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A REVIEW ON EXTRACTION OF LIPID FROM MICROALGAE USING MICROWAVE-ASSISTED EXTRACTION

(Sebuah Ulasan Terhadap Pengekstrakan Lipid Daripada Mikroalga Dengan Pengekstrakan Bantuan Gelombang Mikro)

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Abstract

Microalgae are regarded as suitable feedstock for biofuel due to the~~ir~~ high growth rate and substantial lipid content Furthermore, the physiological functions of microalgal lipids contribute to their effectiveness as bioactive compounds with economic value particularly in pharmaceutical and health supplement industries. Extracting the stored lipid from microalgae is a major challenge for industrial applications as their tough cell wall is difficult to break down. Therefore, extraction solvents and cell disruption techniques are key procedures for high lipid extraction and recovery. Traditional methods used for cell disruption and extraction are effective but time consuming and could be detrimental to the environment. Hence, different innovative cell disruption techniques such as microwave-assisted extraction are developed to overcome these issues. This paper is a review of traditional and microwave-assisted extraction methods that are used for lipid extraction from microalgae biomass. The advantages, challenges and future trends of microwave-assisted extraction are also discussed.

Keywords: lipid extraction, microwave-assisted extraction, microalgae, traditional lipid extraction

Abstrak

Lipid yang dihasilkan oleh mikroalga dianggap sebagai bahan mentah yang sesuai untuk biofuel kerana kadar pertumbuhan dan kandungan lipid yang tinggi. Selain itu, fungsi fisiologi lipid mikroalga juga menjadikannya sebagai sebatian bioaktif yang tinggi dalam industri farmaseutikal dan suplemen kesihatan. Mengekstrakkan lipid daripada mikroalga merupakan cabaran utama untuk aplikasi perindustrian kerana dinding selnya yang kukuh dan sukar dipecahkan. Oleh hal demikian, pelarut pengekstrakan dan teknik gangguan sel adalah prosedur penting untuk pengekstrakan lipid tinggi. Kaedah tradisional yang digunakan untuk gangguan sel dan pengekstrakan adalah berkesan tetapi tidak mesra alam dan mengambil masa. Oleh hal demikian, pelbagai teknik gangguan sel inovatif seperti pengekstrakan bantuan gelombang mikro telah dibangunkan. Kertas kerja ini ialah sebuah ulasan terhadap kaedah tradisional dan pengekstrakan bantuan gelombang mikro yang telah digunakan untuk pengekstrakan lipid daripada biojisim mikroalga. Kelebihan, cabaran dan trend masa depan pengekstrakan bantuan gelombang mikro juga dibincangkan.

Kata kunci: pengekstrakan lipid, pengekstrakan bantuan gelombang mikro, mikroalga, kaedah pengekstrakan lipid tradisional

Introduction

Escalated population and economic development have led to the increase in global energy demands annually. Meanwhile, reducing consumption of fossil fuels should be mandatory considering the negative environmental impact, depleting resources and steep increase in

petroleum prices. Renewable energy is an alternative choice to fulfil energy demands with minimal environmental impact. Among the different types of existing renewable energy, liquid biofuel such as biodiesel has gained considerable attention as a future energy supply due to fact that it is biodegradable, renewable, carbon-neutral and is less flammable [1]. Biodiesel can be extracted from oil-producing, terrestrial plants, however, public conflicts relating to food security, freshwater demand and deforestation issues have been raised [2]. Hence, microalgae are currently regarded as an attractive option for biodiesel production. Compared to oil-producing terrestrial plants, microalgae have better carbon dioxide sequestration and faster growth rate [3]. Moreover, microalgae can grow in non-arable land and utilize wastewater as nutrient sources [4]. Microalgae with 30% lipid in dry biomass is estimated to produce up to 58700 litres of lipids per hectare in one year, which is considerably better than oil-producing terrestrial plants [5]. Besides that, the biodiesel that is trans-esterified from microalgal lipids has been demonstrated to meet European and United State biodiesel specifications (EN 14214 and ASTM D6751). The studies showed that microalgal biodiesel with proper blends can be used in diesel engines with low pollutant emission [6-7]. Apart from the application in biodiesel production, the physiological functions of microalgal lipid such as eicosapentaenoic acid (EPA), docosapentaenoic acid (DPA) and docosahexaenoic acid (DHA) make them high bioactive compounds with huge potential in pharmaceutical and health supplement industries [8-9].

