52 ± 17.9 TE mmol /L	2962 ± 16.21 mg GAE/L	665.4 ± 14.85 mg/L	-	-	[29]
B. amurensis	Press	-	T: 10 min	Fruit juice	ABTS: 71 ± 1 µmol TE/g	636 ± 20 mg GAE/100 g	217 ± 9 mg/100 g	16.60 ± 2.48 mg/100 g	-	[3]
B.microphylla	-	Ethanol	R: 1.5:100, T: 10 min, Temp: 4 ℃	Antioxidant agent	36.6 ± 0.2 $(kg^{-1}) \times 10^{-5}$	11.4 ± 0.6 g/ kg	0.645 mg/ kg	-	-	[74]
B.vulgaris	Hot water bath	Water	R: 2:5, T: 80 min, Temp: 60 ℃	-	DPPH ≈ 72%	368.3 mg GAE/100 mL	167.63 mg/100 mL	≈ 1400	-	[9]
	HPCD	Water	R: 1:1, Pressure: 150 bar, T: 40 min, Temp: 60 ℃	-	DPPH ≈ 77%	214.16 mg GAE/100 mL	168.85 mg/100 mL	≈3500	-	
	SWE	Water	Pressure:170 ± 5 bar, T: 30 min, Temp: 140 ℃	-	DPPH ≈ 87%	457.20 mg GAE/100 mL	≈ 18 mg/100 mL	≈ 400	-	
	Cold press	-	Pressure: 109 MPa	-	DPPH ≈ 83%	310 mg GAE/100 mL	≈ 99 mg/100 mL	≈ 3100	-	
B.vulgaris	SWE	Water	T: 29.64 min Temp: 157.50 ℃ Pressure:170 ± 5 bar	Food additive	DPPH: 91.15%	568.75 mg GAE/100 mL	9.84 mg/mL	-	-	[50]
B.vulgaris	HPCD	Water	T: 44.64 min Temp: 60 ℃ Pressure:200 bar	Food additive	DPPH: ≈ 84%	329.815 mg GAE/100 mL	178.658 mg/L	3468.7 mg/L	-	[66]
B.vulgaris	ME	Ethanol	R: 1:10, T: 72 h Temp: RT	Food additive and antibacterial agent	DPPH: IC_{50}: 88.0 ± 0.5 µg/ mL	51.3 ± 2.5 mg GAE/ mL	39.6 ± 1.2 mg / L	-	-	[1]
B.heteropoda	UAE	70% acidified ethanol (0.1% HCl, v/v)	Three times, R: 1:30, T: 30 min, Temp: 25 ˚C	Antioxidant agent	DPPH (IC_{50}): 20.27 ± 0.26 µg/mL, ABST: 13.89 ± 0.13 mg/mL	68.55 mg GAE /g	19.83 mg /g	-	108.42 mg QE/g	[47]
B.vulgaris	UAE	Water	Temp: 35 ℃	FOOD additive	DPPH: 85.90 ± 0.67 %	282.25 ± 0.02 mg GAE/100 ml	150.90 ± 0.02 mg /100 ml	69.55 ± 0.20 mg/L	-	[48]

Total phenolic content (TPC), total anthocyanin content (TAC), total flavonoid content (TFC), Temp: temperature, T: time, R: ratio of sample/ solvent (g/ml), Accelerated solvent extraction (ASE), high-pressure CO2 (HPCD), subcritical water (SWE), ultrasound assisted extraction (UAE), microwave assisted extraction (MAE), press extraction (PE), maceration extraction (ME), RT: room temperature.

The solvent has a significant impact on the efficiency and selectivity of the extraction process. Studies have shown that different solvents exhibit different selectivity depending on the specific nature of the compounds targeted. It is essential to consider these selectivity properties when tailoring extraction methods in order to isolate specific components from complex mixtures. By choosing the appropriate solvent, the extraction process can be optimized to preferentially extract desired compounds while minimizing co-extraction of unwanted substances [75].

