Chiang Mai J. Sci. 2018; 45(2) : 1015-1029
http://epg.science.cmu.ac.th/ejournal/
Review Article

Strategic Applications and the Challenges of Subcritical Water Extraction Technology in Food Industries

Erasto Mlyuka [a,b], Martha Mbifile [c], Shuang Zhang [a], Zongping Zheng [a] and Jie Chen* [a]

[a] State Key Laboratory of Food Science and Technology, School of Food Science and Technology, Synergetic Innovation Center of Food Safety and Nutrition, Jiangnan University, Wuxi, Jiangsu 214122, China.

[b] National Irrigation Commission, Ministry of Water and Irrigation P.O.BOX 671, Mtwara, Tanzania.

[c] School of Biotechnology, Jiangnan University, Wuxi, Jiangsu 214122, China.

*Author for correspondence; e-mail: chenjie@jiangnan.edu.cn

Received: 4 April 2016
Accepted: 12 July 2016

ABSTRACT

Extraction is a required step for the utilization of most natural bioactive compounds in food, pharmaceutical and cosmetic industries. A green subcritical water extraction (SWE) technique for the extraction of bioactive compounds has been of great interest in recent years. The utilization of clean extraction solvent (subcritical water) in food and pharmaceutical industries has attracted public and scientific interest, due to its tunable polarity at different temperatures above its boiling point. SWE technique uses subcritical water with wide range of polarities attained by temperature programming which enables the selective extraction of polar, moderately polar, and nonpolar bioactive compounds from natural sources (plant or animal origin). Natural sources are the promising source of safe bioactive compounds. Extracts from these sources using subcritical water can be directly used for food and pharmacological purposes. However, to exploit these resources at a commercial scale, relevant strategies for their extraction must be developed. This review addresses the unique characteristics of subcritical water, the principal applications of SWE, parameters influencing the extraction yield and selectivity, engineering scale-up and bio products extraction strategies to ascertain the stability of bioactive compounds in subcritical water conditions and challenges facing the prospect of this technology.

Keywords: subcritical water extraction, bioactive compounds, heat degradation, extraction strategy

1. INTRODUCTION

Plant extracts now serve as ideal sources of bioactive compounds to meet the growing global demand for functional food and beverage. The commercial functional extracts are obtained from plant sources mainly by solvent extraction, such as solid-liquid extraction [1], Soxhlet extraction [2], and ultrasonic/microwave assisted extraction

[3]. However, the use of these methods in recent years faces challenges as most of them use organic solvents apart from being less efficient, manual and with a low selectivity [4].

To address the above challenges, the novel extraction techniques have been widely investigated to efficiently extract bioactive compounds from plants with a great commercial potentials [5-6]. The novel extraction techniques which have gained much publicity and interest include supercritical fuid extraction (SFE) and subcritical water extraction (SWE). SFE is a green novel extraction technique since it uses carbon dioxide, as extraction solvent to produce extract with no solvent residue. It also has other advantages, such as a high extraction rate, is suitable for heat sensitive material and it does not pollute the environment. However, the industrial application of SFE is limited due to high pressure equipment requirements and initial investment costs [7]. In addition, the density of supercritical CO_2 has showed to impede the isolation of the compounds of low or medium polarity because it possess non-polar behavior at conditions above the critical temperature and pressure of CO_2 [7]. This drawback has led to in-depth research on the subcritical water extraction (SWE) technique which uses subcritical water with a wide tunable properties such as dielectric constant, surface tension, viscosity, and dissociation constant achieved through adjusting the temperature at a moderate pressure to keep water in the liquid state [8]. Unlike supercritical water extraction, SWE is operated at subcritical conditions which is technically friendly to both equipment and extraction process. Thus, it has a great potential to overcome limitations of classical extraction methods. SWE uses environmentally friendly solvents such as water which can replace hazardous organic solvents. It also provides higher selectivity and higher extraction efficiency with a high yields achieved within a shorter extraction times. Recently, SWE has received a significant attention and has become one of the most used in both extraction and chromatographic analysis [4-6, 9].

Therefore, the objective of this review is to provide current literature on the unique characteristics of subcritical water, the principal applications of SWE, instrumentation development, parameters influencing the extraction selectivity and yield, engineering scale-up and bio products extraction strategies to ascertain the stability of useful bioactive compounds in subcritical water conditions.

2. PHYSICOCHEMICAL PROPERTIES OF WATER AND THE PRINCIPAL APPLICATIONS OF SUBCRITICAL WATER EXTRACTION TECHNIQUE

The term subcritical water refers to water below its critical temperature and pressure (Tc = 374 °C, Pc = 22.1 MPa), but it should be at temperature and pressure above the ambient conditions to keep water in liquid state [10]. The polarity of subcritical water become almost similar to some common organic solvents at ambient conditions (Figure 1), and as such it can selectively extract polar, semi-polar or nonpolar organic compounds depending on the temperature and pressure used (Figure 1). Dielectric constant of water decreases as temperature increases to near critical conditions. At this condition, it was observed to mimic dielectric constant of organic solvents at ambient conditions [4, 11].

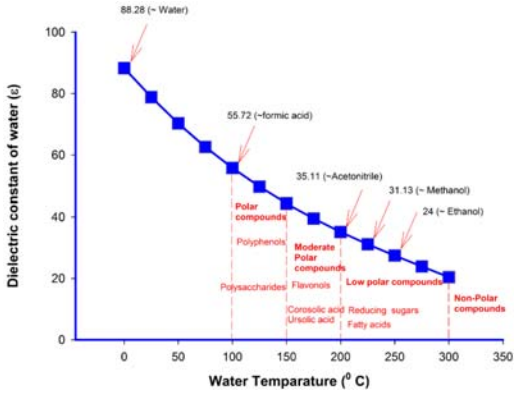

Figure 1. Change in dielectric constant of water as a function of temperature. At subcritical temperatures (less or equal to 250 °C) useful polar bioactive compounds are extracted by subcritical water, with a dielectric constant ca. 31 and 24, equivalent to values of methanol and ethanol at room temperatures.