Lipid production from microalgae involves several key processes which are cultivation, harvesting and lipid extraction. Transesterification may be included as part of the process for biodiesel production. Among these processes, lipid extraction has been found to be challenging particularly as it can affect the overall quality of the biodiesel [10-11]. During the conventional process of lipid extraction, organic solvents such as chloroform and hexane are employed, but these solvent may not be suitable enough for the complete extraction of lipids due to the hindrance of the rough cell wall contained in microalgae [12]. Some of the lipids might embedded in or cannot pass through the cell wall, and therefore cannot be extracted by the solvent [13]. Hence, it is crucial to ensure that the microalgal cell structure has been completely damaged to improve the extraction efficiency. However, selecting an ideal cell disruption technique is quite a challenging task. In lieu of considering the efficiency of the extraction process, finding a greener and more economical lipid extraction method is necessary to ensure that it will be environmentally friendly, energy efficient and suitable for upscale lipid production. Various methods are applied for extracting lipids from microalgae [14-15], out of which microwave-assisted extraction (MAE) is one of the more attractive green methods because it offers several benefits including efficient cell disruption, fast extraction and requires less consumption of solvents [16].

In this review, some basic information on microwaves and traditional methods of lipid extraction from microalgae biomass are discussed and compared. In additional, an overview of the factors, challenges and future trends of MAE are presented.

Traditional lipid extraction

Soxhlet extraction is a traditional technique used for extracting lipids from microalgae [17-18]. In the conventional Soxhlet extraction (Figure 1), the sample is placed in a porous thimble and once the distillation flask is heated, the extraction solvent evaporates and flows into the condenser where it is cooled down and condenses into liquid. This liquid then drips back into the thimble and extracts the lipids from the sample. When the thimble is almost full, a siphon aspirates the solvent from the chamber and returns it into the distillation flask. This process is repeated for several cycles until the extraction of lipids is completed. After extraction, no filtration or centrifugation is required to separate the samples and extraction solvent. Furthermore, the process is automated and no manual operation is required to rinse the sample with solvent [19]. However, several studies revealed that the lipid yield using Soxhlet extraction was very low compared to both the Folch Method and Bligh & Dyer method [20-22]. This is probably because hexane, which was commonly used in Soxhlet extraction, is nonpolar therefore is unable to effectively extract neutral lipids from microalgae [21-22]. Therefore, it was suggested that hexane be replaced by a mixture of nonpolar and polar solvents such as hexane: ethanol to extract the microalgal lipids. The studies showed that the lipid and fatty acid yield improved significantly using this combination of solvents compared to just using hexane [23-24]. Still, the time required to complete Soxhlet extraction usually lasts for several to twenty-four hours, which is extremely time-consuming compared to other lipid extraction methods, resulting in more a laborious and ineffective method for extracting high numbers of samples [23]. In the analysis of fatty acid profiles by previous research, the extraction yield of unsaturated lipids was very low compared to other extraction

methods [21, 25]. This was probably caused by the instability of unsaturated lipids due to the long-time exposure at elevated temperatures which caused the degradation of these lipids during reflux [26].

