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Recent advances in the extraction of bioactive compounds with subcritical water: A review

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ABSTRACT

Background: Because of the important role of bioactive compounds in functional foods and health care, more and more attention has been paid to the active components extracted by green extraction methods. However, how to ensure the extraction yield and biological activity during the extraction process is an urgent problem to be solved. Subcritical water extraction (SWE) is a promising engineering method, which provides an environmentally friendly technology for extracting various bioactive compounds from natural products. Especially, under high temperature and high pressure, subcritical water can change the polarity and dielectric constant of solvents, thus contributing to a better extraction process, improving the mass transfer efficiency of the extracts and maintaining its biological activities, which has a high application prospect.
Scope and approach: This review provided an update overview on the fundamental principles and bioactive compounds extraction with subcritical water. This will contribute to deepen the understanding of SWE and provide theoretical basis and reference value for further improving the application of subcritical water.
Key founds and conclusions: It is expected that this green and efficient extraction technology will be increasingly applied in the extraction of more bioactive ingredients in the near future. In addition, future research should consider combining SWE with other physical extraction techniques to ensure the retention of the biological ingredients better. These active compounds with SWE have great potential in health care medicine and functional foods. Meanwhile, future researches should focus on consumer acceptability, safety, legal aspects, and commercial availability of health products.

1. Introduction

Natural active ingredients play an important role in life activities. More and more studies focus on these active ingredients (Chan, Ngoh, & Yusoff, 2012; Chien & Norman, 2009; Kai, Michela, Antonio, & Annamaria, 2015; Levac, Rivard, & Missiuna, 2012; Rojas-Graü, Soliva-Fortuny, & Martín-Belloso, 2009; Wen, Zhang, Zhang, et al., 2019; Zhang, Wen, Zhang, et al., 2019; Zhang, Zhu, & Jiang, 2014). Different active ingredients have different biological effects and were widely used in the manufacture of functional foods and the treatment of human diseases (Kroyer, 2004; Liu, 2017; Zhang, Zhang, Wen, et al., 2019). The discovery and extraction of biological ingredients have important practical significance for the development of human society. Therefore, obtaining bioactive substances with suitable extraction methods from natural products is a frontier topic in food and pharmaceutical industries (Joana Gil-Chávez et al., 2013).

At present, a wide variety of biologically active ingredients are separated from all sorts of natural products, such as animals (Seinen et al., 1977), plants (Rios & Recio, 2005), fungi (Zjawiony, 2004), and microorganisms (Georgiou, Lin, & Sharma, 1992), among others. In order to better characterize and quantify the active compounds, it is very important to choose an effective and appropriate extraction method. There are many factors which can influence the extraction process, including the matrix properties, solvent, temperature, pressure, time applied, and ratio of solvent to matrix (Hernández, Lobo, & González, 2009). In recent years, the active compounds have been extracted by using various extraction methods, including Soxhlet extraction, impregnation method, and hot water extraction (Kimbaris et al., 2006; Trochimczuk, Kabay, Arda, & Streat, 2004; Zhao et al., 2010). However, these methods have a number of obvious disadvantages. For example,

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Soxhlet extraction may cause a large amount of waste of organic reagent, and the extraction efficiency is low. These shortcomings limit the application of this method in industrial amplification (Armenta, Esteve-Turrillas, Garrigues, & de la Guardia, 2017). The disadvantages of the impregnation method are that the extraction time is long, and the extraction efficiency is low. Besides, the extracts with this method is prone to mold, and it is necessary to add a preservative. In addition, the volume of the extracts is large, and then a concentration step is required. For hot water extraction, low extraction rate is still one of the defects. Apart from this, the temperature of hot water extraction is high, and there is also a risk of denaturation of heat sensitive compounds (Chi et al., 2018). Based on above situation, a variety of mature innovative extraction techniques have been developed for the extraction of highly active compounds from natural products, including subcritical water extraction (SWE) (Zhang, Chen, et al., 2019; Zhang, Wen, Duan, et al., 2019; Zhang, Wen, Gu, et al., 2019; Zhang, Wen, Li, et al., 2019; Zhang, Wen, Qin, et al., 2018; Zhang, Wen, Zhang, et al., 2018), supercritical fluid extraction (SFU) (Clifford & Williams, 2000; McHugh & Krukonis, 2013; Reverchon & De Marco, 2006), ultrasound-assisted extraction (UAE) (Wen, Zhang, Yao, et al., 2018; Wen, Zhang, Zhang, et al., 2018; Wen, Zhang, Zhou, et al., 2019; Wen, Zhang, Zhou, et al., 2018), microwave-assisted extraction (MAE) (Kaufmann & Christen, 2002; Lopez-Avila, Young, & Beckert, 1994; Mandal, Mohan, & Hemalatha, 2007), ultrahigh pressure-assisted extraction (UPE) (Prasad et al., 2009; Prasad et al., 2010), pulsed electric field extraction (PEF) (Corrales, Toepfl, Butz, Knorr, & Tauscher, 2008; Fincan, DeVito, & Dejmek, 2004), among others. Especially, SWE has captured more and more attention due to its safety, efficiency, and environment protection. Large amounts of bioactive ingredients such as polysaccharides, proteins, antioxidants, and polyphenols (Herrero, Cifuentes, & Ibañez, 2006; Zakaria & Kamal, 2016) were extracted by using subcritical water. In addition, subcritical water has a modification effect on the molecular structure, which is beneficial with improving its biological activities of active ingredients (Getachew & Chun, 2017). As an environmentally-friendly and efficient extraction technology, SWE technology has shown potential value for application in multiple extraction fields.

Based on these, this review concluded the recent progress in the application of SWE to the extraction of various bioactive constituents in the food and pharmaceutical industrials. The first section highlighted the properties of subcritical water, including its principles, mechanism, influencing factors, and devices. The second section discussed the extraction of various biologically active constituents by using subcritical water. It is expected that all these results could contribute to the application of SWE in the related industries.

2. Fundamental principles of SWE

2.1. Changes in properties of water

In general, water has three states including solid, liquid, and gas. Water is a highly polar solvent at room temperature and atmospheric pressure, and has a high dielectric constant (ε) because of its extensive hydrogen bonding structure (Teo, Tan, Yong, Hew, & Ong, 2010). Therefore, researchers didn't regard water as an effective extraction solvent for extracting non-polar or organic compounds. The nature of water is very different from other solvents, as it is the lightest in the gas state, lighter as a solid but much denser than predictable in liquid state. Many unique properties are due to the fact that there are two very strong hydrogen bonds in the water molecule. The hydrogen bonds were broken in the range of water with the increase of the temperature and pressure, thereby changing its properties. The phase diagram of water (Fig. 1) shows the different states of water under different temperature and pressure.