3. INSTRUMENTATION AND SUBCRITICAL WATER EXTRACTION PROTOCOLS

The basic SWE equipment is simple and the extractor shown in Figure 2 consists of several parts (1-11). The extractor is an advanced laboratory machine with a pump capable to accelerated solvent up to 83.33 mL/min. It is advanced mainly in terms of capacity (2000 mL extraction cell volume) and extraction efficiency, compared to most reported laboratory scale machine elsewhere [8, 12-16]. Its flow rate is the second highest next to 100 mL/min which has recently been reported by other authors [17]. The extraction cell has a bed density of 10 kg /m^3. In addition, its operation protocol is user friendly. The pump can be opened only after assembling the extraction cell in the high-pressure extraction vessel (6), followed by extraction unit been filled with water pumped at a desired flow-rate (while back-pressure regulator have to be kept closed). The same extractor can be used for static, dynamic or their combined extraction modes.

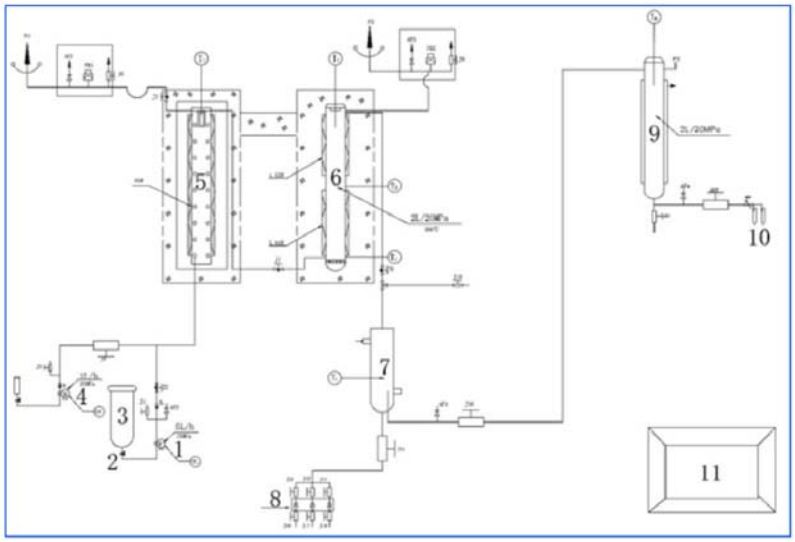

Figure 2. Semi-pilot-laboratory scale system diagram. (1) high-pressure pump 1, (2) isolation valve, (3) deionized water reservoir, (4) pump 2, (5) preheater cylinder, (6) high-pressure extraction vessel, (7) first cooling system, (8) sampler, (9) second cooling system, (T1-T6) temperatures of the system, (P1-P2) system pressure, (P3) back-pressure regulator, (10) extract collecting vessel, (11) subcritical machine digital control panel.

The extractor could perform SWE involving sequential stages which take place in the extraction cell filled with sample materials. The stages are known to include: rapid fuid entry, desorption of solutes from matrix active sites, diffusion of solutes through organic materials, diffusion of solutes through static fuid in porous materials, diffusion of solutes through layer of stagnant fuid outside particles, and elution of solutes by the flowing bulk of fluid [18]. The first stage is the washing stage, at this stage pumped fluid pass vertically through the extraction cell to wash the loaded extraction sample. The second stage involves desorption of solutes from the various active sites in the sample matrix under the pressurized and elevated extraction temperature. The third stage may involve the diffusion of extraction fluid into the matrix. At the rest stages, depending on the sample matrix, the solutes may distribute themselves from the sample matrix into the extraction fluid and finally be collected at the extraction bottle.

4. FACTORS AFFECTING THE EFFICIENCY OF SUBCRITICAL WATER EXTRACTION

The efficiency of SWE has been reported to depend on the type of extraction, mode of extraction, water properties, and the nature of the sample matrix and other factors which are known to affect extraction efficiency as depicted in Figure 3. Additionally, degradation of extracts [19] has been reported to affect the extraction efficiency of this green technology, which often performed in either solubility controlled or diffusion controlled extractions.

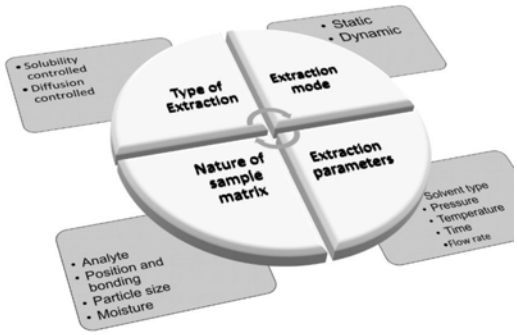

Figure 3. Factors affecting the efficiency of subcritical water extraction.

4.1 Type of Extraction, Nature of Sample Matrix and Subcritical Water

The type of extraction refers to the extraction process which is either solubility or diffusion controlled. In either extraction type, the sample matrix, position, bonding, particle size and moisture are reported to have influence on the extraction rate and recoveries of bioactive compounds [6]. Transfer of the analyte from matrix to subcritical water is affected by diffusion and convection. This is very particular for the diffusion controlled extraction in which large surface area to volume ratio can improves SWE rate [20]. In static extraction mode, SWE efficiencies strongly depend on the partition-equilibrium constant and the solubility of compounds [21]. However, in dynamic extraction mode, the equilibrium is disrupted continuously as the fresh solvent is introduced through the sample at the set flow rate and time. The flow rate in dynamic extraction mode helps to determine the final volume at the set extraction time. In this mode, extraction efficiency can be increased with flow rate for it has influence on the extraction rate and total volume of extracts at a given time.

4.2 Extraction Mode

The modes of extraction used in SWE system is either dynamic, static or dynamic-static. The efficiency of extraction based on modes of extraction relies on the processing parameters involved in each case. The choice of one mode extraction over the other will depend on whether long exposure time to subcritical temperature will lead to degradation (for static mode) or whether the extract yields need to be highly concentrated in the final extract mixture (for dynamic mode). Also it is possible to use a combined extraction mode (static-dynamic mode) in SWE system. Extraction modes combination could lead to high yield of extractions. Furthermore, it uses lower amount of subcritical water than dynamic mode alone. Moreover, it uses lower exposure time than static and dynamic when used separately [22]. Static-dynamic mode produces more concentrated extracts within a short contact time with subcritical water.

