Hindawi
Journal of Chemistry
Volume 2022, Article ID 7349052, 11 pages
https://doi.org/10.1155/2022/7349052

Research Article

Extraction of Municipal Sewage Sludge Lipids Using Supercritical CO_2 for Biodiesel Production: Mathematical and Kinetics Modeling

Alyaa Abdulhussein Alsaedi,[1] Md. Sohrab Hossain,[2] Venugopal Balakrishnan,[3] Ahmad Naim Ahmad Yahaya,[4] Norli Ismail,[1] Mu. Naushad,[5] Chinna Bathula,[6] and Mardiana Idayu Ahmad[1]

[1]*Environmental Technology Division, School of Industrial Technology, Universiti Sains Malaysia, Penang 11800, Malaysia*
[2]*Fundamental and Applied Sciences Department, Universiti Teknologi PETRONAS, Seri Iskandar 32610, Perak, Malaysia*
[3]*Institute for Research in Molecular Medicine (INFORMM), Universiti Sains Malaysia (USM), Gelugor 11800, Penang, Malaysia*
[4]*University of Kuala Lumpur-Malaysian Institute Chemical & Bioengineering Technology (UniKL-MICET), Melaka, Alor Gajah 78000, Malaysia*
[5]*Department of Chemistry, College of Science, King Saud University, P.O. Box 2455, Riyadh 11451, Saudi Arabia*
[6]*Division of Electronics and Electrical Engineering, Dongguk University-Seoul, Seoul 04620, Republic of Korea*

Correspondence should be addressed to Md. Sohrab Hossain; dr.sohrab80@gmail.com

Received 12 July 2022; Revised 17 August 2022; Accepted 20 August 2022; Published 23 September 2022

Academic Editor: Arun Suneja

Demand for determining renewable lipids feedstock for the production of biodiesel is increasing with the rapid depletion of petroleum diesel. The present study was conducted to assess the feasibility of utilizing municipal sewage sludge (MSS) as a potential lipids feedstock for biodiesel production. The lipids' extraction and separation from MSS were conducted using supercritical CO_2 ($scCO_2$) with varying treatment time (15–120 min), temperature (30–80°C), pressure (10–50 MPa), and addition of cosolvents (1–10 wt.%). The modified Gompertz equation and Arrhenius equation were employed to evaluate lipids' extraction and kinetics behavior from municipal sewage sludge using $scCO_2$. About 27% of lipids were extracted from MSS with $scCO_2$ at a temperature of 60°C, pressure of 30 MPa, treatment time of 60 min, and 5 wt.% of ethanol (EtOH) as cosolvent. The modified Gompertz equation was adequately fitted with experimental data of the lipids' extraction from MSS using $scCO_2$. The kinetics properties analyses revealed that the $scCO_2$ extraction technology was highly dependent on pressure than the temperature for the extraction of the lipids from MSS. The physicochemical characteristics and fatty acid contents of the $scCO_2$ extracted lipids from MSS and sewage sludge biodiesel were determined using a variety of analytical techniques. The physicochemical properties of the sewage sludge biodiesel were compared with the international standard specifications of biodiesel, such as the American Society for Testing and Materials specifications for diesel fuel (ASTM D6751) and European Standard (EN 14214) specifications.

1. Introduction

There is an increasing concern on the rapid diminution of fossil fuel energy with increasing energy consumption due to rapid population growth, urbanization, and expanding economies. It is being reported that the estimated daily consumption of diesel fuel is about 5.7 million barrels per day, which may increase to 109.4 million barrels per day by 2040 [1]. Therefore, it is urgent to determine alternate sources of diesel fuel to reduce rising demands on petro-diesel, since energy demand and consumption patterns are expanding in an unsustainable manner [2, 3]. Renewable energy is considered a significant energy resource in many countries worldwide. This approach is dependent on natural resources, which can produce the required energy and protect surrounding environments. The major challenge is to expand the amount of renewable energy in our existing supply system. Biofuel is an alternative energy resource that has the advantage of a flexible supply system as fossil fuel [4]. Biomass feedstock can be used to produce a range of gaseous biofuels, like hydrogen and methane, and liquid biofuels, like ethanol, methanol, and biodiesel. Biofuel is considered eco-friendly fuel as its emissions are biodegradable and create a little impact on the environment. As such, using biofuel as an energy source provides a substitute and a sustainable supply of clean energy [1, 3].