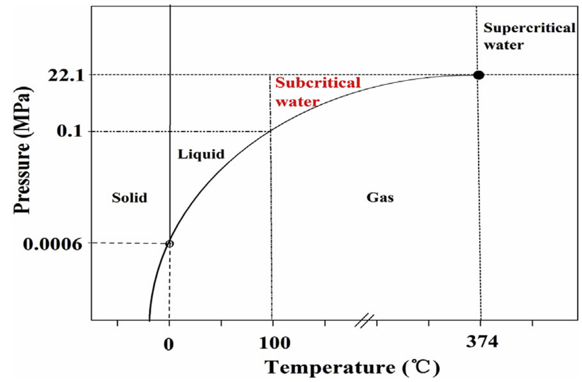

Fig. 1. Physical state of water at different temperature and pressure.

2.2. Principles of SWE

Subcritical water is defined as hot water at sufficient pressure to maintain the liquid state at critical temperature between 100 °C (the boiling point of water) and 374 °C (the critical point of water) under the critical pressure (1–22.1 MPa) (Ju & Howard, 2005; Ramos, Kristenson, & Brinkman, 2002). With the increase of temperature, its dielectric constant, viscosity and surface tension will decrease steadily, but its diffusivity characteristics are improved. At high temperature, sufficient pressure can be used to keep the water in a liquid state. The initial value of the dielectric constant of water at 25 °C is 80. Interestingly, when the temperature is raised to 250 °C and the pressure is 25 bar, the dielectric constant drops to 25, which falls between those of methanol (ε = 33) and ethanol (ε = 24) at 25 °C.Under such conditions, some properties of water are similar to organic solvents which can dissolve various medium and low polarity compounds (Hassas-Roudsari, Chang, Pegg, & Tyler, 2009; Kim et al., 2009; Nieto, Borrull, Marcé, & Pocurull, 2008; Zaibunnisa, Norashikin, Mamot, & Osman, 2009). The excellent property of SWE is that the dielectric constant can be varied over an extended range by varying the temperature and pressure (Gbashi, Adebo, Piater, Madala, & Njobeh, 2017). In addition, SWE causes mass transfer through diffusion and convection process (Xu, Huang, Wang, & Guo, 2016). The energy supplied with subcritical water can interrupt the interaction between adhesive (solute-matrix) and cohesive (solute-solute) by reducing the activation energy required for the desorption process (Teo et al., 2010), while the elevated pressure can assist in the extraction by forcing water to penetrate into the matrix (pores), where it is impossible to achieve it under the normal pressure (Pillot et al., 2019). Fig. 2 showed the various properties of water respond to the changes of temperature and pressure. As shown in Fig. 2, the polarity of

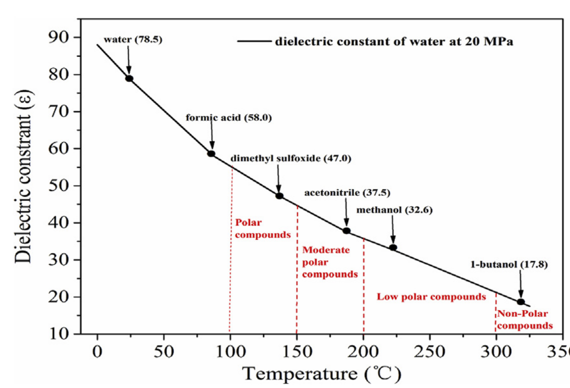

Fig. 2. Changes of water dielectric constant as a function of the temperature at constant pressure (20 MPa). The figure presents the dielectric constant values equivalents to some common organic solvents at room temperature and pressure (25 °C and 0.1 MPa).

subcritical water decreases with the increasing of temperature. Therefore, the polar, medium-polar, low-polar, and non-polar compounds can be separated, respectively.

2.3. Mechanism of SWE

The extraction mechanism of SWE involves four consecutive steps. The first step is to desorb the solute at various active sites in the sample matrix under high elevated temperature and pressurized conditions. The second step is mainly the diffusion of the extracts into the matrix. The third step depends on the sample matrix, and the solutes may partition themselves from the sample matrix into the extraction fluid. The final step is to elute and collect the sample solution from the extraction cell by chromatography (Hawthorne, Yang, & Miller, 1994; Ong, Cheong, & Goh, 2006). Previous studies have shown that the extraction mechanism of subcritical water conforms to the thermodynamic model (Holgate & Tester, 1994). In this model, two steps are required to extract a compound from a matrix. (1) The compounds must be desorbed from the original binding site of the sample matrix. (2) The compounds must be eluted from the sample in a manner which was similar to a front elution chromatography.

The reasons for improving the extraction efficiency of subcritical water can be summarized as the following two aspects: (1) improvement in solubility and mass transfer effects and (2) increased damage to surface balance (Ong et al., 2006). As the temperature increase of subcritical water, its properties change continuously and the ability of dissolving the analyte increases. This process is accompanied by a decrease in the viscosity and an increase in diffusibility, which allows better penetration of the matrix particles. In the dynamic extraction process of subcritical water, fresh water is continuously inflow, which can improve the mass transfer efficiency and increase the extraction yield. Besides, at high temperature and pressure, the surface of material can be destroyed. The increase of temperature can overcome the solute-matrix interaction which caused by hydrogen bonds, van der Waals forces, active sites in the matrix, and dipole attraction of solute molecules (Cvjetko Bubalo, Vidović, RadojčićRedovniković, & Jokić, 2015). When the temperature of water exceeds the boiling point, it is necessary to apply sufficient pressure to keep it in a liquid state. The presence of pressure can further promote the dissolution of the analytes from the pores of the matrix (Wijngaard, Hossain, Rai, & Brunton, 2012).

2.4. Influencing factors of SWE

2.4.1. Temperature

Temperature is the most important factor in the SWE process, which can influence the extraction efficiency and selectivity (Hawthorne, Grabanski, Martin, & Miller, 2000). The temperature not only affects the physicochemical properties of the water, but also causes degradation of the thermally labile analyte (Kronholm, Hartonen, & Riekkola, 2007). During SWE, the temperature is usually higher than the boiling point of the used fluid. Subcritical water has the advantages of high diffusivity, low viscosity and low surface tension under high temperature conditions. The increase in vapor pressure and rapid thermal degradation of the target compounds can improve the extraction efficiency of subcritical water (Smith, 2002). The high temperature changes the nature of subcritical water, the property of the water changes from polar to non-polar as the temperature increasing. This will promote the dissolution of less polar compounds in water (Budrat & Shotipruk, 2009; Cheng & Li, 2004; Ong, Woo, & Yong, 2000). However, under high temperature conditions, degradation of compounds and enhancement of reactions such as oxidation and hydrolysis may occur. For example, the amount of Terpene extracted from basil and oregano leaves by using subcritical water didn't increase between 200 and 250 °C, and there was a significant degradation (Yang et al., 2007). When subcritical water temperature exceeds 300 °C, it has a very low dielectric constant, the solubility of non-polar compounds can increase, thereby the extraction efficiency can be improved (Kronholm et al., 2004; Lüthje, Hyötyläinen, Rautiainen-Rämä, & Riekkola, 2005). Therefore, it is necessary to choose the suitable extraction temperature according to the various compounds when extracting them with subcritical water.