4.3 Extraction Parameters

Solvent type is a key consideration when dealing with extractions. In fact, solvent extraction is the common technique utilized in both laboratory and industrial applications [23]. The success of this technique mostly relies on the selection of solvent used during extraction process. Use of proper solvents mostly lead to selective extractions, or complex extractions requiring post extraction procedures which involves clean up, concentration and purification of the target bioactive compounds [24]. Organic solvent extractions generally show little or no com-pound class selectivity, which implies fractionation is often performed after extraction before analysis stage [4]. Unlike organic solvent, subcritical water can perform selective extraction with respect to temperature programming [4, 10-11]. Subcritical water at lower temperatures is a very polar solvent and it becomes less polar as the temperature is increased, until its dielectric constant (polarity) becomes similar to methanol or acetonitrile at 200 °C (Figure 1). Polar bioactive compounds are easily extracted in subcritical water at lower temperatures, whereas less polar bioactive compounds require moderate polar water which is achieved at temperatures up to 250 or 300 °C operated at system pressure capable to keep water in liquid state. The subcritical water temperature range between 100 °C and 370 °C is sufficient to produce physicochemical properties of water making it a suitable solvent for the extraction of different classes of bioactive compounds (polar, moderately polar and non-polar organic compounds (Figure 1).

Subcritical water (as solvent) can be compared with other most common extraction solvents in regard to their solvent polarities (dielectric constants). The dielectric constant of some common extraction solvents are as follows: hexane (ε=2), acetonitrile (ε = 36), acetone (ε = 21), methanol (ε = 33), and methylene chloride (ε=9) [10]. This implies, subcritical water is always substantially more polar than many common extraction solvents regardless of the temperature used for extraction.

Pressure has an important function in SWE processes. It permits subcritical water to retain its liquid state at high temperatures [25]. However, pressure has limited effects on the manipulations of the dielectric constant of water in liquid state. In fact, pressure has only minor effects on bioactive compounds yield obtained by SWE [6]. Thus, the increase in the pressure often helps to keep water in the liquid state at high temperature used in SWE without compromising the achieved water polarity.

Temperature is the main parameter

influencing the physicochemical properties of water and the compounds to be extracted, and it has a great influence on the extraction rate, efficiency, and selectivity in SWE. Extraction rate is improved through improving the physical state of water that leads to fast diffusion, low viscosity, and low surface tension in favor of mass transfer during extraction process. Improved extraction efficiency could be associated with the increased vapor pressures and accelerated thermal desorption of the compounds under subcritical conditions [26]. SWE can easily provide class-selective extractions as shown in Figure 1. Selective extraction can be achieved through temperature programming which offers subcritical water with a wide range of polarities obtained by changing the temperature and pressure. Temperature is a critical parameter in the SWE process [8, 25]. Generally, the increase in the temperature produces a subsequent increase in the extraction yield, but when dealing with temperature sensitive bioactive compounds, too high temperatures [8, 25] could lead to the degradation of bioactive compounds.

The extraction time in SWE is defined as the time at which the solvent is in contact with the sample being extracted at the desired temperature and pressure conditions. It is another factor that would influence the extraction efficiency and selectivity of the subcritical water. In our previous studies we reported that corosolic and ursolic acids were extracted at different optimum extraction times [27-28], a long extraction time favored ursolic acid yield while shorter extraction time favored the corosolic acid extract yield [22]. On the other hand, extraction beyond one hour likely there were changes molecule structure [19] of both corosolic and ursolic acids, which were indicated by their respective decline in yields.

Water flow rate is reported to affect the efficiency of SWE of bioactive compounds from natural sources [13, 27-28]. The SWE (dynamic mode) flow rates have considerable influence on the rate of extraction and the final volume of the extract at a given time. In dynamic mode, flow rate affects the extraction efficiency indirectly by disrupting equilibrium concentration while affecting the final volume for a specified time [27]. Also, other authors reported an increase of essential oil yield from *Z. multifloraat* achieved by increasing the subcritical water flow rate during the SWE [13]. Increase in flow rate resulted in increase in subcritical velocity that favored quicker mass transfer of matrices in subcritical conditions. However, working at higher flow rates more water would be pumped into extraction cell to produce more dilute extracts. Higher flow rates are not suitable to obtain concentrated final extracts. The concentration procedures to remove excess water is the extract is tedious requiring considerable efforts and time-consuming, due to the fact that the heat of vaporization of water is relatively higher compared to most organic solvents. Practically, concentrated extracts can be obtained by operating SWE at the optimum flow rates.

Organic and inorganic modifiers when used as additives in SWE can enhance the solubility of target bioactive compounds in subcritical water by increasing the interactions between solvent and solute. They also tend to modify the physicochemical properties of water at elevated temperature [17, 29]. SWE with ethanol-modified water was also reported to enhance the extraction removal of atrazine from beef kidney [29]. In addition, the degradation of bioactive compounds in SWE at elevated temperature and pressure could be reduced by incorporating protective additives particularly ascorbic acid for the oxidative prone bioactive compounds.

5. KINETICS AND DECOMPOSITION OF ORGANIC COMPOUNDS IN SUBCRITICAL WATER

There have been much interests from various researchers on subcritical water primarily due to its fascinating properties as a reaction medium [30]. The efficiency of SWE has been reported to rely on kinetic steps and temperature among other extraction parameters [6, 13, 31]. The ionization product of water increases by three orders of magnitude from ambient to near-critical conditions, producing both hydronium and hydroxide ions. These ions perform as catalysts by inducing the formation and interconversion of byproducts to produce useful bioactive compounds. The ionization products of water are of great interest when using water as a novel extraction solvent to obtain bioactive compounds from natural sources (Table S1). Khajavi and others [30] studied the decomposition of maltose in subcritical water using a tubular reactor at the temperature range of 180 °C to 260 °C at 10 MPa, and found out the reaction was accelerated by increase of extraction temperature. The rate of decomposition was approximated by first order kinetics at the early stages, but was accelerated and deviated from these kinetics at the later stages [30]. In fact, extraction kinetics is complex requiring multistep to understand its mechanism. Several mathematical models approaches have been proposed to analyze extraction kinetics [32]. Islam and others [21] used four models to describe the subcritical water extraction kinetics of polycyclic aromatic hydrocarbons at elevated temperatures, among the four models, the two-site kinetic desorption model provided the best description of subcritical water extraction of phenanthrene, fluoranthene, and pyrene. In their study, the model and experimental results suggested that the first desorption step was more important than the volumetric mass transfer process [29].