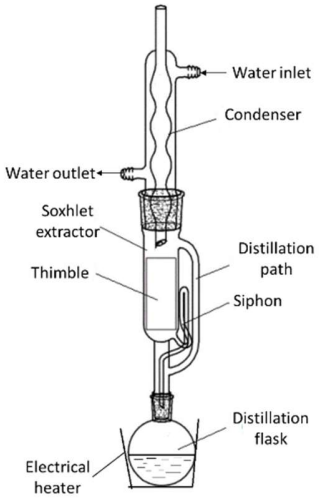

Figure 1. Soxhlet extraction

Folch Method [27] and Bligh & Dyer method [28] are common lipid extraction procedures that are frequently used for lipid extraction. In the Folch method, a mixture of organic solvents, usually chloroform and methanol at a ratio of 2:1 (v/v), is added to the microalgae biomass then vortexed for 30 seconds to several minutes. Water is then added to induce phase separation. Centrifugation is subsequently carried out in some studies to generate a clear phase separation [21, 29]. The organic phase on the top is collected and the lipids can be recovered after rotary evaporation or vacuum evaporation. The process in the Bligh and Dyer method are similar to the Folch Method whereby a mixture of chloroform, methanol and water at the ratio of 2:2:1.8 (v/v) is used as the extraction solvent [28]. The process of these two methods is easy to perform and do not require high pressure or high temperature during the extraction.

Although both the Folch and the Bligh & Dyer methods are well established for lipid extraction from solid animal tissue, the lipid extraction from microalgae could be lower [49]. In order to achieve better extraction results, the modifications of the Bligh and Dyer method has been investigated by several studies. One of the proposed modifications is the addition of sodium chloride solution instead of water [29-30] to restrict the binding of acidic lipids to denatured lipids [31]. In another study, the parameters in the Bligh and Dyer method were modified using response surface methodology [32]. The optimal extraction of 1 g dry biomass was obtained by using a solvent mixture of chloroform: methanol: water with ratio of 5.7:3:1 (v/v) under 25°C and 2-hours extraction [32].

Another reason for low extraction yield of microalgae lipids using Folch and Bligh & Dyer method is the difference between microalgal cell structure and animal tissue. Microalgae are usually covered with cell walls that isolate the intracellular compounds from the outer environment. In some cases, these cell walls are recalcitrant, complex and thick thereby hindering solvent penetration, resulting in low recovery of lipids [13, 33]. Cell disruption has been suggested to disintegrate the microalgal cell wall followed by the lipid extraction process. Many studies have shown that the yield of average lipids after cell disruption are much higher compared to lipid extraction without any cell disruption [33-37].

Microwave-assisted extraction

Microwave is an electromagnetic wave that is positioned between the X-ray and infrared rays in the electromagnetic spectrum with frequencies ranging from 300 MHz to 300 GHz. The electric and magnetic fields of the microwave are responsible for the heating effects under through the microwave dielectric heating and magnetic loss heating effects respectively. In the microwave dielectric heating, dipolar polarization and ionic conduction are two main energy transfer mechanisms that render localized and superheating of the reaction material within a very short time [38]. According to Balasubramanian et al. [25], microwaves can reach up to 80-°C or 95-°C within 100 seconds or less whereas conventional heating requires more than 1000 seconds to reach the target temperature. The slow heating rate in conventional heating is due to the heat transfer through thermal conduction and convection in which heat is transferred to the wall of the target object before reaching the internal object [38]. In this process, the energy is utilized inefficiently as it might be lost to the environment. In contrast, the molecules in the reaction material that have dipole moment absorb the microwave energy and convert it to heat through dipolar polarization and ionic conduction. In the case of MAE on microalgae, inner molecules in the microalgae cells are heated up and lead to a tremendous increase in pressure within the cells. The cell wall is then disrupted when the internal pressure exceeds the endurance limit [39]. The comparison between microwave heating and conventional thermal cell disruption is summarized in Table 1.

Table 1. Comparison between microwave heating and other conventional thermal cell disruption on microalgae.