2.4.2. Pressure

By adjusting the pressure, the effect of changing the water phase can also be achieved. Medium pressure such as 15 bar at 200 °C and 85 bar at 300 °C is required to maintain the liquid state of water. During the process of SWE, the pressure is usually controlled between 10 and 80 bar to maintain the phase of the water in the liquid state under the extraction temperature. Unlike temperature, the pressure has no significant effect on the recovery efficiency of compounds from natural products by using subcritical water (Krieger, Wynn, & Yoder, 2000; Kronholm et al., 2004). Some previous studies have also shown that different pressures didn't improve the recovery of compounds during the process of SWE (Deng, Li, & Zhang, 2004; Deng, Yao, Wang, & Zhang, 2005; Kim et al., 2009).

2.4.3. Solvent flow rate

If the kinetics of compounds extraction depends on its solubility in the solvent, increasing the flow rate can improve the extraction rate of the compounds (Plaza & Turner, 2015). The higher flow rate not only shortens the residence time of the compounds in high temperature water, but also greatly improves the extraction efficiency. It is worth noting that too high extractant flow rate may result in an excessive dilution of the extracts, which requires an additional step of concentration after the end of extraction. However, if the extraction kinetics is only limited by the resolution and diffusion within the pores of the sample matrix, improving the flow rate will not increase the extraction yield of the compounds. In addition, the highest flow rate (4 mL/min) exhibited the best extraction yield of essential oils from coriander seeds (*Coriandrum sativum* L.), which mainly due to the facts that the mass transfer of essential oils from the surface of the solid phase into the water phase regulated most of the extraction process (Eikani, Golmohammad, & Rowshanzamir, 2007). Therefore, the extraction time and solid to liquid ratio need to be optimized during the dynamic SWE process. Similarly, it is necessary to consider optimizing the extraction time and solid to liquid ratio in the static of SWE process.

2.4.4. Particle size

Particle size is also a key factor in the SWE as it also has an important impact on the extraction process (Eikani et al., 2007; Khajenoori, Asl, Hormozi, Eikani, & Bidgoli, 2009; Wiboonsirikul & Adachi, 2008). In general, the extraction yield for small particle sizes is relatively high, while the extraction efficiency for large particle sizes is low and the extraction time needs to be extended (Wiboonsirikul & Adachi, 2008). Finer particle sizes reduce the diffusion distance of the compounds in the matrix and increase the contact area between the sample matrix and the extractant, thereby reducing extraction time and increasing extraction efficiency.

2.4.5. Other factors

There are some other factors that can affect the extraction process of subcritical water, including extraction time (Zhang, Wen, Chen, et al., 2019), modifiers and additives (Arapitsas & Turner, 2008; Kiathevest, Goto, Sasaki, Pavasant, & Shotipruk, 2009), solvent-to-sample ratio (Ravber, Knez, & Škerget, 2015; Rezaei, Rezaei, Haghighi, & Labbafi, 2013), moisture content of the sample (Monrad, Srinivas, Howard, & King, 2012; Monrad et al., 2014), dynamic or static extraction modes (Teo et al., 2010).

2.5. Devices

When water is as the extraction solvent, it must be ensured that the

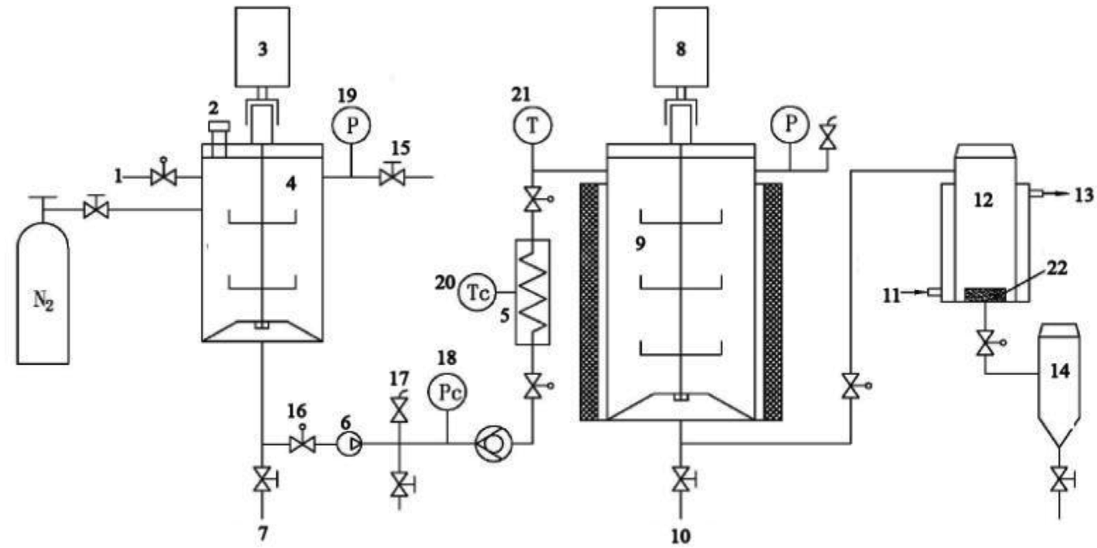

Fig. 3. Schematic diagram of SWE system. (1) water inlet; (2) feed inlet; (3) stirring system; (4) solid samples extraction cell; (5) heat exchanger; (6) pressure pump; (7) impounding reservoir; (8) stirring system; (9) solid samples extraction cell; (10) impounding reservoir; (11) cooling water inlet; (12) cooling pan; (13) cooling water outlet; (14) collector; (15) globe valve; (16) spherical valve; (17) safety valve; (18) pressure regulator controller; (19) pressure indicator; (20) temperature regulator controller; (21) temperature indicator; (22) filter plate.

water doesn't contain oxygen to make certain that the extracts are not oxidized. A common method of achieving water degassing is ultrasound (sonication) or nitrogen purging. The cost of ultrasound degassing is relatively low, but is less efficient than nitrogen purging. At least 60 min is necessary when degassing with ultrasound, as most of the oxygen in the water must be removed.

SWE equipment is not complex and mainly includes two types: dynamic (continuous-flow) systems and static (batch) systems, showed in Fig. 3 and Fig. 4.

2.5.1. Dynamic mode

Dynamic SWE devices typically include a pump, an extraction vessel, a heating device, a pressure controller, and a collector (Fig. 3). The pump used in the extraction process can be replaced with an old HPLC pump, because the accuracy of the flow rate during extraction is not as important as in chromatography. The extraction solvent is pumped into the extraction vessel by pump and the pressure controller delivers the water into the collector. The pump should reach a certain pressure (usually 3.5–20 MPa) to keep the water in a liquid state during the extraction process. The heating of the water usually uses an oven, a heat exchanger, a heating belt, and heating jacket, among others. In general, the stainless steel tube should be coiled inside the heater to ensure that the water temperature in the extraction vessel is the same as the set temperature. The role of pressure controller is to control the

Fig. 4. Simple static equipment of SWE in laboratory (A); industrial dynamic equipment of SWE (B, C) produced by Jiangsu University.

pressure in the extractor and prevent the boiling effect of the water. Fig. 4 (B, C) showed the industrial SWE equipment which were manufactured by Jiangsu University.