Biodiesel has become a viable substitute for petrodiesel in recent years. In addition, it is considered an eco-friendly energy resource that can meet high worldwide energy demands, achieve sustainability goals, and decrease environmental pollution [2, 5]. Generally, biodiesel can be synthesized from multiple lipids feedstock, including those generated from plants and animal fats [5, 6]. Transesterification is the main biochemical process for synthesizing biodiesel, which occurs when the alkoxy group of an ester is dislodged by the alcohol group [3]. In the process of catalytic transesterification, alcohol combines with triglycerides in the existence of an acid or basic catalyst producing biodiesel and glycerol as by-products [1, 6]. Studies reported that biodiesel isolated from edible crops, such as oil palm and grape seeds, had a similar engine performance to diesel fuel [7, 8]. Therefore, biodiesel could be utilized as a viable replacement for petroleum diesel due to its environmentally favorable features and is a secure and sustainable energy resource for the foreseeable future [9]. Municipal sewage sludge (MSS) is a by-product of a wastewater treatment plan. The concern on the safe disposal and sustainable utilization of MSS are increasing with increasing MSS generation due to the increase in urbanization and industrialization. Existing practices of treating MSS and its disposal include an application as organic fertilizer in crop production, ocean, landfill disposals, and incineration [10, 11]. These inappropriate disposal practices of MSS pose potential hazards to the environment and human health. However, the MSS contains 5–30 wt.% of lipids, which is close to the lipid content in some vegetative feedstock of lipids [10, 12]. Kwon et al. [13] reported that the biodiesel conversion of lipids extracted from MSS would be a new paradigm for mining renewable energy from municipal hazardous waste. Melero et al. [14] implemented simultaneous extraction and conversion of lipids from MSS and obtained about 15.5 wt.% biodiesel from primary MSS and about 10 wt.% from secondary MSS. Khalil et al. [15] utilized supercritical carbon dioxide ($scCO_2$) as a waterless extraction technology for the extraction of lipids from MSS for biodiesel production. Thus, the MSS could be utilized as a potential lipids feedstock for biodiesel production.

Supercritical carbon dioxide ($scCO_2$) is reported to be a promising and eco-friendly extraction technology for the extraction and separation of lipids from various matrices [16, 17]. There are some distinct advantages of the $scCO_2$ extraction technology over the conventional extraction technologies, including the absence of organic solvents and eco-friendliness, and it does not produce any waste residue after extraction [3, 17]. The fluid CO_2 is considered as an ideal supercritical fluid due to its nontoxic, inflammable, lipophilic nature, low critical temperature (31.1°C), and moderate critical pressure (7.38 MPa) [2, 18, 19]. $ScCO_2$ has a faster reaction rate, easier lipids separation, and higher quality lipids than solvent extraction, as indicated by many studies [3, 19, 20]. Studies have been conducted for the extraction of lipids from MSS using conventional solvent extraction methods [21, 22]. For example, Zhu et al. [21] used soxhlet extraction, acid hydrolysis, and water-bath shaking to extract lipids from sewage sludge. The percentage of lipids' extraction obtained was 1.30%, 6.35%, and 4.10% for acid hydrolysis, soxhlet extraction, and water-bath shaking, respectively. There are rare studies in the literature on the extraction and separation of lipids from MSS using $scCO_2$ extraction technology. Therefore, the present study was conducted to determine the influence of $scCO_2$ on lipids' extraction from MSS. The modified Gompertz mathematical model and Arrhenius equations were employed to elucidate the extraction behavior and kinetics for the lipids' extraction from MSS. Subsequently, biodiesel was produced from the lipids extracted with $scCO_2$ in the alkaline catalytic transesterification process. The physicochemical properties and fatty acid compositions in $scCO_2$ extracted lipids from MSS and sewage sludge biodiesel were determined with various analytical means. The physicochemical properties of the sewage sludge biodiesel were then compared with the biodiesel standards specifications of EN 14214 and ASTM D6751. The present study's findings will be a harmony in implementing the sustainable deployment of MSS for biodiesel production.