Aspects	Microwave heating	Conventional thermal cell disruption
Heating mechanism	Dipolar polarization & ionic conduction	Conduction/convection
Time	Very fast, usually less than 1 hour	Slow, can up to several hours
Heating direction	Heat transfer from inner molecule or solvent to wall of object	Heat transfers from wall of object to the cells
Selectivity	Only polar solvent can convert microwave energy to heat	Non-selectivity
Cellular image	Microalgal cell wall is severely disrupted	Microalgal cell wall is remained intact

The cellular images under microscopy from several studies have illustrated that the microalgal cell wall was severely disrupted after microwave treatment whereas the cell wall of these microalgae remained intact after conventional heating [40-42]. Thus, target molecules such as lipid can easily spill out from the ruptured cell wall. Besides that, the volumetric heating generated by the microwave, induce the sudden rising of temperature within the cells thereby creating pressure effects on the cell wall. This phenomenon causes the diffusion of intracellular components to the exterior of the cells, eventually leading to the destruction of the cell structure and subsequent shrinking of the cell wall [42].

Different conditions of MAE can generate various lipid extraction yields and fatty acid profiles from microalgae. The parameters and lipid yields from various studies are summarized in Table 2. The effects of parameters such as solvents, extraction time, microwave power and mass of microalgae used in the lipid extraction must be studied carefully in order to achieve high extraction yield. Among these parameters, the solvent plays a determining factor on extraction yield of lipids. In some studies, the solvent in MAE acted as "pretreatment solvent" to break down the cell wall of microalgae by absorbing the microwave irradiation and increasing the temperature in the cells. The lipid was then extracted using other extraction solvents [37, 43-44]. Whereas, in other studies, the solvents not only have the function thereof, but also act as an extraction solvent to extract the lipid [41, 45-46]. To break down the cell wall effectively, polar solvents such as water, ethanol and methanol are usually chosen because of their high dielectric loss constant which is able to absorb the microwaves and convert them into heat [39-40]. On the other hand, the nonpolar solvents such as hexane and chloroform are excellent to dissolve lipids, however, they are microwave-transparent and are thereby unable to transform microwave energy into heat [46]. Lin and Lin [45] showed that the lipid extracted from *Isochrysis galbana* using nonpolar hexane was significantly lower than when polar isopropanol was used. Mansour et al. [41] also showed that the polar solvents such as methanol and ethanol, can extract higher amounts of lipid compared to nonpolar solvents. This is probably due to the strong association of lipids with proteins via hydrogen bonds which are difficult to be disrupted by nonpolar solvents. However, this association can easily be destroyed by polar solvents through the formation of hydrogen bonds [47]. Moreover, the presence of polar lipids such as phospholipid and glycolipids, are more soluble in polar solvents thereby enhance the lipid yield. Nevertheless, high amount of phospholipids might not beneficial for biodiesel production during transesterification because free fatty acids are enclosed by phospholipids which makes it difficult to be trans esterified into fatty acid methyl ester [48]. Moreover, some of the polar lipids and polar compounds that are non-saponifiable, when extracted by polar solvents may destroy the catalyst during transesterification, thereby reducing the conversion of lipids into fatty acid methyl esters [49]. In another study conducted by Dai et al. [46], however, contrasting results were obtained where nonpolar n-heptane produced better lipid extraction yields from dry microalgae powder. This contradictory result could probably be attributed to the different types of lipids present in different microalgae species.

In order to optimize lipid yield, most studies use a mixture of polar and nonpolar solvents. Several studies demonstrated that solvent mixtures can produce higher extraction yields compared to using a single solvent [15, 47, 50]. In this context, polar solvents have the capacity to absorb the microwaves and quickly induce heat production. The breakdown of cell walls and lipid-

protein linkages result in the rapid mass transfer of lipids from the interior to the exterior of the cells. The neutral lipids are then dissolved in the nonpolar solvents [50]. Besides of types of solvents, the ratio of solvents in mixture are also an important factor for extracting lipids that are suitable for biodiesel production. Iqbal et al. [49] showed that lipid extraction yields using methyl soyate with 60% ethanol was 50% higher than when methyl soyate was used with 80% ethanol. Similar results were also obtained by Saifuddin et al. [51] and Dai et al. [46] who showed that a lower proportion of polar solvents could generate higher lipid extraction.