2.5.2. Static mode

Static SWE equipment (Fig. 4A) does not require a pump. However, if a pump is used to deliver water into the extraction vessel, two valves (inlet and outlet) need to be installed in the extraction vessel. If a pump is not used, the solvent needs to be added into the extraction vessel manually. When the vessel is closed and heated, the extraction process can only be carried out under the saturation pressure of the system. During the static SWE process, a magnetic stirrer is used to implement the convection to accelerate heat and mass transfer. For heating, an oven, a heating jacket or heating tape is appropriate. If the speed at which the extract is removed from the extractor needs to be controlled, a pressure limiter needs to be installed. During the static SWE process, the extraction yield of compounds is completely dependent on the equilibrium constant and solubility. For high concentration and low solubility compounds, complete extraction may not be possible due to the limitation of water volume.

2.5.3. Safety, legal aspects and current obstacles for large scale application

Up to now, most studies on bioactive compounds extraction with subcritical water still stagnated in laboratory scale, and the pilot scale also has rarely been reported (Kwon & Chung, 2015; Lachos-Perez et al., 2016; Liu et al., 2015; Yildiz-Ozturk, Tag, & Yesil-Celiktas, 2014). Therefore, the development of SWE equipment for large scale is still in its infancy, and it is still the most important facing issue currently. With the development of equipment, it is necessary to consider various problems encountered from small to large. For example, how to ensure safety, control energy consumption, and fully guarantee the yield and bioactivity of the extracts when the equipment is large enough. This is the first problem to be solved. Besides, legal aspects should be in place to refine the production standards and standardized use rules for SWE equipments. Only when these problems are all solved, the obstacles such as safety and energy consumption of large subcritical water equipment can be overcome.

2.6. Advantages and disadvantages of SWE

The advantages and disadvantages of SWE were shown in Table 1. SWE is an environmentally friendly method because it uses water as the extraction medium. Water is a green solvent that is non-toxic, non-flammable, and does not produce greenhouse gases and wastes. Water as an extraction solvent is economical because it is readily available, reproducible, and has a positive effect which ensures a safe and superior extracts (Chemat, Vian, & Cravotto, 2012). In addition, as the temperature and pressure change, the dielectric constant of the water changes, so that the polar, medium polarity, weakly polar and non-polar compounds can be extracted separately (Liang & Fan, 2013). Moreover, SWE equipment is much simpler than supercritical fluids, so the price is less expensive. Furthermore, the continuous operation is possible with SWE.

However, there are also some disadvantages of SWE. The biggest one is the need to raise the temperature. High temperatures are not suitable for the extraction of some heat sensitive compounds, as this may result in thermal degradation (Mokgadi, Turner, & Torto, 2013). In addition, water in subcritical state may be more reactive and corrosive than water at ambient conditions, since water in this state can catalyze or accelerate the hydrolysis and oxidation of some compounds (Teo et al., 2010). Apart from that, the moisture in the extraction solution is not easily removed and may need to be supplemented by some additional procedures, such as evaporation, chemical dehydration or precipitation. It is also worth noting that SWE equipment is not easy to clean.

3. Subcritical water extraction of bioactive compounds

3.1. Polysaccharides

Polysaccharides have a variety of biological activities, including immunological activity (Chen & Huang, 2018; Luo, Dong, et al., 2018), anti-tumor activity (Liu, Zhang, & Meng, 2018; Mao et al., 2019), and antioxidant activity (Ballesteros, Teixeira, & Mussatto, 2017; Wang, et al., 2016), among others. It is worth noting that many studies have focused on extracting polysaccharides by using subcritical water in recent years (Table 2). For example, our previous work has extracted polysaccharides with SWE from *Sagittaria sagittifolia* L. The conditions for obtaining the maximum yield of polysaccharides were pH 7, extraction temperature 170 °C, extraction time 16 min, and liquid to solid ratio 30:1 (mL/g), respectively. Especially, the immunological activity of polysaccharides with SWE is significantly better than traditional hot water extraction (Zhang, Chen, et al., 2019). A similar conclusion was confirmed by our other study (Luo et al., 2017). A bioactive polysaccharide from spent coffee grounds was extracted by combining ultrasound pretreatment followed with SWE. The maximum yield of polysaccharides was 18.25 ± 0.21%. Interestingly, this polysaccharide showed good antioxidant activities and a moderate hypoglycemic activity *in vitro* (Getachew, Cho, & Chun, 2018). In addition, ultrasonic-enhanced SWE of polysaccharides from *Lentinus edodes* was also compared with SWE, and the results showed that the polysaccharides with SWE had better antioxidant activities (Zhang, Wen, Qin, et al., 2018). Conversely, a polysaccharide was isolated from *Lycium barbarum* L. with ultrasound-enhanced SWE, and it had better antioxidant activity than SWE (Chao, Ri-fu, & Tai-qiu, 2013). The reason for the difference in these results may be due to the difference in raw materials or experimental conditions. However, it still proved that the combination of SWE and other technologies has great potential application. In addition, bioactive polysaccharide was extracted from Pacific oyster (*Crassostrea gigas*) by using subcritical water. This polysaccharide was confirmed to be a D-glucan with α-(1 → 4) configuration and showed good antioxidant, antihypertensive, and hypoglycemic activities (Getachew, Lee, Cho, Chae, & Chun, 2019). The β-glucans were extracted from waxy barley by pressurized hot water extraction. The results showed that the temperature (110–180 °C) and extraction time (15–75 min) had a strong influence on extraction process. Compared with the conventional process, pressured hot water caused a significant reduction of extraction time and an increase of Mw (almost 4 times) (Benito-Román,

Table 1
Advantages and disadvantages of SWE method.

Method	Advantages	Disadvantages
Subcritical water extraction	Water as an extraction solvent has the advantage of being green, cheap, and readily available. Polar, moderately polar, low-polar and non-polar compounds can be extracted separately. Less expensive instrumentation. Short extraction time and high efficiency. Continuous operation is possible.	It is not easy to remove moisture from the extracts and may require additional procedures including evaporation, chemical dehydration or precipitation. Thermal degradation may occur at higher temperatures. Equipment is not easy to clean.

Table 2
Recent studies of bioactive compounds extracted from natural products with SWE.