Table 1. Thermal degradation and stability of extracts in subcritical water extraction conditions.

Sample	Pressure (MPa)	Temperature (°C)	Time (min)	Extracts/compounds	Reference
Fatty acids	20	300	30	Stearic, oleic, linoleic acids	[37]
azo dye Orange G	7	180-250	-	Orange G	[58]
Azo dye Acid Red 274	-	217	60	AR274	[59]
Benzoic acid derivatives	-	150	30	anthranilic acid, salicylic acid, syringic acid	[60]
Benzoic acid	-	250	30	Benzoic acid	[61]
RR120	-	200	120	dye	[62]
Rice stem		230	5	Total carbohydrate, total phenolic	[63]
Atacama Desert soils	20.7	250	0	biomarker molecules	[11]
Polysaccharides	3	150	-	Racemic compounds	[63]
sucrose	10	160-200	-	Glucose, fructose	[30]

6. ENGINEERING SCALE-UP AND EXTRACTION STRATEGIES TO ASCERTAIN THE STABILITY OF USEFUL BIOACTIVE COMPOUNDS IN SUBCRITICAL WATER CONDITIONS

The schematic diagram of SWE apparatus presented in Figure 2, is a product of engineering advancement modification from laboratory scale SWE system (200 mL) into semi-pilot laboratory scale system (2000 mL) as shown in Table 2. Extractions procedures are similar in both SWE systems, subcritical water extractor specifications and experimental operating conditions are also advanced to favor efficiency extractions

(Table 2). Compared to most published SWE system [16], the volume of the extraction cell in our system was increased to 2 L and other parameters were modified accordingly, to favor better extraction efficiency (>90%). The size of extraction cell in the semi-pilot lab-scale in our previous work is one quarter the size of extraction cell in pilot-scale system with 8 L tubular extraction cell (143 mm i.d. by 520 mm high) reported by other authors [33]. In their extraction studies of the curcuminoids from turmeric, they found out that the lab-scale results were similar to the pilot-scale with respect to the temperature and the static time (with 50% ethanol mixture) [33]. Even though, there is no commercial SWE system in the market, still there is a promising future for this extraction technique because it uses subcritical water, which is generally accepted as a green and ecofriendly solvent. In addition, research work by various researchers is ongoing to scale up this system. In an effort to demonstrate the need for SWE scaling up to an industrial scale, Islam and others [34] reported more than 99% extraction efficiency of the SWE of pesticides from contaminated soil samples following the scaling up of their SWE system in which experiments were conducted at 30- and 167-fold scale-up. Furthermore, in an effort to scale up SWE, in case of our previous work, the system was scaled up to 2 L and designed to operate in three modes: static-dynamic mode, static mode and dynamic mode (Table 2). In dynamic-mode extractions, high-pressure pumps (5 L/h or 1 L/h) in the advanced SWE were efficient enough to pressurize the water and deliver it through the sample matrix in the extraction cell and through the two cooling systems before reaching the collection tank. Moreover, in previous work, the static, dynamic or static-dynamic modes were used to selectively extract pentacyclic triterpenoids from dry loquat using pure water as a solvent at various subcritical conditions (Table 2) without causing significant degradation of bioactive compounds.

Table 2. Subcritical water extractor specifications and laboratory scaling up.

SWE system cell specification	Lab-scale	Semi-pilot Lab-scale	Pilot scale	References
Cell height, cm	20	35.5	52	[22, 33, 64, 65]
Cell inner dia., cm	3	6	14.3	[22, 33, 64, 65]
Cell volume, mL	200	2000	8000	[22, 33, 64, 65]
Operating condition				[22, 33, 64, 65]
Pressure, MPa	4-10	4-17	0.5-10.1	[22, 33, 64, 65]
Temperature, □C	80-250	80-250	110-150	[22, 33, 64, 65]
Water flow rate, mL/min	2-8.3	16.67-83.67	200-1000	[22, 33, 64, 65]
Cell loaded, g of sample	1-133.33	10-133.33	250	[22, 33, 64, 65]
Extraction time[1], min	15-90	5-120	1-120	[22, 33, 64, 65]

[1]The counting of extraction time was started after the reactor temperature reached the desired value

Subcritical water extraction is a rapid and efficient technique which has gradually become a useful option for the isolation of bioactive and nutritional compounds mainly from plants functional food utilization [35-36]. SWE is a clean and green method to recover bioactive compounds without cleanup step. Therefore, the implementation

of this method can help to reduce costs, as the extracts obtained are safe for further analysis, processing and eventually for human consumption. Table 1 summarized the studies on thermal degradation and stability of extracts in subcritical water extraction conditions at optimized extraction conditions obtained from researches published in recent years. These studies demonstrated the feasibility of SWE for the extraction of bioactive components from plants and other sources at their optimized conditions.

The stability of bioactive components at elevated temperature and their extraction efficiencies compared with other methods of extraction as reported in Table 2. Additionally, fatty acids in subcritical water were found to be stable up to 300 °C [37]. Furthermore, the hydrolysis of vegetable oils and fats using subcritical water could be carried out below 300 °C at 20 MPa for 30 min as an optimum condition to obtain stable fatty acids (Table 2).