Temperature is another crucial factor that greatly influences the extraction yield of MAE [40]. It can be controlled directly by altering the microwave setting or indirectly by adjusting the microwave power or irradiation time. Moderate power (180 – 800W) or high temperatures with long irradiation time (2- 40min) usually can generate a good lipid yield [52-55]. High temperatures with short irradiation time also can generate a good lipid yield. In the optimization study conducted by Menéndez et al. [53], the lipid and fatty acid yield extracted using MAE at 60 °C for 20 minutes was similar to the result at 90 °C for 10 minutes. Conversely, high temperature or high power with long irradiation time reduces the lipid yield and their fatty acid profiles [56-58]. At high temperatures, the amount of saturated fatty acid extracted increases while the amount of unsaturated fatty acids decreases [40, 58]. This phenomenon can be elucidated by the production of hydroxyl free radicals during MAE which have strong oxidation capacity that can cleave the double bonds of unsaturated fatty acids [44]. The reduction of unsaturated fatty acids, however, is not favorable for pharmaceutical or food production since microalgae polyunsaturated fatty acids such as DHA and EPA are bioresources with high value [8]. However, low amounts of polyunsaturated fatty acids have a positive effect on biodiesel production as high level of polyunsaturated fatty acid causes poor ignition quality and low oxidative stability [59]. Hence, temperature, power and irradiation time should be monitored carefully based on the requirement of product quality and its use.

The amount of biomass used for MAE has a considerable effect on the recovery of lipids. High amounts of biomass with either low microwave power or short irradiation time [21, 55] can result in low extraction yield. Longer irradiation time or high microwave power are required to break down the cell and improve the yield. Whereas, the lipid yield extracted from low amounts of biomass with high microwave power and long irradiation time are also suboptimal [52]. Therefore, it is essential to carefully select the optimal amount of biomass for MAE in order to maximize the lipid yield.

Advantages of MAE

Numerous studies have reported the comparison of MAE with other extraction techniques for lipid. Owing to its unique heating effect, MAE has been found to extract high amounts of lipid very quicky, usually within 40 minutes. Whereas, conventional extraction techniques such as Soxhlet extraction and water bath heating have been shown to require up to ten hours to extract similar amounts of lipids [25, 50-51]. Moreover, MAE of lipids can be operated in lower temperature environments [14]. Short reaction time and low temperature not only can reduce the change of oxidization of unsaturated lipids but also avoid degradation of proteins and bioactive compounds which can be used in bio-refinery process.

In addition, water, which is non-toxic and safe, can serve as an excellent solvent to disrupt and extract lipids using MAE [43-44]. Before extraction, dewatering and drying is usually required prior to extraction to remove water from microalgae biomass. In MAE, several studies reveal that removal of water is not necessary [60-63]. The water content in microalgae biomass or cultivation medium can be used as solvent to absorb microwaves and break down the cells [55]. Pôjo et al. [69] showed that the drying process required 89% of energy input and 70-75% total processing costs. Consequently, utilization of wet microalgae biomass can reduce the cost and energy consumption. In terms of energy consumption in different extraction techniques, MAE was observed to require lower amounts of energy (70 - 270 MJ/kg) whereas sonication, high-pressure homogenization and bead milling require more extensive energy usage (132, 529 and 504 MJ/kg respectively) [58]. In terms of cost analysis, the cost required to extract 1 kg lipid from microalgae using MAE is more than 50% lower than using Soxhlet extraction [21].