2. Materials and Methods

2.1. Sludge Sampling and Preparation. Primary MSS was collected from Indah Water Konsortium, Lebuh Permai, Pulau Pinang, Malaysia. The sludge collected from the wastewater treatment plant was concentrated by settling. Subsequently, the concentrated sludge was dewatered by centrifuging at 1968 g for 10 min. The dewatered sludge was then oven-dried overnight at 70°C and mechanically pounded and sieved to fine particle size (0.5–1.0 mm). The fine sludge was stored at 4°C prior to further studies.

2.2. Extraction of Lipids from Municipal Sewage Sludge by $scCO_2$. The lipids from MSS were extracted using $scCO_2$ with varying temperature (32–80°C), pressure (10–50 MPa), treatment time (15–120 min), and cosolvents (H_2O, C_2H_5OH, and H_2O_2). Commercial liquefied CO_2 with a purity of 99% was used as a solvent to extract lipids from MSS. The $scCO_2$ reactor used in the present study comprised an extraction vessel (300 mL), a chiller, a reservoir to recycle CO_2, a CO_2 pressurize pump, and a separation vessel. A certain amount of MSS was placed into the extraction vessel, and the temperature of the extraction vessel and separation vessel was set to the desired experimental temperature. Once the temperature of extraction and separation vessels reached set temperatures, the liquefied CO_2 was pumped into the extraction vessel to obtain the desired pressure. After the extraction time elapsed, the extracted lipids from MSS were collected from the separation vessel. The experiments were conducted three times, and the outcomes were presented as means ± standard error. The percentage of lipids extracted from MSS using $scCO_2$ was determined using the following equation.

$$\text{Lipids}\,(\%) = \frac{\text{Mass of lipids (g)}}{\text{Mass of MSS (g)}} \times 100. \quad (1)$$

2.3. Modified Gompertz Mathematical Model. Gompertz equation is used to describe a sigmoidal curve, which includes the lag phase, growth phase, and asymptotic phase. Generally, the Gompertz equation can be expressed as follows.

$$Y = a\,\exp[-\exp(b - ct)], \quad (2)$$

where T is the yield of extracted lipids subjected to $scCO_2$ extraction from MSS. However, equation (2) contains three important parameters, such as a, b, and c. It may be problematic to differentiate these parameters because of the difficulties in calculating the start value of these parameters of the lipids' extraction. In order to elucidate the lipids' extraction from MSS using the Gompertz equation, it is important to reparameterize the equation with the more meaningful parameters of λ (lag phase), km (extraction rate), and A (asymptote value). To obtain the inflection point of the curve, equation (2) can be derivatized as

$$\frac{dY}{dt} = ac\,\exp\{-\exp(b - ct)\}\exp(b - ct), \quad (3)$$

$$\frac{d^2Y}{dt^2} = ac^2 \cdot \exp\{-\exp(b - ct)\}\exp(b - ct)\{-\exp(b - ct)\}. \quad (4)$$

At inflection point, $t = t_i$. Thus, the second derivative can be equal to zero. So, we can write it as

$$\frac{dy}{dt} = 0 \longrightarrow t_t = \frac{b}{c}. \quad (5)$$

An expression of the lipids' extraction rate (km) can be derived by calculating the first derivative in equation (3) at an inflection point.

$$k_m = \left(\frac{dY}{dt}\right)_{t_i} = \frac{ac}{e}, \quad (6)$$

$$c = \frac{k_m e}{a}, \quad (7)$$

where e is the dummy constant. Thus, the parameter c in the Gompertz equation can be substituted by $c = k_m e/a$. The description of the tangent line through the inflection point is

$$Y = k_m t + \frac{a}{e} - k_m t_i. \quad (8)$$

The lag time is defined as the t-axis intercept of the tangent through the inflection point. Thus,

$$0 = k_m t + \frac{a}{e} - k_m t_i. \quad (9)$$

From equations (6)–(9), the lag page can be expressed as below.