Recent studies have shown that water, methanol, and different concentrations of ethanol are three of the most popular solvents used for extraction of bioactive compounds from barberry (Fig. 3.). The most commonly used one was water (42.86%). Methanol 80% was also the most common hydroalcoholic ones (22.86%). Water, in particular, is the most commonly used solvent in analytical processes due to its affordability and efficacy. Additionally, its ability to interact with a variety of compounds, particularly polar bioactive molecules, further contributes to its popularity. Further, water has expanded its applications in analytical chemistry as a result of its unique ability to undergo changes in its physicochemical properties, such as its temperature and pressure. For instance, water is capable of solvating polar

compounds at elevated temperatures and pressures, allowing extraction of less polar compounds, thereby expanding the range of substances that can be extracted [76]. Furthermore, water is an essential and environmentally friendly solvent for biochemical reactions in nature. The fact that it is non-toxic as well as its ability to dissolve a wide range of polar organic compounds, such as alcohols and carboxylic acids, further supports its utility in extracting bioactive compounds. Although water is ineffective at extracting non-polar compounds, this limitation can be overcome through the use of co-solvents or by adjusting the parameters of extraction. In general, water remains a key solvent for the extraction of bioactive compounds from barberry, due to its versatility, environmental safety, and adaptability to a range of conditions [76,77]. Methanol (80%) is well known for its effectiveness in extracting bioactive compounds from barberries due to its optimal polarity, which makes it capable of dissolving both polar and moderately non-polar compounds. It enhances the solubility of phenolics, flavonoids, and antioxidants, while maintaining their stability. Furthermore, the presence of water in the 80% methanol solution facilitates the extraction of water-soluble compounds, improving the overall yield of the extraction. Additionally, methanol is compatible with several analytical techniques, including HPLC and spectrophotometry, which supports its use in the extraction of bioactive compounds. This makes it an effective and reliable solvent for extractions [57,78]. Ethanol at various concentrations is also an effective solvent for extracting bioactive compounds from barberry due to its ability to dissolve both polar and non-polar compounds. Generally, higher concentrations (70-90%) extract lipophilic compounds, while lower concentrations (40-60%) target more polar compounds such as flavonoids and phenolic acids. This versatility allows for the selective extraction of a variety of bioactive molecules. Moreover, ethanol is non-toxic, environmentally friendly, and compatible with analytical techniques, making it a suitable solvent for both industrial and research purposes [79,80].

Abdykerimova *et al.* [2] evaluated the antiradical activity and phenolic content of four different extracts (water, ethanol, ethanol-water 7:3 v/v, and ethanol-water 1:1 v/v) derived from three parts of the barberry plant. The ethanol-water (1:1 v/v) extract from the leaves exhibited the highest antiradical potential and phenolic content, which was likely influenced by the abundant presence of simple phenolic acids, flavonoids, and glucaric acid esters [2].

Aliakbarlu *et al.* [33] assessed the antioxidant activities of acetone, ethanol, and water extracts (infusion and decoction) from *Berberis vulgaris* fruit. The acetone and ethanol extracts showed the highest radical scavenging activity. In addition, acetone extract and decoction exhibited the strongest antioxidant effects in DPPH and reducing power assays. The antioxidant potential of water extracts increased with longer heating times, with the decoction being more effective than the infusion. The acetone extract had the highest phenolic content, suggesting its potential as a natural antioxidant in the food industry [33].