Table 2. Lipids extracted from microalgae by MAE

Microalgae Species	Dry/Wet	Solvent	Sample Weight; Solvent Volume	Microwave Setting	Lipid Extraction Yield*	Reference
Chlorella vulgaris	Wet	Chloroform-methanol (add after microwave)	1:2	100°C, 5 min	17.5%	[35]
Scenedesmus obliquus	Wet	Water	1:1	95°C, 30 min	31%	[25]
Nannochloropsis occulata	Wet	Dichloromethane	NA	140°C, 15 min	11.3%	[58]
Chlorogloeopsis fritschii				120°C, 15 min	1.4%	
Pseudochoricystis ellipsoidea				140°C, 15 min	37.5%	
Chlorella pyrenoidosa	Wet	Chloroform: methanol (1:1)	1g; 8 mL	500W, 40 s	19%	[61]
Nannochloropsis sp.	Wet	Methyl soyate: ethanol (3:2)	3.3 g; 20 mL	120 °C, 20 min	56.6%	[49]
		Chloroform: ethanol (1:2)	3.3 g; 20 mL		53.1%	
Dunaliella tertiolecta	Dry	Chloroform: methanol (2:1)	0.2g; 20 mL	490 W; 2.67 min	57.02%	[52]
Nannochloropsis sp.	Wet	Methanol: Hexane (1:2)	-	65 °C, 5 min	38.31%	[39]
Nannochloropsis sp.	Wet	Isopropanol: hexane (2:3)	15 mL; 50 mL	65 °C, 500 W; 5 min	8.19%	[62]
Tetraselmis sp.	Wet	Chloroform: methanol (2:1)	15 mL; 75 mL	65 °C, 500 W; 5 min	8.47%	
Tetraselmis sp.	Wet	NA	NA	80 - 90 °C, 5 min	20.26%	[63]
Microalgae^{+}	Wet	Chloroform: methanol (2:1)	0.5 g: 75 mL	530 W, 75s	11.6%	[60]
Nannochloropsis gaditana	Dry	Methanol	5g; 50 mL	90 °C, 10 min	40%	[53]
Scenedesmus dimorphus	Dry	Chloroform: methanol (2:1) (add after microwave)	NA	557 W, 3 min	17%	[64]
Selenastrum minutum					23%	
Chlorella					17%	

protothecoides						
Isochrysis galbana	Dry	hexane/isopropanol (2:1)	NA	NA	22.13%	[45]
Chlorococcum sp.	Dry	Distilled water	0.2 g; 100 mL	100 °C, 2 min	24.12%	[37]
Botryococcus sp. MCC31				100 °C, 6 min	48.33%	
Chlorella sorokiniana				100 °C, 6 min	24.43%	
Chlorella vulgaris	Dry	Chloroform: methanol (2:1)	1:10	100 °C, 15 min	22.68%	[65]
Nannochloropsis oculata	Wet	Ethanol (add after microwave)	1:5	443 W, 5 min	0.149 g/g	[56]
Nannochloropsis sp.	Wet	Biodiesel: ethanol (2:3)	8 g; 50mL	180 W, 15 min	0.654 g/g	[51]
Chlorella sorokiniana *Nannochloropsis salina* *Galdieria sulphuraria*	Dry	[BMIM][HSO_4] (Add After microwave)	1 g; 5g	800W, 120 °C, 60 min	0.23 g/g 0.10 g/g 0.19 g/g	[66]
Spirulina platensis	Dry	Water	1g; 10 mL	620 W, 20s	0.385 g/g	[43]
Chaetoceros calcitrans	Dry	Water	0.3 g; 20 mL	1400W, 40s	24.2%	[44]
Scenedesmus obliquus	Dry	chloroform/methanol (2:1)	NA	400W, 130°C, 30 min,	0.234 g/g	[42]
Scenesdemus quadricauda	Wet	Methanol: sulphuric acid (50:1)	500 mL; 500 Ml	473W, 8 min	41.94%	[54]
Nannochloropsis gaditana	Dry	Distilled water	NA	800W, 80 °C, 60 min	11.22%	[67]
Chlorella vulgaris	Dry	Chloroform: methanol (1:2) (Add after microwave)	NA	700W, 3 min	0.183 g/g	[68]
Chlorella pyrenoidosa	Wet	NA	NA	700W, 5 min	16.73%	[55]

* in percent dry weight

+ The name of microalgae species is not stated in original article.