$$\lambda = \frac{b - 1}{c}. \quad (10)$$

Thus, the parameter b in the Gompertz equation can be substituted as

$$b = \frac{k_m e - 1}{a}\lambda + 1. \quad (11)$$

Assume that the asymptotic value will be reached as t approaches infinity; thus,

$$t \longrightarrow \infty;\, y \longrightarrow a \Rightarrow A = a. \quad (12)$$

By substituting the parameter values of "a," "b," and "c" in the Gompertz equation, yielding the modified Gompertz equation can be expressed as below [23].

$$Y = A\,\exp\left[-\exp\left\{\frac{k_m e}{A}(\lambda - t) + 1\right\}\right], \quad (13)$$

where Y is the yield of extracted lipid (g/100 g sludge) subjected to $scCO_2$ extraction. A is the higher asymptote, km denotes the maximum extraction rate (g/min), λ refers to the lag phase, and t represents the treatment time. t_t refers to the time length required to obtain the maximum lipids' extraction from MSS. The t_t can be calculated using the following equation:

$$t_t = \lambda + \frac{A}{k_m}. \quad (14)$$

The values for A, λ, and km were determined using experimental data. However, the estimation of the starting value for computation of λ, k_m, and A was carried out using graphical software, namely, Kaleida Graph 4.5.4 (Synergy software ver. 2021). The model fitting accuracy was determined using the regression coefficient (R^2) values at the 95% confidence level.

2.4. Biodiesel Production from Municipal Sewage Sludge. Extracted MSS lipids may contain high free fatty acids (FFAs) with high levels of acidity; therefore, the pretreatment of MSS lipids to remove FFAs and acids values is crucial prior to conversion into biodiesel [20]. The current study's pretreatment of MSS lipids was accompanied by the sulfuric acid (purity 96%) esterification process, utilizing methanol as a reactant. The experiment was performed using a 250 mL three-neck reactor equipped with a reflux condenser. The experiment was conducted at 60°C for 6 h with a lipid, reactant, and catalyst ratio of 20 : 4 : 41 in a weight basis. After the stipulated time period, the esterified lipids were collected and centrifuged at 1968 g for 10 min. The methanol layer was discarded, and the esterified lipids were washed three times with deionized water. Subsequently, vacuum evaporation at 105°C was applied to remove the water content from the lipids.

The esterified MSS lipids yielded biodiesel after undergoing alkaline transesterification process, with methanol as solvent and NaOH as a catalyst. Methanol was mixed with NaOH (1 wt.%) in three-neck reactors equipped with a reflux condenser. The esterified oil was then taken into the reactor with a lipids and methanol ratio of 1 : 5 in a weight basis and heated at 60°C for 4 h. After the transesterification process had elapsed, the produced biodiesel mixture was taken in the separation funnel and allowed to settle down the glycerol in the bottom. Subsequently, the methyl ester layer was separated and the left-over methanol and water were evaporated by heating at 110°C. The percentage yield of biodiesel has been calculated using the following equation.

$$\text{Yield}\,(\%) = \frac{\text{Amount of Biodisel produced}}{\text{Amount of MSS lipids}} \times 100. \tag{15}$$

2.5. Characterization. The physicochemical properties and fatty acid compositions in $scCO_2$ extracted lipids from MSS and sewage sludge biodiesel were determined. The percentage of moisture content in $scCO_2$ extracted lipids and biodiesel was identified with test method of AOAC 930.15. The density of MSS lipids and sewage sludge biodiesel was specified through the hydrometer method in accordance with the standard method of ASTM D1298. A viscometer measured kinematic viscosity in line with the standard test of ASTM D445. Acid value of both lipids and biodiesel was then determined by the AOAC 940.28 test method. The phenolphthalein indicator (3 drops) was added to a mixture of 10 mL EtOH and 1 g of sample. The mixture was then titrated using 0.1 N potassium hydroxide. Mixture turned pink in colour, and the titration process was stopped. Subsequently, acid value was identified through the use of equation (5).