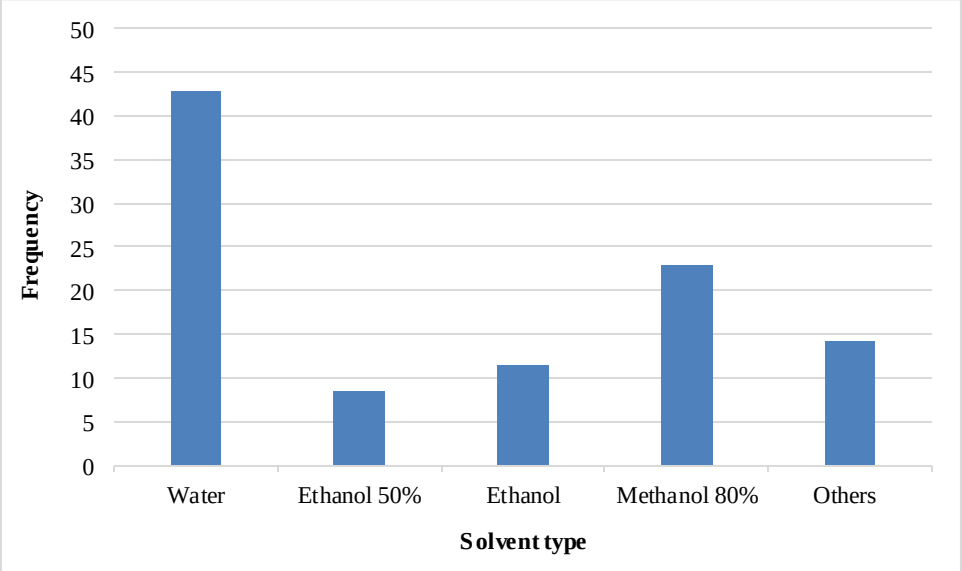

Fig. 3. Frequency distribution of solvent types used for the extraction of bioactive compounds from *Berberis* species in studies published between 2009 and 2023.

Antioxidants stabilize free radicals by donating or accepting an electron. This suppresses their high reactivity caused by unpaired electrons. Free radicals cause oxidative damage by undergoing chain reactions. In these reactions, the unpaired electrons are passed on to the recipient molecule converting it into a free radical, and thus neutralizing the donor molecule. Free radicals in biological systems are mostly derivatives of oxygen known as “ROS” (reactive oxygen species). However, nitrogen derivatives also exist (“reactive nitrogen species,” RNS). Molecules with loosely bound hydrogen atoms can donate these atoms, in a similar manner to

electrons, to free radicals to reduce or neutralize them. Examples of free radicals are hydroxyl (OH), peroxyl (LOO), glutathione (GSH), tocopherol (Toc), ascorbate (Asc), and Fe3+ -EDTA [81]. Fig. 4. summarizes the DPPH antioxidant activity of barberry extracts obtained by different extraction methods, as reported in the included studies. In the compiled data, antioxidant activity varied significantly with temperature, extraction technology, and extraction time. Overall, SWE tended to yield higher DPPH values than the other methods *($P < 0.05$)*, and pairwise comparisons between methods were statistically significant. In SWE, phenolic compounds appear at high temperatures and due to the correlation of these compounds and antioxidant activity, antioxidant activity has increased [82]. One of the disadvantages of this method is damage to temperature-sensitive compounds such as vitamin C. The second place belongs to UAE. The high DPPH in UAE is due to ultrasound's ability to enhance mass transfer, break down cell walls, and efficiently release antioxidant compounds like polyphenols, without thermal degradation [83]. Furthermore, PE, as the most widely used method, ranks third in this field. The method preserves antioxidant properties by using pressure and low temperatures, making it highly effective [84].

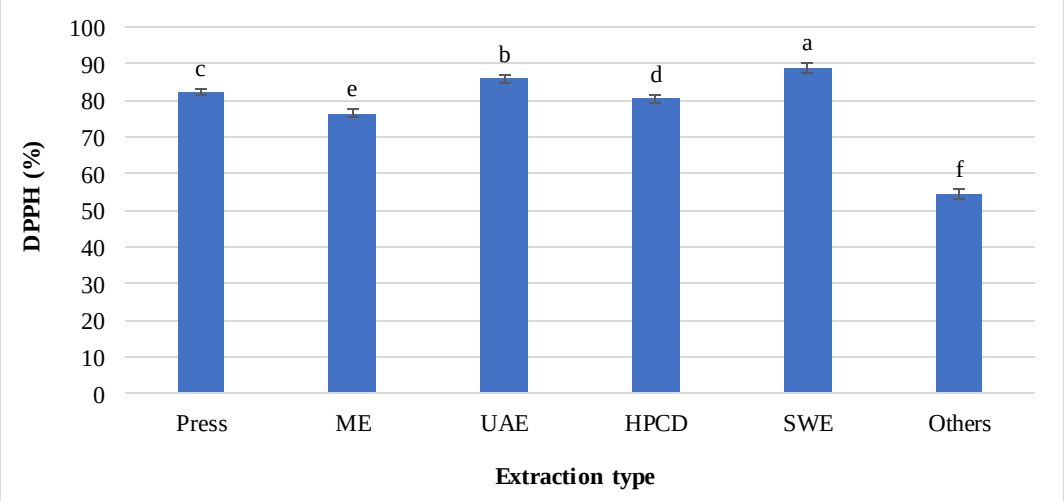

Fig. 4. Effect of different extraction methods on the DPPH (%) of barberry (*Berberis spp.*) extracts, based on aggregated data extracted from the included studies (see Table 1 for detailed references). Values represent the mean DPPH reported in individual publications, and different letters indicate statistically significant differences *($p < 0.05$)*.