Compounds	Raw materials	Mode	SWE conditions	Functions	References
Polysaccharides	*Sagittaria sagittifolia* L.	Static	170 °C, 1 MPa, 16 min	immunity	Zhang, Chen, et al. (2019)
	Cordyceps militaris	Static	180 °C, 750 psi, 17 min	immunity	Luo et al. (2017)
	Spent coffee grounds	Static	178.85 °C, 20 Bar, 5min	Antioxidant	Getachew et al. (2018)
	Lentinus edodes	Static	140 °C, 5 MPa, 40 min	Antioxidant	Zhang, Wen, Qin, et al. (2018)
	Crassostrea gigas	Dynamic	125.01 °C, 14.93 min	Antioxidant	Getachew et al. (2019)
	Lentinus edodes	Static	100–150 °C, 5 MPa, 10–30 min	Antioxidant Antitumor	Zhang, Wen, Gu, et al. (2019)
	Waxy barley	Dynamic	110–180 °C, 15–75 min	–	Benito-Román et al. (2013)
	Areschoug	Dynamic	100–150 °C, 10–50 bar	Antioxidants	Saravana, Cho, et al. (2018)
	Lycium barbarum L.	Dynamic	110 °C, 5 MPa	Antioxidants	Chao et al. (2013)
Pectin	Apple pomace, citrus peel	Static	100–170 °C, 5 min	Antioxidants Antitumor	Wang, Chen, and Lü (2014)
	Passiflora edulis	Static	100–160 °C	–	Klinchongkon, Khuwijitjaru, and Adachi (2018)
	Sugar beet pulp	Static	120 °C, 10.7 MPa, 30 min	–	Chen, Fu, and Luo (2015)
	Citrus grandis L.	Dynamic	120 °C, 20 Bar	–	Liew, Teoh, Tan, Yusoff, and Ngoh (2018)
	Apple pomace	Static	140 °C, 5 min	Antioxidants Antitumor	Wang and Lü (2014)
	Cacao pod husks	Dynamic	121 °C, 103.4 bar, 30 min	–	Muñoz-Almagro, Valadez-Carmona, Mendiola, Ibáñez, and Villamiel (2019)
	Citrus fruits	Dynamic	60–160 °C, 20 MPa	–	Ueno, Tanaka, Hosino, Sasaki, and Goto (2008)
	Jackfruit peel waste	Static	138 °C, 9.15 min	Heat stability	Li, Fan, Wu, Jiang, and Shi (2019)
Proteins	Defatted rice bran	Static	180–280 °C, 5 min	Antioxidants	Hata, Wiboonsirikul, Maeda, Kimura, and Adachi (2008)
	Flaxseed meal	Dynamic	130–190 °C, 750 psi	–	Ho, Cacace, and Mazza (2007)
	Black rice bran	Static	200–260 °C, 0.002–4.7 MPa, 30–120 min	Antioxidants Properties	Wiboonsirikul, Hata, et al. (2007)
	Soy meals	Static	120 °C, 20 min	Physical properties	Lu, Chen, Wang, Yang, and Qi (2016)
	Microalgae	Dynamic	205–325 °C, 20.7 MPa	–	Garcia-Moscoso, Obeid, Kumar, and Hatcher (2013)
	Ginseng roots	Static	120–200 °C, 6 MPa, 20 min	Antioxidants	Wen, Zhang, Zhang, et al. (2018)
	Deoiled rice bran	Static	100–220 °C, 101.35 kPa-3.97 MPa, 0–30 min	Antioxidants	Sereewatthanawut et al. (2008)
	Soybeans	Dynamic	150 °C, 0.03–3.86 MPa	–	Ndlela, De Moura, Olson, and Johnson (2012)
	Porcine Placenta	Dynamic	170 °C, 10 bar, 10–30 min	–	Park, Kim, Min, Jo, and Chun (2015)
	Rice bran	Dynamic	150–250 °C, 4–10 MPa, 5–60min		Sunphorka, Chavasiri, Oshima, and Ngamprasertsith (2012)
	Rice Bran	Static	100–250 °C, 0.012–3.97 MPa, 5 min	Antioxidants Properties	Wiboonsirikul, Kimura, et al. (2007)
Polyphenols	*Sorghum bicolor* L.	Static	144.5 °C, 21 min	Antioxidants Antitumor	Wen, Zhang, Zhang, et al. (2018)
	Lotus seed epicarp	Static	160 °C, 15 min	Antitumor	Yan et al. (2019)
	Moringa oleifera leaf	Dynamic	100–150 °C, 2–20 min	Antioxidants	Matshediso, Cukrowska, and Chimuka (2015)
	Pistacia vera L.	Dynamic	100, 190 °C, 6.9 MPa	Antioxidants	Erşan, Üstündağ, Carle, and Schweiggert (2018)
	Salvia officinalis L.	Dynamic	120–220 °C, 30 bar, 10–30 min	Antioxidants	Pavlić et al. (2016)
	Coffea arabica L.	Static	160–180 °C, 5 MPa, 35–55 min	Antioxidants	Xu, Wang, Liu, et al. (2015)
	Coriandrum sativum L.	Static	100–200 °C, 30–90 bar, 10–30 min	–	Zeković et al. (2016)
	Ginseng roots	Static	120–200 °C, 6 MPa, 20 min	Antioxidants	Zhang, Zhang, Taha, et al. (2018)
	Waste onion skin	Dynamic	170–230 °C, 30 bar, 30min	Antioxidants	Munir, Kheirkhah, Baroutian, Quek, and Young (2018)
	Punica granatum L.	Dynamic	80–280 °C, 6 MPa, 15–120 min	Antioxidants	He et al. (2012)
	Grape skins and grape seeds	Dynamic	80–120 °C, 10 MPa, 0–120 min	–	Duba, Casazza, Mohamed, Perego, and Fiori (2015)
	Crocus sativus	Dynamic	120–160 °C, 20–60 min	Antioxidants	Ahmadian-Kouchaksaraie, Niazmand, and Najafi (2016)
	Hippophaë rhamnoides L.	Dynamic	120 °C, 36 min	Antioxidants	Gong et al. (2015)
	Flaxseed meal sticks	Static	160–180 °C, 1500 psi, 5–60 min	–	Kanmaz (2014)
	Thymus vulgaris	Static	50–200 °C, 1500 psi, 5–30 min	Antioxidants	Vergara-Salinas, Pérez-Jiménez, Torres, Agosin, and Pérez-Correa (2012)
	Tagetes erecta L.	Dynamic	80–260 °C, 15–90 min	Antioxidants	Xu, Wang, Jiang, et al. (2015)
	XiLan olive fruit dreg	Dynamic	100–180 °C, 5–60 min	Antioxidants	Yu, Zhu, Zhong, Li, and Ma (2015)
Essential oils	Soybeans	Dynamic	66–234 °C, 0.03–3.86 MPa, 13–47 min	–	Ndlela et al. (2012)
	Origanum onites	Dynamic	100–175 °C, 60 bar, 30 min	–	Ozel and Kaymaz (2004)
	Kaempferia galangal L.	Static	120 °C, 10 MPa, 30 min	Antioxidants	Ma, Fan, Liu, Qiu, and Jiang (2015)
	Foeniculum vulgare	Static	150 °C, 50 bar, 30 min	–	Gamiz-Gracia and De Castro (2000)
	Marjoram leaves	Dynamic	150 °C, 50 bar, 15 min	–	Jimenez-Carmona, Ubera, and De Castro (1999)
	Coriandrum sativum L.	Dynamic	100–175 °C, 0–120 min	–	Eikani et al. (2007)
	Ground oregano	Dynamic	125 °C, 2 MPa, 24 min	–	Ayala and De Castro (2001)
	Thymbra spicata	Dynamic	100–175 min, 20–90 bar, 0–25 min	–	Ozel, Gogus, and Lewis (2003)
	Bunium persicum	Dynamic	100–150 °C	–	Mortazavi, Eikani, Mirzaei, Jafari, and Golmohammad (2010)
	Trachyspermum ammi Seed	Dynamic	175 °C, 2 MPa, 60 min	–	Khajenoori, Asl, & Eikani (2015)
	Matricaria Chamomilla L.	Dynamic	100–175 °C, 20 MPa, 0–120 min	–	Khajenoori, Asl, and Eikani (2013)
	Coriandrum sativum L.	Static	65,100 and 150 °C, 870 and 1000 psi, 3 h		Saim, Osman, Yasin, and Hamid (2008)
	Origanum micranthum	Dynamic	100–175 °C, 40–80 bar, 30 min	–	Gogus, Ozel, and Lewis (2005)