The stability of reducing sugar was reported to be between subcritical temperature of 160 °C and 200 °C (Table 2). Water at subcritical condition is capable to exert catalytic hydrothermal effect in the conversion of macro-algae-derived alginate to produce furfural and valuable organic acids with the help of pH changes caused by hydrolysis of water [38]. Lin and others [5] reported the highest yield of reducing sugar at 280 °C. Based on their model they achieved the highest production of reducing sugar with the lowest possible degradation rates.

Subcritical water was also used to hydrolyze and decompose the macromolecules of the rice bran biomass which produced monomers of phenolic and other antioxidants [39]. These bioactive compounds play an important role in improving human health for they help to reduce diseases risks when are regularly incorporated in the food systems.

7. APPLICATION OF SUBCRITICAL WATER EXTRACTION IN FOOD INDUSTRY

SWE has been successfully used to extract most compounds (Table 3) which are soluble in methanol or aqueous ethanol, such as flavonoids, polyphenolic compounds and triterpenes [40-43]. The use of SWE extraction produced higher yields of phenolics (81.83 mg/100 g) than the yields obtained with methanol extraction (46.36 mg/100 g) or with ethanol extraction (29.52 mg/100 g) [8]. In addition, SWE has been used as an alternative and greener processing method for simultaneous removal of oil- and water-soluble phase from sunflower seeds [36]. Various researchers have previously reported the highest amounts of oil obtained in 30 min when extraction was carried out at 130 °C using material to solvent ratio 1/20 g/mL. Recently SWE has been used in conjunction with protease enzymes to extract protein from heat-denatured soy meal [44]. Enzyme-assisted subcritical water extraction has a potential for producing nutrient-enhanced soy proteins with excellent emulsifying properties as novel functional ingredients applied in food industry [44]. In addition, SWE produced high yields of pentacyclic triterpenoids from dry loquat (*Eriobotrya japonica*) leaves (25.02 ± 0.71 mg/g) obtained at SWE conditions of 200 °C, 41.67 mL/min and extraction time of 30 min (10 min static mode and 20 min dynamic mode) compared to 4 h extraction with conventional solid-liquid extraction (14.39 ± 1.12 mg/g) [22]

Plant extracts containing bioactive compounds can be used as functional ingredients in food industry. Plant extracts in pharmaceutical industry are commonly used to produce medicines and cosmetics

[60]. About 80% and 30% of the active bioactive compounds from natural sources are used in food and pharmaceutical industries, respectively [46]. Therefore, based on the great demand of safe extracts from natural sources, SWE has a great potential to be considered as a powerful alternative to obtain bioactive compounds needed in food and pharmaceutical industries.

Table 3. Recent application of sub-critical water extraction in food industry.

Source	Bioactive products	Temperature (°C)	Pressure (MPa)	Static/ Dynamic	Time(cycles/ Flowrate)	Reference
Black tea, celery, and ginseng leaf.	Flavonols	200	10	Static	15 min	[42]
grape skins and defatted grape seeds	Polyphenols	120	10	Dynamic	120 min/ 2.mL/min	[66]
Mango leaves	phenolic compounds	100	12	Dynamic	180 min/ 10.mL/min	[67]
birch bark	betulinic acid	184.52	2	Static	27.37 min	[6]
Sugarcane bagasse	reducing sugars	250	5,10,15	Static-Dynamic	9-12.5mL/min	[47]
Miscanthus	Phenols	374	21	Static	60 min	[68]
rice straw	reducing sugars	280	20	Static	8 min	[5]
sediments	alkylphenols	200	14	Static	7 min	[69]
poultry tissues	Amphenicols	150	10	Static	3 min/2	[70]
Bamboo	total reducing ugars	180	1	Static	25 min	[12]
Kaempferia galangal L.	ethyl trans-p-methoxycinnamate	120	10	Static	20 min	[71]
giant reed and miscanthus	lignin	200	5.5	Static	60 min	[72]
sunflowerseeds	oil	130	-	static	30 min	[36]
Barley grain	β-glucan	130-170	10	Static	30 min	[73]
Loquat leaf	Corosolic acid	180	10	Static-Dynamic	33.33mL/min	[22]
Loquat leaf	Ursolic acid	200	10	Static-Dynamic	41.67mL/min	[22]

8. THE CHALLENGES OF SUBCRITICAL WATER EXTRACTION TECHNOLOGY IN FOOD INDUSTRIES

Even though, water is the greenest solvent to use in extraction of bioactive compounds (Table 3), it has disadvantage in terms of operation cost to be specific. It has been observed that extracts obtained using water as a solvent, concentration procedures to remove water from the extracts (non-lipid extracts) are tedious requiring considerable efforts and is time consuming. This is because the heat of vaporization of water is relatively high compared to that of many organic solvents. Moreover, the presence of water could decrease the stability of the extract [17]. Therefore, concentrating water in rotary evaporator at a reduced pressure is a required step to obtain concentrate extract suitable for freeze drying. Freeze drying is used with heat sensitive products since moisture is removed without a phase change. Thus, one way to dry subcritical water extract is by freeze-drying, although is rather costly and time consuming, and could lead to a slight degradation of the bioactive compounds due to heat, light and oxygen [17].

As previously stated, currently there is no specic commercially available extractor for SWE. Most of the published results were obtained using subcritical water extractor at a laboratory and pilot scales [5-6, 26, 33, 40, 47]. Plant active ingredients in crude

plant extracts obtained by SWE recognized to be complex and similar and therefore, the desired purity could not be met by SWE technique alone. This implies the development of SWE it may require clean-up step coupled to the SWE system. This it can facilitate clean-up step to be done before final analysis is carried out. In addition, using water as a solvent in extractions, makes post extraction stage time consuming. It is very difficult to obtain concentrate extracts from SWE through rotary evaporation at a reduced pressure, this is because the heat of vaporization of water is relatively high compared to most of organic solvents. This calls for SWE coupled with a drying step. Moreover, SWE extraction conditions vary greatly, with respect to the sensitivity to temperature of the bioactive compounds to be extracted. This challenge can be resolved by working at optimal extraction conditions [48]. Despite these challenges, SWE when compared to other classical extraction method methods, it seems to be a feasible green extraction method with a bright future for it uses green solvent.