The most common antioxidant in the human diet is polyphenol, which is a secondary metabolite found in plant-based foods. These compounds include a variety of flavonoids (such as anthocyanins, flavanols, flavanones, flavones, flavonols, and isoflavonoids), tannins, stilbenes, and phenolic acids, as well as their derivatives [85]. The ability of polyphenols to neutralize free radicals allows them to play an important role in disease prevention as well as improving health [86]. There is evidence that polyphenols can enhance performance in healthy individuals [87], stimulate the growth of health-promoting species, and inhibit the development of pathogenic organisms in the gut microbiota [88]. The supplementation of polyphenolic compounds can assist in treating inflammatory bowel diseases [89], improving the functions of the brain [90], and improving the lipid profile and inflammation status [91].

Fig. 5. illustrates the total phenolic content of barberry reported in the selected studies for different extraction methods. The data were grouped into two categories: values expressed on a dry-matter basis (blue, mg GAE/100 g) and values expressed on a solution basis (red, mg GAE/100 mL). The classification was chosen because some studies reported phenolic content on a dry weight basis whereas others reported it on a fresh weight basis (soluble). Hence, this classification encompasses both aspects and facilitates comparisons among different research studies. To our knowledge, this type of classification has not been presented before. This study provides an improved understanding of the efficiency of extraction, allowing researchers to make more accurate comparisons and improve the quality of results in the field. As shown in Fig. 5., when TPC was expressed on a dry-matter basis, UAE generally resulted in the highest reported values among the evaluated methods. This is due to its ability to enhance mass transfer and break down plant cell walls using ultrasonic waves. This results in the more efficient extraction of phenolic compounds, particularly those bound within the plant matrix [92]. Additionally, the SWE and ME methods also showed high phenolic content, as SWE utilizes high temperature and pressure to increase the solvent's extracting power [93], while ME benefits from prolonged solvent contact with the plant material, allowing for more thorough extraction [52]. All extraction methods were statistically significant ($P < 0.05$). When TPC was expressed on a solution basis, ME showed the highest mean values among the methods, which may be related to its relatively efficient extraction of soluble phenolic compounds [52]. SWE and PE also exhibited comparatively high soluble-phase TPC values.