(*continued on next page*)

Table 2 (*continued*)

Compounds	Raw materials	Mode	SWE conditions	Functions	References
Antioxidants	Onion Peel	Static	165 °C, 500 psi, 10 min	Antioxidants Antibacterial	Lee et al. (2011)
	Apple Byproducts	Dynamic	25–200 °C, 1500 psi, 3–17 min	Antioxidants	Plaza, Abrahamsson, and Turner (2013)
	Winery wastes	Dynamic	100–140 °C, 8–15 MPa	Antioxidants	Aliakbarian, Fathi, Perego, and Dehghani (2012)
	Hippophae rhamnoides	Dynamic	25–200 °C, 1500psi, 15 min	Antioxidants	Kumar, Dutta, Prasad, and Misra (2011)
	Haematococcus pluvialis	Dynamic	50–200 °C, 1500 psi	Antioxidants Antibacterial	Rodríguez-Meizoso et al. (2010)
	Inonotus obliquus	Static	50–300 °C, 0.002–5 MPa, 10–60 min	Antioxidants	Seo and Lee (2010)
	Rosemary Plants	Dynamic	25–200 °C, 40, 70 bar, 15 min	Antioxidants	Ibanez et al. (2003)
	Coriandrum sativum seeds	Dynamic	100–200 °C, 30–90 bar, 10–30 min	Antioxidants	Zeković et al. (2014)
	Morinda citrifolia	Dynamic	150–200 °C, 4 MPa	Antioxidants	Pongnaravane et al. (2006)
Amino acids	Rice bran	Static	100–220 °C, 0–30 min	–	Sereewatthanawut et al. (2008)
	Mars analog soils	Dynamic	185–215 °C, 10–120 min	–	Noell, Fisher, Fors-Francis, and Sherrit (2018)
	Porcine Placenta	Dynamic	170 °C, 10 bar, 10–30 min	–	Park et al. (2015)
	Atacama Desert soils	Dynamic	30–325 °C,17.2 and 30 MPa	–	Amashukeli, Pelletier, Kirby, and Grunthaner (2007)
	Saccharina japonica	Dynamic	180–420 °C, 13–532 bar	–	Saravana, Choi, Park, Woo, and Chun (2016)
Oils	grape seeds	Dynamic	150–340 °C, 45 min	–	Yedro, García-Serna, Cantero, Sobrón, and Cocero (2015)
	Rice bran	Dynamic	120–240 °C, 10–20 min	–	Pourali, Asghari, and Yoshida (2009)
	Cottonseeds	Static	180–280 °C, 5–60 min	–	Abdelmoez, Abdelfatah, Tayeb, and Yoshida (2011)
Phenolic acids	Rice bran	Static	125–200 °C, 20 bar, 30 min	–	Fabian, Tran-Thi, Kasim, and Ju (2010)
Lipids	Wet algae	Dynamic	25–220 °C, 0–60 bar	Stability	Reddy et al. (2014)
	activated sludge	Static	175 °C, 2 MPa, 15 min	Properties	Huynh, Kasim, and Ju (2010)
Volatile fraction	Satureja montana	Static	79.15–220.5 °C, 30 bar, 5.9–34.1 min	Antioxidants	Vladić et al. (2017)
	Coriandrum sativum L.	Static	100–200 °C, 30–90 bar, 10–30 min	–	Zeković et al. (2016)
	Cinnamomum zeylanicum	Static	150 and 200 °C, 6 MPa, 10 min	Antioxidants	Pramote et al. (2012)
Dietary fiber	*Citrus junos* peel	Dynamic	160–320 °C, 20 MPa	Properties	Tanaka, Takamizu, Hoshino, Sasaki, and Goto (2012)
	Coconut flour	Static	120–200 °C, 10–50 min	Antioxidants	Du, Bai, Gao, and Jiang (2019)
Caffeine	Black tea leaf	Dynamic	100–175 °C, 0–180 min	–	Shalmashi, Golmohammad, and Eikani (2008)
	Tea waste	Dynamic	100–200 °C, 20–40 bar, 0–150 min	–	Shalmashi, Abedi, Golmohammad, and Eikani (2010)
Oligosaccharides	Coconut meal	Static	100–300 °C, 10–15 min	–	Khuwijitjaru, Pokpong, Klinchongkon, and Adachi (2014)
	Passion fruit peel	Static	100–245 °C, 0–12 min	–	Klinchongkon, Khuwijitjaru, Wiboonsirikul, and Adachi (2017)

Note: "-" represents not studied.

Table 3
Specific samples of biological compounds with SWE.