9. THE PROSPECT OF SUBCRITICAL WATER EXTRACTION TECHNIQUE AND ITS IMPACT ON GLOBAL SOCIAL LIFE

As illustrated in Table 3, most articles published recently used subcritical water as an alternative solvent for the extraction of phytochemicals from natural sources. It can be noted that the future trend of SWE technology is towards scaled-up operation aiming at obtaining a large volume of extracts. The design of industrial scale equipment is usually preceded by laboratory and pilot-scale systems as described above (Table 2). The feasibility of SWE as a green solvent extraction method for industrial applications has been established in a pilot-scale project to extract curcuminoids from *Curcuma long* L [33].

Currently, subcritical water extraction technology has been used to obtain triterpenes from dry loquat leaves [22]. Loquat leaf extract contain triterpenes (corosolic acid, ursolic acid and oleanolic acid) which have been shown to exhibit pharmaceutical activities. Corosolic, ursolic and oleanolic acids are examples of naturally occurring triterpenes which have attracted global attention due to their hypoglycemic activity [49-52]. They are useful plant bioactive compounds to deal with global health problems including obesity, diabetes, asthma, epilepsy, cancer and HIV/AIDS.

The antidiabetic activity of the extract from the leaves of *Lagerstroemia speciosa* standardized to 1% corosolic acid (Glucosol™) has been demonstrated in a randomized clinical trial involving diabetes mellitus where subjects received a daily oral dose of Glucosol™ at dosages of 32 and 48 mg for 2 weeks showed a significant reduction in the blood glucose levels [53]. This suggested SWE of pharmaceutical extracts could play potential role in the field of medicinal plants to deal with global twin problems (obesity and diabetes mellitus) of the twenty first century. This is because, extracts from subcritical water can be directly used for pharmacological and toxicological testing.

Ursolic acid is a well-known compound with various promising biological activities including, anti-cancer, anti-inammatory, hepatoprotective, antiallergic and anti-HIV properties [54-56]. Also ursolic acid is reported to exhibits anti-diabetic potential and immunomodulatory properties by increasing insulin levels with preservation of pancreatic β-cells and modulating blood

glucose levels, T-cell proliferation and cytokines production by lymphocytes in type 1 diabetic mice fed a high-fat diet [57]. More so ursolic acid is a potential therapeutic agent for the treatment of diabetic complications, including accelerated atherosclerosis, and provides a novel mechanism for the anti-atherogenic properties of ursolic acid [49].

SWE is likely to bring a significant economic benefits, environmental benefits and improved social life as demonstrated in Figure 4. The information depicts the relationship between social life style, artificial antidiabetic drug, and natural antiabetic plant extracts to deal with obesity and diabetes mellitus. The objectives of the relationships are portrayed at the apices of triangles. Desirable connections (upper) and actual problems (lower) are shown between them.

To have a sustainable global community, it demands that we specifically examine problems that appear in relation to means, in order to prevent or cure diabetes. However, the variations between means to deal with diabetes often bring other problems. Personal choice and life style has a lot to do with diabetes dealings. Furthermore, artificial drugs though they are effective and efficient when co-used with good living standard but their side effect pose a lot of challenges to the user. Thus, if used for a long time, it would become a lifelong medication bringing economic burdens. Therefore, to address these challenges, antidiabetic extracts from natural sources obtained by subcritical water (Table 3) could be a better and affordable solution.

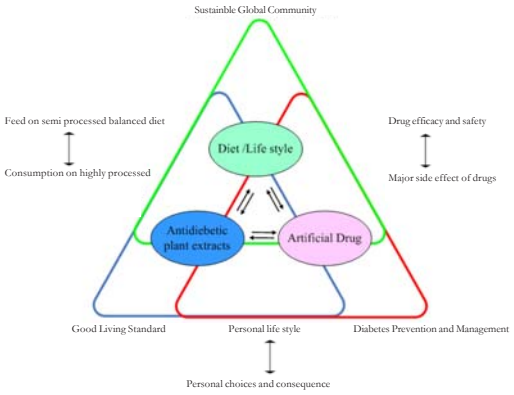

Figure 4. Relationship between social life style, artificial antidiabetic drug, and natural antidiabetic plant extracts for sustainable global community.

10. CONCLUSION AND RECOMMENDATION

From the available literature on the extraction technologies development in food industry, SWE has shown to have the promising potential for the selectivity of either bioactive compounds obtained at subcritical water conditions, or for different analyte classes achieved by temperature programming through careful optimization of extraction parameters. Furthermore, subcritical water produces a high ion product, a property suitable for hydrolysis reactions. Consequently, water at elevated temperature and pressure could act as an acid or base catalyst to produce bioactive compounds from natural sources. The degradation kinetics of natural resources under subcritical condition has shown to produce useful new compounds through isomerization of fatty acids. Moreover, from 200 °C to 300 °C, the dielectric constant for subcritical water is almost the same as those of methanol and ethanol at ambient

conditions, indicating that subcritical water can be used for extracting hydrophobic substances from natural resources. Based on the potential and the prospect of SWE, it is recommended that future research work should be devoted in scaling up of SWE to a commercial scale level with a great emphasis on energy efficiency and water as a green alternative extraction solvent for scientic and commercial purposes. It is hoped that such a research initiative would significantly contribute to the understanding, advancement, and future applications of natural extracts obtained by SWE in dealing with obesity and diabetes mellitus, the global twins of the twenty first century.

ACKNOWLEDGEMENTS

This study was supported, in part, by National Natural Science Foundation of China (Grant No. 31271946 and 31101287 and 973 projects from the Ministry of Science and Technology (No. 2012CB720801).

REFERENCES

[1] Bernatoniene J., Cizauskaite U., Ivanauskas L., Jakstas V., Kalveniene Z. and Kopustinskiene D.M., *Ind. Crop. Prod.*, 2016; **84**: 72-79.

[2] Zhao S. and Zhang D., *Sep. Purif. Technol.*, 2014; **133**: 443-451.

[3] Cheng X.L., Wan J.Y., Li P. and Qi L.W., *J. Chromatogr. A.*, 2011; **1218(34)**: 5774-5786. DOI 10.1016/j.chroma.2011.06.091.