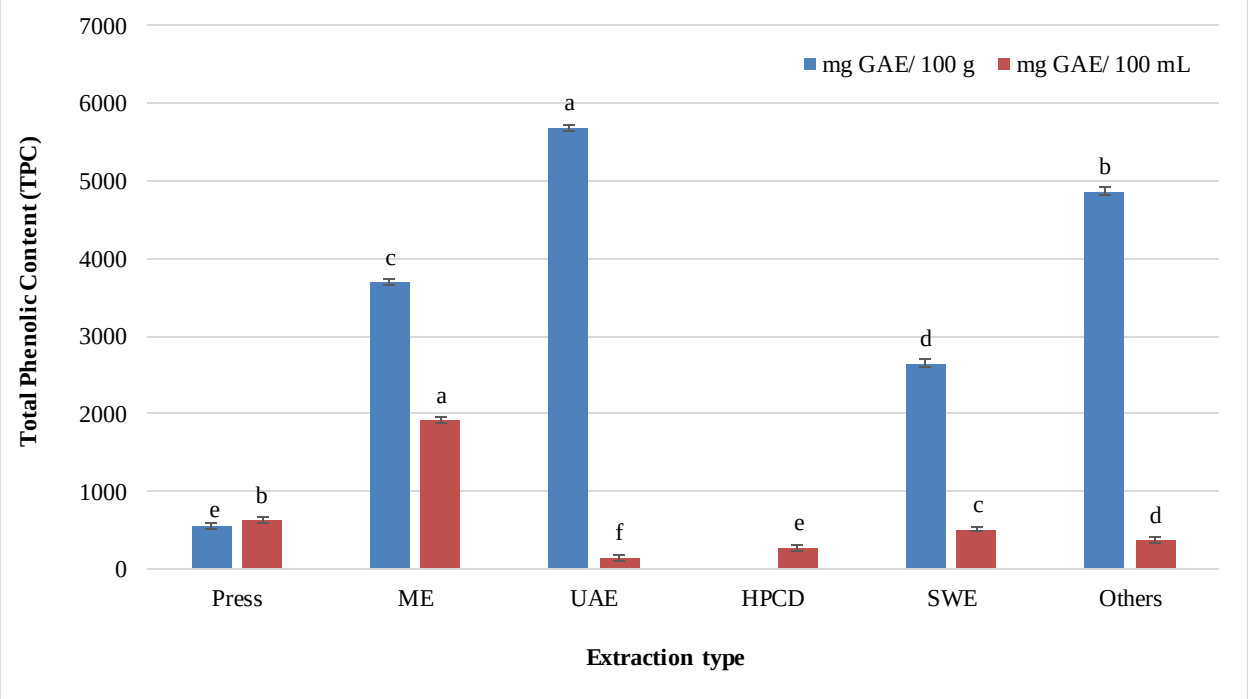

Fig. 5. Total phenolic content (TPC) of barberry extracts obtained using different extraction methods, based on aggregated data reported in the included studies (see Table 1 for detailed references). Blue bars represent TPC values expressed on a dry-weight basis (mg GAE/100 g), while red bars represent values expressed on a fresh or soluble basis (mg GAE/100 mL), as reported by the original authors. Different letters above the bars indicate statistically significant differences among extraction methods *($p < 0.05$)*.

In the plant kingdom, anthocyanins are phenolic compounds classified as flavonoids [94]. These large and most significant groups of water-soluble pigments are responsible for the color of many fruits and flowers such as red, blue, purple and orange [95]. Therefore, anthocyanins are ideal candidates for use in the food industry as potential alternatives to synthetic dyes. This is due to their attractive colors and high water solubility. This allows their incorporation into aqueous-based food media. Moreover, anthocyanins have antioxidant activity. It plays a crucial role in the prevention of neuronal and cardio-vascular disease, cancer, and inflammation, among other things [96]. Anthocyanins have a flavylium cation structure (C_6-C_3-C_6) and vary based on the number and position of hydroxyl, methoxyl groups, sugar types (mainly glucose, rhamnose, xylose, etc.), and attached acids. They can be mono-, di-, or tri-glycosides, with aglycones called anthocyanidins. The most common anthocyanidins include cyanidin, delphinidin, pelargonidin, malvidin, peonidin, and petunidin [18].

Fig. 6. shows the total anthocyanin content of barberry reported in the literature for different extraction methods. The classification of anthocyanins was also based on dry and soluble matters, as with TPC. There are two categories of values: the first represents values expressed in terms of dry matter (blue, mg/100 g), while the second represents values expressed in terms of soluble matter (red, mg/100 mL). According to the compiled data, TAC expressed on a dry-matter basis was highest for UAE, similar to the trend observed for TPC. High-frequency sound waves generate cavitation bubbles that create micro-shocks, increasing mass transfer and improving solvent penetration. This leads to a more efficient extraction of anthocyanins from the plant matrix, resulting in a higher yield than other extraction methods [92]. Other techniques, including reflux, solid–liquid extraction, HPCD, infusion, decoction, MAE, and ASE, also yielded relatively high TAC values in individual studies. The overall comparison between methods in our meta-analysis indicated statistically significant differences *($P < 0.05$)*. For TAC expressed on a solution basis, SWE presented the highest mean values among the evaluated methods. Subcritical water, used in SWE, has a higher solving power than water at room temperature. This allows it to better dissolve and extract anthocyanins and other phenolic compounds from plant material [97]. Additionally, the UAE and PE methods also exhibited high TAC.