Compounds	Raw materials	Target compounds	Yields	Reference
Polysaccharides	*Nizamuddinia zanardinii*	Fucoidans	Total fucoidans (13.5%)	Alboofetileh et al. (2019)
	Saccharina japonica	Fucoidans	Total fucoidans (13.56%)	Saravana, Tilahun, et al. (2018)
Pectins	Sugar beet pulp	Pectin-enriched material (PEM)	Total PEM (24.62%)	Chen et al. (2015)
	Citrus grandis L. peels	Low methoxyl pectin	Total (19.6%)	Liew et al. (2018)
	Apple pomace	Pectic polysaccharides		Wang and Lü (2014)
Polyphenols	Liquid grape seed extract	Anthocyanins	Total anthocyanins (85%)	Bleve et al. (2008)
	Potato peel	Phenolic acids	Phenolic acids (117%)	Singh and Saldaña (2011)
Essential oils	*Trachyspermum ammi* Seeds	Thymol	12.9634 mg/g dry sample	(Maryam Khajenoori et al. (2015))
Antioxidants	Apple byproducts	Flavonols	1.3 μmol/g dry sample	Plaza et al. (2013)
	Morinda citrifolia	Anthraquinones	> 81.07% recovery	Pongnaravane et al. (2006)

Alonso, & Cocero, 2013). At the same time, effects of subcritical water extraction microenvironment on the structure and biological activities of polysaccharides from *Lentinus edodes* were investigated. The results showed that the structure and biological activities of polysaccharides were changed significantly with the increase of extraction temperature. Moreover, when the temperature exceeded 150 °C, the triple helix structure of the lentinan was destroyed (Zhang, Wen, Gu, et al., 2019). Interestingly, the triple helix structure of polysaccharides is closely correlated with antitumor activity (Ren, Perera, & Hemar, 2012). Therefore, when extracting polysaccharides with subcritical water, it is necessary to optimize the extraction conditions so as not to affect its structure and biological activities. Especially, the specific samples of polysaccharides with SWE were shown in Table 3.

3.2. Pectin

Pectin is a natural high molecular compound which is widely found in the cell wall and middle lamella structures of higher plants (Qiu, Tian, Qiao, & Hong, 2009). Pectin has the properties of gelatification, thickening and stabilization, and can be widely used in food, medical, textile and other industries (Sato et al., 2011). Pectin has also been reported to have good biological activity similar to polysaccharides (Ho et al., 2015; Xu et al., 2018). More and more researches have begun to focus on the pectin with SWE (Table 2). For example, pectin was extracted from apple pomace and citrus peel by using subcritical water. The results showed that the properties of pectin were significantly affected by extraction temperature and raw material. Besides, the pectin exhibited anti-oxidative activity and anti-tumor activity against HT-29 cells (Wang, Chen, & Lü , 2014). Pectin was extracted from passion fruit (*Passiflora edulis*) by using diluted nitric acid, and was further hydrolyzed in subcritical water. The results showed that hydrolyzed pectin had lower viscosity and different solution characteristics under different temperatures. From these results, the conditions of obtaining certain molecular mass pectin can be predicted (Klinchongkon et al., 2018). Pectin-enriched material (PEM) was extracted from sugar beet pulp by using subcritical water combined with ultrasonic-assisted treatment, the optimum extraction conditions were liquid/solid ratio of 44.03, extraction temperature of 120.72 °C, extraction time of 30.49 min and extraction pressure of 10.70 MPa (Chen et al., 2015). The low methoxyl pectin was extracted from *Citrus grandis* L. peels with dynamic SWE, and the optimum extraction yield (18.8%) was at the conditions of 120 °C and 30 bar. Interesting, the low methoxyl pectin could be obtained in one-step extraction process rather than the conventional two-steps extraction process (Liew et al., 2018). In addition, response surface methodology (RSM) was used to extract pectin from apple pomace with hot-compressed water. The results indicated that the pectin with SWE have weaker inter- and intra-molecular action according to its rheological properties compared with commercial pectin. Moreover, the pectin with SWE showed higher antioxidant capability and inhibitory effect on HT-29 colon adenocarcinoma cells *in vitro* (Wang & Lü, 2014). As the same, the pectin was extracted from cacao pod husk by-products with SWE and compared with conventional extraction method. The pectin with SWE had many obvious features, including higher pectin yield, higher galacturonic acid content and higher degree of methyl esterification (Muñoz-Almagro et al., 2019). Therefore, the pectin with SWE has good rheological properties and antioxidant activity, and has great potential application in the food industry. The specific samples of pectins with SWE were shown in Table 3.

3.3. Proteins

The most common method of extracting proteins is alkali hydrolysis followed by acid precipitation. This method is simple to operate and the required reagents are also readily available (Jiamyangyuen, Srijesdaruk, & Harper, 2005). However, at high pH conditions, proteins are prone to degradation, which resulting in the low yield. Besides, the production of molecular cross-linking and rearrangements led to a reduction in nutritional value and the production of some toxic substances (Phillips & Finley, 1989). In addition, the alkali in the solution needs to be washed with a large amount of water, which resulting in waste of water. Although the enzymatic reaction without the production of toxic substances is used to produce proteins, the disadvantage is that the enzymatic hydrolysis time is too long and requires a large amount of enzyme. Therefore, numerous studies have used subcritical water as a solvent to extract proteins (Table 2). For example, the protein from deoiled rice bran was extracted by subcritical water hydrolysis. The results showed that subcritical water can be used to produce useful protein, and the yields of protein are higher than those obtained by conventional alkali hydrolysis. However, when the temperature of the subcritical water is too high for extended period of time, the protein will thermally degrade (Sereewatthanawut et al., 2008), so it is necessary to optimize the extraction parameters. Additionally, the proteins were produced from defatted rice bran by subcritical water treatment, which having high radical scavenging and antioxidant activity by treating at 260–280 °C for a shorter period of time (Hata et al., 2008). Besides, the proteins were extracted from flaxseed meal with pressurized low polarity water. The optimal conditions for protein extraction were pH 9, solvent to solid ratio of 210 mL/g meal and 160 °C. As the temperature increased, the extraction efficiency continued to increase. However, a temperature of 130–160 °C is recommended, as proteins are vulnerable to thermal degradation (Ho et al., 2007). Notably, the combination of various techniques for protein extraction has also become a research hotspot. For example, protease prehydrolysis followed by subcritical water (SW) treatment was carried out to extract soybean protein isolate (SPI) from heat-denatured soy meal. This technique greatly increased the extraction yield of the protein, but its purity is reduced. Compared with native SPI, the protein extracted by this method has a higher hydrophobic amino acid content and a higher surface hydrophobicity. These structural changes significantly improved the emulsifying ability and physical stability of emulsion (Lu et al., 2016). Based on the use of subcritical water to extract proteins with better physical properties, this technique should be applied more extensively to protein extraction.