[4] Luong D., Court R.W., Sims M.R., Cullen D.C. and Sephton M.A., *Planet Space Sci.*, 2014; **99**: 19-27. DOI 10.1016/j.pss.2014.05.001.

[5] Lin R., Cheng J., Ding L., Song W., Qi F., Zhou J. and Cen K., *Bioresour. Technol.*, 2015; **186**: 8-14. DOI 10.1016/j.biortech.2015.03.047.

[6] Liu J., Chen P., Yao W., Wang J., Wang L., Deng L., He J., Zhang G. and Lei J., *Ind. Crop. Prod.*, 2015; **74**: 557-565. DOI 10.1016/j.indcrop.2015.05.064.

[7] Bogdanovic A., Tadic V., Arsic I., Milovanovic S., Petrovic S. and Skala D., *J. Supercrit. Fluid.*, 2016; **107**: 234-242. DOI 10.1016/j.supflu.2015.09.008.

[8] Singh P.P. and Saldana M.D.A., *Food Res. Int.*, 2011; **44**: 2452-2458.

[9] Kapalavavi B., Marple R., Gamsky C. and Yang Y., *Int. J. Cosmetic. Sci.*, 2015; **37**: 306-311.

[10] Hawthorne S.B., Grabanski C.B., Martin E. and Miller D.J., *J. Chromatogr. A.*, 2000; **892(1-2)**: 421-433. DOI 10.1016/S0021-9673(00)00091-1.

[11] Amashukeli X., Grunthaner F.J., Patrick S.B. and Yung P.T., *Astrobiology*, 2008; **8**: 597-604.

[12] Mohan M., Banerjee T. and Goud V.V., *Bioresour. Technol.*, 2015; **191**: 244-252. DOI 10.1016/j.biortech.2015.05.010.

[13] Khajenoori M., Asl A.H and Hormozi F., *J. Chem. Eng.*, 2009; **17**: 359-365. DOI 10.1016/S1004-9541(08)60217-7.

[14] Kumar M.S.Y., Dutta R., Prasad D. and Misra K., *Food Chem.*, 2011; **127**: 1309-1316. DOI 10.1016/j.foodchem.2011.01.088.

[15] Ibanez E., Kubatova A., Senorans F.J., Cavero S., Reglero G. and Hawthorne S.B., *J. Agric. Food Chem.*, 2003; **51**: 375-382.

[16] Ko M.J., Cheigh C.I. and Chung M.S., *Food Chem.*, 2013; **143**: 147-155. DOI 10.1016/j.foodchem.2013.07.104.

[17] Plaza M. and Turner C., *Trac-Trend. Anal. Chem.*, 2015; **71**: 39-54. DOI 10.1016/j.trac.2015.02.022.

[18] Asl A.H. and Khajenoori M., *Creative Commons Attribution License*, 2013. DOI 10.5772/54993.

[19] Yang Y., Kayan B., Bozer N., Pate B., Baker C. and Gizir A.M., *J. Chromatogr. A.*, 2007; **1152**: 262-267.

[20] Santos A.S.F., Agnelli J.A.M. and Manrich S., *Food Addit. Contam. Part A*, 2010; **27**: 567-573. DOI 10.1080/19440040903440372.

[21] Islam M.N., Jo Y.T., Jung S.K. and Park J.H., *J. Ind. Eng. Chem.*, 2012; **19**: 129-136. DOI 10.1016/j.jenvman.2015.08.007.

[22] Mlyuka E., Zhang S., Zheng Z., He Z., Zeng M., Mbifile M. and Chen J., *Chiang Mai J. Sci.*, 2016; **44(4)**: 1-14.

[23] Kong W., Kang Q., Feng W. and Tan T., *Chem. Eng. Res. Des.*, 2015; **104**: 1-10.

[24] Chemat F., Fabiano-Tixier A.S., Vian M.A., Allaf T. and Vorobiev E., *Trac-Trend. Anal. Chem.*, 2015; **71**: 157-168.

[25] Turner C. and Waldeback M., *Separation, Extraction and Concentration Processes in the Food, Beverage and Nutraceutical Industries*, in Rizvi S.S.H., ed., Woodhead Publishing. 2013: 39-70.

[26] Yildiz-Ozturk E., Tag O. and Yesil-Celiktas O., *J. Supercrit. Fluid*, 2014; **95**: 422-430.

[27] Mlyuka E., Zhang S., Wang L., Zheng Z. and Chen J., *Int. J. Food Eng.*, 2016. DOI 10.1515/ijfe-2016-0054.

[28] Mlyuka E., Zhang S., Zheng Z. and Chen J., *Afr. J. Biotechnol.*, 2016; **15(22)**: 1041-1049.

[29] Curren M.S.S. and King J.W., *J. Agric. Food Chem.*, 2001; **49(5)**: 2175-2180.

[30] Khajavi S.H., Kimura Y., Oomori T., Matsuno R. and Adachi S., *Biosci. Biotechnol. Biochem.*, 2004; **68(1)**: 91-95.

[31] Sunphorka S., Chavasiri W., Oshima Y. and Ngamprasertsith S., *J. Supercrit. Fluid*, 2012; **65**: 54-60.

[32] Chan C.H., Yusoff R. and Ngoh G.C., *Chem. Eng. Res. Des.*, 2014; **92(6)**: 1169-1186.

[33] Kwon H.L. and Chung M.S., *Food Chem.*, 2015; **185**: 58-64.

[34] Islam M.N., Jo Y.T., Jung S.K. and Park J.H., *Water Air Soil Poll.*, 2013. DOI 10.1007/s11270-013-1652-8.

[35] Wang X. and Lu X., *Carbohyd. Polym.*, 2014; **102**: 174-184.

[36] Ravber M., Knez Z. and Skerget M., *Food Chem.*, 2015; **166**: 316-323.

[37] Shin H.Y., Ryu J.H., Park S.Y. and Bae S.Y., *J. Anal. Appl. Pyrol.*, 2012; **98**: 250-253.