Several studies also revealed the potential of microwave for direct transesterification of lipids into fatty acids, where lipid extraction and transesterification are carried out in the same process. Higher amount of fatty acid methyl ester could be attained in less time compared to transesterification after microwave-assisted extraction of lipids [61, 70-72]. Moreover, less impurities such as chlorophyll are detected in fatty acid methyl ester using microwave-assisted direct transesterification. Such processes minimize the requirement to remove impurities while simultaneously enhances the production of other high-valuable bioactive compounds [70].

Challenges and future trends

Although microwaves have been successful utilized to

disrupt the microalgae cells and extract lipids, there are several limitations in using MAE. In many studies, organic solvents especially chloroform and methanol are usually used to extract lipids during or after microwave treatment due to their excellent ability to absorb microwaves and their high solubility for different types of lipids. However, chloroform is toxic and therefore poses a health risk to the operator and may, in addition, cause environmental pollution [71]. There is a study which used ionic liquids to extract the lipids and the results showed that it could extract higher lipid yields compared to chloroform and methanol [72]. In addition to considering the extraction efficiency, safety, and being environmentally friendly, the cost of the solvent used in the MAE should not be too expensive to the point that it would hinder the development towards up-scale production. Some of the green solvents also known as deep eutectic solvents have been explored using MAE technology to recover natural products from plant material [73-75] but the application for lipid extraction from microalgae is less extensively studied.

Another challenge of MAE is identifying critical parameters from a pool of different factors for achieving high lipid extraction efficiency. There are multiple parameters in MAE that could simultaneously influence the extraction efficiency, hence, it would be better to study and optimize these parameters at the same time. In this extent, a multi-factorial approach would be superior than a one-factor-at-a-time approach because the levels of all the factors of interest can be changed simultaneously [76]. By utilizing advanced software, researchers can systematically estimate the interactions between multiple factors and decide the number of experiments required for optimizing these factors simultaneously.

In most MAE studies, once the microalgal cells have been disrupted and the lipids extracted by adding solvents, an additional separation process is needed to remove microalgae residues. Centrifugation is usually carried to achieve this. However, centrifugation consumes high energy thereby increasing production costs [77]. Herein an innovative idea is required to separate lipids from microalgae residues effectively but with low energy consumption.

Conclusion

As microalgae can accumulate high lipid content within a short period of time, it has been explored as suitable feedstock for biofuel, pharmaceutical and health supplement industries. Traditional lipid extraction such as Soxhlet extraction, Folch extraction and Bligh & Dyer extraction have been used to extract lipid from microalgae. However, the lipid extraction yield using these methods are less efficient due to the presence of microalgal cell wall. Therefore, MAE has been proposed to break down the cell wall and enhance the extraction efficiency of lipids from microalgae. It is evident that MAE has resulted in the increase in extraction efficiency and rate. These superior results can be attributed to the distinct heating mechanism of the microwave which is different from conventional heating. To optimize the extraction yield, the selected solvent should utilize the microwave to break down the cell wall prior to extracting the lipids. Most studies select a mixture of polar and nonpolar solvents as they are able to generate higher extraction yield. Other parameters including temperature, microwave power, irradiation time and amount of biomass should also be studied and optimized to achieve a higher extraction yield of lipids. Apart from high extraction efficiency and short extraction time, wet biomass can be directly used for extraction in MAE. Lipid extraction and transesterification also can be carried out in single step using microwave treatment thereby reducing the process time and necessity to remove impurities. Thus, MAE has the potential to extract microalgal lipids at the industrial level in the future. Nevertheless, it is undeniable that most of the results collected so far are from studies that still use a mixture of toxic chloroform and methanol, and centrifugation is needed to remove microalgae residues. Certainly, comprehensive research is required to explore the possibility of a greener solvent and to reduce the energy consumption in separation after extraction.

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