3.4. Polyphenols

So far, subcritical water has been widely used in the extraction of polyphenol compounds. Polyphenolic compounds are widely studied because of their potential health benefits such as anti-tumor activity (Cao, Han, Xiao, Qiao, & Han, 2016; Yang et al., 2016). Polyphenolic compounds have been shown to play important roles in the prevention of diseases associated with oxidative stress, such as cardiovascular diseases, cancer and neurodegenerative diseases (Arts & Hollman, 2005; Ebrahimi & Schluesener, 2012; Nichenametla, Taruscio, Barney, & Exon, 2006). Polyphenolic compounds have been extracted with SWE from many different sources, such as plants and food-industry by-products (Table 2). For example, our team extracted polyphenolic compounds from *Sorghum bicolor* L. and lotus seed epicarp with SWE, and the results showed that the polyphenols exhibited the higher radical scavenging activities and the more efficient antiproliferative activity than hot water extraction (Luo, Cui, Zhang & Duan, 2018; Yan et al., 2019). The phenolic compounds were extracted by using subcritical water under the conditions of temperature ranging from 100 to 180 °C, residence time of 5–60 min, and solid-to-liquid ratio of 1:20 to 1:60. Compared with methanol-extracted polyphenols, the polyphenols with SWE had higher yield and better antioxidant activity (Yu et al., 2015). In many other studies, polyphenols extracted under higher temperature and longer time with SWE have higher antioxidant activity than that of low temperature and shorter time (Ahmadian-Kouchaksaraie et al., 2016; Erşan et al., 2018; He et al., 2012; Kanmaz, 2014; Vergara-Salinas et al., 2012; Xu, Wang, Jiang, et al., 2015; Xu, Wang, Liu, et al., 2015; Zhang, Zhang, Taha, et al., 2018). However, some studies have reached the opposite conclusion. For example, the polyphenols were extracted from *Coriandrum sativum* L. with SWE under the temperature range of 100–200 °C. A good yield at optimal conditions for polyphenols content was obtained at 100 °C, 60 bar and 10 min (Zeković et al., 2016). In addition, polyphenols were extracted with subcritical water from the sea buckthorn seed residue (after oil recovery), and the extraction parameters were optimized by using response surface methodology (RSM). The optimal extraction parameters for the extracts with highest ABTS radical scavenging activity were 120 °C, 36 min, water to solid ratio of 20 (v/m), and the maximize antioxidant capacity value was 32.42 mmol Trolox equivalent (TE)/100 g (Gong et al., 2015). Furthermore, the bioactive phenol compounds were extracted from onion skin with subcritical water. The results showed that temperature is the key factor which can affect the SWE process, and the maximum total phenolic content was obtained at lower temperature (Munir et al., 2018). The reasons for the difference in the above results have not been elaborated and should be further studied. In these studies, only the total amount of polyphenols and their antioxidant capacity were determined, which has great limitations. Therefore, more advanced techniques should be used to quantify polyphenolic compounds and explore other potential biological activities. Table 3 includes the specific samples of polyphenols with SWE.

3.5. Essential oils

Essential oils extracted from natural products can be used as food seasonings, primarily as flavoring agents in the liquor, cocoa and chocolate industries. It can also be used as a repellent or flavoring agent in the medical field. Essential oils are more stable than any other oils and can maintain a pleasant scent for a longer period of time (Diederichsen, 1996). The results of recent studies were listed in Table 2 and the specific samples of the essential oils were shown in Table 3. For example, the essential oils were extracted from many materials with SWE under different conditions. The yields obtained by using SWE were higher than those from conventional methods, such as steam distillation extraction, Soxhlet extraction, among others (Ayala & De Castro, 2001; Gamiz-Gracia & De Castro, 2000; Jimenez-Carmona et al., 1999; Khajenoori et al., 2013; Khajenoori et al., 2015; Ozel & Kaymaz, 2004). It is worth noting that the temperature of essential oils extraction with subcritical water should not be too high, otherwise it will cause the formation of some degradation products (Gogus et al., 2005). However, the opposite results had also been reported. Hydrodistillation and Soxhlet extraction showed higher extraction efficiencies than SWE, but SWE was quicker and with respect to the valuable oxygenated components, it was more selective (Eikani et al., 2007; Mortazavi et al., 2010). The combination of multiple technologies applied to essential oil extraction has also received more and more attention. For example, ultrasound-enhanced subcritical water extraction (USWE) of essential oils from *Kaempferia galangal* L. and their comparative antioxidant activities were studied, and the results showed that USWE was found to be superior to the other extraction methods (SWE and steam distillation extraction) in terms of its higher recovery yields and its stronger antioxidant ability (Ma et al., 2015). Therefore, multi-technology combination has great application prospects in bioactive compounds extraction.

3.6. Antioxidants

Some antioxidants were extracted by using subcritical water (Table 2). The antioxidants were extracted from industrial apple byproducts with SWE. Especially, the new antioxidants were obtained at the higher extraction temperatures (Plaza et al., 2013). The antioxidant compounds were extracted from Seabuckthorn leaves with SWE. The present study reports the cytoprotective and antioxidant properties of SBT against tertiary-butyl hydroperoxide (tert-BOOH) induced oxidative stress in murine macrophages (Raw 264.7). The chemical composition of these antioxidant compounds were composed of phenol and flavonoid (Kumar et al., 2011). Some other antioxidant compounds were also extracted with SWE from other materials, such as Chaga mushroom (Seo & Lee, 2010), onion peel (Lee et al., 2011), rosemary plants (Ibanez et al., 2003), *Mangifera indica* leaves (Fernández-Ponce, Casas, Mantell, Rodríguez, & de la Ossa, 2012), and *Haematococcus pluvialis* microalga (Rodríguez-Meizoso et al., 2010), among others. All these antioxidant compounds exhibited strong antioxidant activity and can be used in the food or pharmaceutical industry. Further specific samples of antioxidants with SWE were shown in Table 3.

3.7. Other bioactives

As mentioned above, the use of subcritical water for the extraction of biologically active compounds also included amino acids (Amashukeli et al., 2007; Marcet, Álvarez, Paredes, & Díaz, 2016; Noell et al., 2018; Park et al., 2015; Saravana et al., 2016; Sereewatthanawut et al., 2008), oils (Abdelmoez et al., 2011; Pourali et al., 2009; Yedro et al., 2015), phenolic acids (Fabian et al., 2010; Mukhopadhyay, Luthria, & Robbins, 2006), lipids (Huynh et al., 2010; Reddy et al., 2014), volatile fraction (Vladić et al., 2017; Zeković et al., 2016), dietary fiber (Du et al., 2019; Tanaka et al., 2012), caffeine (Shalmashi et al., 2010; Shalmashi et al., 2008), oligosaccharides (Khuwijitjaru et al., 2014; Klinchongkon et al., 2017), and PHA (Kronholm, Kuosmanen, Hartonen, & Riekkola, 2003), among others.

4. Conclusion and future trends

In conclusion, the bioactive compounds from natural products with SWE are preferred for use in the food and pharmaceutical industries, and its biological activity and stability can be maintained during the extraction process. The use of SWE to extract compounds from natural products provides an even better method, especially in environmental protection. In addition, subcritical water can greatly improve heat and mass transfer efficiency during extraction, which can increase extraction yield, and shorten extraction time. Interestingly, SWE have positive effect on the activity and structure of bioactive compounds. According to the available literatures on SWE technologies, subcritical water has demonstrated the good selectivity for the extraction of bioactive compounds and can be used to extract different analyte classes by controlling temperature and pressure.

Based on the potential and prospect of SWE, future research should focus on large-scale operation and the design of industrial equipments. It is hoped that such a research initiative would significantly contribute to the understanding, advancement, and future applications of natural extracts obtained with SWE in dealing with health problems.

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