[38] Jeon W., Ban C., Park G., Yu T.K., Suh J.Y., Woo H.C. and Kim D.H., *J. Mol. Catal. A*, 2015; **399**: 106-113.

[39] Salak F., Pourali O. and Yoshida H., Proceedings of the World Congress on Engineering and Computer Science 2009, San Francisco, USA 2009.

[40] He L., Zhang X., Xu H., Xu C., Yuan F., Knez Z., Novak Z. and Gao Y., *Food Bioprod. Process.*, 2012; **90(2)**: 215-223.

[41] Pelaez-Samaniego M.R., Yadama V., Garcia-Perez M., Lowell E., *Biomass Bioenerg.*, 2015; **81**: 117-128.

[42] Cheigh C.I., Yoo S.Y., Ko M.J., Chang P.S. and Chung M.S., *Food Chem.*, 2015; **168**: 21-26. DOI 10.1016/j.foodchem.2014.07.047.

[43] Ko M.J., Cheigh C.I., Cho S.W. and Chung M.S., *J. Food Eng.*, 2011; **102(4)**: 327-333.

[44] Lu W., Chen X.W., Wang J.M., Yang X.Q. and Qi J.R., *J. Food Eng.*, 2016; **169**: 250-258.

[45] Bitencourt R.G., Queiroga C.L., Duarte G.H.B., Eberlin M.N., Kohn L.K., Arns C.W. and Cabral F.A., *J. Supercrit. Fluid*, 2014; **95**: 355-363.

[46] Ren Q., Xing H., Bao Z., Su B., Yang Q., Yang Y. and Zhang Z., *Chinese J. Chem. Eng.*, 2013; **21(9)**: 937-952.

[47] Lachos-Perez D., Martinez-Jimenez F., Rezende C.A., Tompsett G., Timko M. and Forster-Carneiro T., *J. Supercrit. Fluid*, 2016; **108**: 69-78.

[48] Xu Y., Cai F., Yu Z., Zhang L., Li X., Yang Y. and Liu G., *Food Chem.*, 2016; **194**: 650-658.

[49] Ullevig S.L., Zhao Q., Zamora D. and Asmis R., *Atherosclerosis*, 2011; **219(2)**: 409-416.

[50] Murakami C., Myoga K., Kasai R., Ohtani K., Kurokawa T., Ishibashi S., Dayrit F., Padolina W. and Yamasaki K., *Chem. Pharm. Bull.*, 1993; **41(12)**: 2129-2131.

[51] Yoshikawa M. and Matsuda H., *Biofactors*, 2000; **13(1-4)**: 231-237.

[52] Teodoro T., Zhang L., Alexander T., Yue J., Vranic M. and Volchuk A., *FEBS Lett.*, 2008; **582(9)**: 1375-1380.

[53] Judy W.V., Hari S.P., Stogsdill W.W., Judy J.S., Naguib Y.M.A. and Passwater R., *J. Ethnopharmacol.*, 2003; **87(1)**: 115-117.

[54] Dar B.A., Lone A.M., Shah W.A. and Qurishi M.A., *Eur. J. Med. Chem.*, 2016; **111**: 26-32.

[55] Yun J.W., *Phytochemistry*, 2010; **71(14-15**): 1625-1641.

[56] Kashyap D., Tuli H.S. and Sharma A.K., *Life Sci.*, 2016; **146**: 201-213.

[57] Jang S.M., Yee S.T., Choi J., Choi M.S., Do G.M., Jeon S.M., Yeo J., Kim M.J., Seo K.I. and Lee M.K., *Int. Immunopharmacol.*, 2009; **9**: 113-119.

[58] Yuksel A., Sasaki M. and Goto M., *J. Hazard. Mater.*, 2011; **190(1-3)**: 1058-1062.

[59] Kayan B. and Gözmen B., *J. Hazard. Mater.*, 2012; **201-202**: 100-106.

[60] Lindquist E. and Yang Y., *J. Chromatogr. A.*, 2011; **1218(15)**: 2146-2152.

[61] Daskalaki V.M., Timotheatou E.S., Katsaounis A. and Kalderis D., *Desalination*, 2011(1-3); **274**: 200-205.

[62] Tangkhavanich B., Kobayashi T. and Adachi S., *J. Ind. Eng. Chem.*, 2014; **20(4)**: 2610-2614.

[63] Droux S., Roy M. and Félix G., *J. Chromatogr. B.*, 2014; **968**: 22-25.

[64] Jinzhao Y., Zeng M.M., He Z., Qin F. and Chen J., *Food Ind.*, 2013; **34**: 189-192.

[65] Jinzhao Y., Jie C., Extraction of Ursolic Acid from Loquat Leaf using Subcritical Water, MSc Thesis, Jiangnan University, China, 2013.

[66] Duba K.S., Casazza A.A., Mohamed H.B., Perego P. and Fiori L., *Food Bioprod. Process.*, 2015; **94**: 29-38.

[67] Fernández-Ponce M.T., Casas L., Mantell C. and Martínez de la Ossa E., *Innov. Food Sci. Emerg.*, 2015; **29**: 94-106.

[68] Isa K.M., Snape C.E., Uguna C. and Meredith W., *J. Anal. Appl. Pyrol.*, 2015; **113**: 646-654.

[69] Salgueiro-González N., Turnes-Carou I., Muniategui-Lorenzo S., López-Mahía P. and Prada-Rodríguez D., *J. Chromatogr. A.*, 2015; **1383**: 8-17.

[70] Xiao Z., Song R., Rao Z., Wei S., Jia Z., Suo D. and Fan X., *J. Chromatogr. A.*, 2015; **1418**: 29-35.

[71] Ma Q., Fan X.D., Liu X.C., Qiu T.Q. and Jiang J.G., *Sep. Purif. Technol.*, 2015; **150**: 73-79.

[72] Savy D., Mazzei P., Roque R., Nuzzo A., Bowra S. and Santos R., *Fuel Process. Technol.*, 2015; **138**: 637-644.

[73] Kodama S., Shoda T., Machmudah S., Wahyudiono Kanda H. and Goto M., *Chem. Eng. Process.*, 2015; **97**: 45-54.