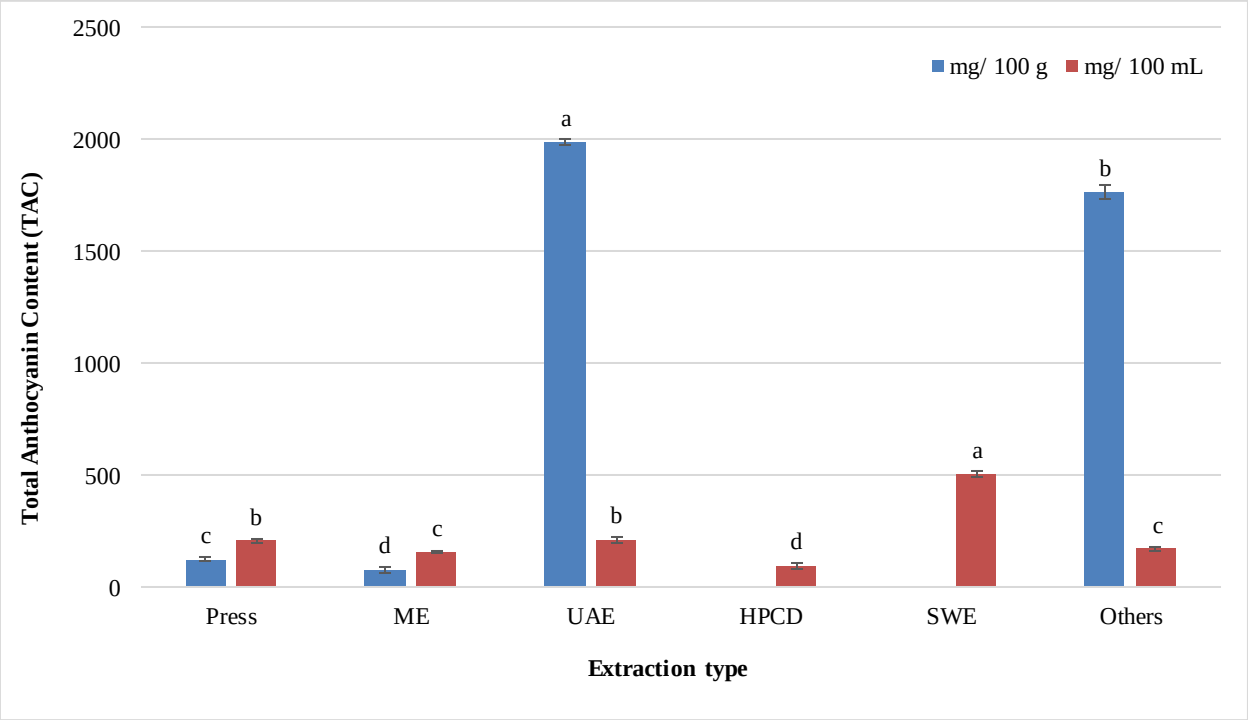

Fig. 6. Total anthocyanin content (TAC) of barberry *(Berberis spp.)* extracts obtained using different extraction methods, based on aggregated data extracted from the included studies (see Table 1 for detailed references). Blue bars represent TAC values expressed on a dry-weight basis (mg/100 g), while red bars represent soluble or fresh-weight values (mg/100 mL), as reported in the original studies. Different letters above the bars indicate statistically significant differences among extraction methods ($p < 0.05$).

4. Conclusions

This meta-analysis and systematic review, provides a thorough evaluation of various extraction methods for bioactive compounds from *Berberis* species, emphasizing their efficiency in extracting key compounds such as phenolics, anthocyanins, and antioxidants. The meta-analysis indicates that press extraction and ultrasound extraction are the most widely used techniques, while subcritical water extraction stands out for its superior antioxidant activity. Water and methanol were identified as the most effective solvents, further influencing the extraction yield and composition. These results underscore the importance of selecting the appropriate extraction method and solvent to optimize both the quantity and quality of bioactive compounds from barberry, which has significant implications for their use in the pharmaceutical, food, and nutraceutical industries. Moreover, while current methods show promising results, further research is necessary to optimize extraction parameters, evaluate the sustainability of these processes, and explore their scalability for large-scale industrial applications.

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