$$\text{Acid value} = \frac{56.1 \times N \times V}{m}, \tag{16}$$

m denotes the mass of lipids, N and V refer to the normality of KOH and its volume. Lipids and biodiesel FFA levels' calculation is as in equation (6).

$$\text{FFAs} = \frac{\text{Acid value}}{1.989}. \tag{17}$$

The bomb calorimeter method was utilized to determine the calorific values of sewage sludge biodiesel and MSS lipids in line with ASTM D5865. The Pensky–Marten apparatus was used to gauge flashpoint of sewage sludge biodiesel and MSS lipids. ASTM D613 standard test then determined the cetane number of sewage sludge biodiesel. Biodiesel and MSS lipids saponification values were measured via AOAC920.160 test. Iodine levels of MSS biodiesel and lipids were identified with AOAC 920.159 testing. Pour points and cloud points of both biodiesel and MSS lipids were then estimated with ASTM D2500 and ASTM D7683 standard methods. Gas chromatography (GC), equipped with the flame ionization detector (GC-FID), was used to determine the fatty acids compositions in sewage sludge biodiesel and MSS lipids. Approximately 0.05 μg of sewage sludge lipids or biodiesel had been taken into GC capillary column at a split ratio of 1 : 10. The initial oven temperature was set to 40°C, and then the temperature was raised to 100°C at a rate of 10°C/min. The oven temperature of 100°C was held for 15 min and then increased to 150°C and held for 3 min. Ultimately, the final temperature was increased to 240°C with a rising rate of 5°C per min. The injector and detector temperatures were fixed at 200°C and 220°C, respectively.

3. Results and Discussion

3.1. Lipids' Extraction from Municipal Sewage Sludge. Figure 1 shows the extraction of lipids from MSS using the $scCO_2$ with varying temperatures (30–80°C), pressure (10 MPa–50 MPa), treatment times (15–120 min), and addition of cosolvents. The influence of $scCO_2$ pressure (10 MPa–50 MPa) on the lipids' extraction from municipal sewage sludge was determined at a treatment time of 60 min and a temperature of 60°C, as shown in Figure 1(a). It was found that the percentage of lipids' extraction increased with increasing the scCO2 pressure from 10 MPa to 30 MPa. However, the percentage of lipids' extraction was negligible with increasing pressure from 30 MPa to 50 MPa. About 8% of lipids was extracted at $scCO_2$ pressure of 10 MPa, and the lipids' extraction was increased to 20.34 ± 0.40% at 30 MPa. However, the lipids' extraction was further increased to 21.36 ± 0.38% at a pressure of 50 MPa. The percentage of lipids' extraction increased with increasing temperature from 32°C to 80°C at $scCO_2$ pressure of 30 MPa and treatment time of 60 min (Figure 1(b)). The highest lipids' extraction obtained was 21.35 ± 0.42% at 80°C for the constant pressure of 30 MPa and treatment time of 60 min. The influence of the treatment time on the percentage of lipids' extraction from municipal sewage sludge using $scCO_2$ was determined at a pressure of 30 MPa and a temperature of 60°C (Figure 1(c)). It was found that the percentage of lipids' extraction was increased rapidly with increasing treatment time from 15 min to 60 min and slightly increased from 60 min to 120 min. The lipids' extraction obtained was 3.67 ± 0.21% at a treatment time of 15 min, which was substantially increased to 20.34 ± 0.41% at a treatment time of 60 min, and the lipids' extraction was further increased to 22.58 ± 0.26% at the treatment time of 120 min.

Extraction efficiency from MSS with $scCO_2$ depends on the solvating properties of fluid CO_2 in the supercritical state [24, 25], wherein the pressure and temperature have a significant impact on the CO_2's solvating characteristics [25]. The increase of $scCO_2$ pressure increases the extraction because of the increased density of the fluid CO_2 [4, 26]. The distance between the fluid CO_2 and lipids molecules decreases with increasing density of the CO_2, which increases the collision between the fluids CO_2 and lipids molecules. These substantially increase interaction between the fluid CO_2 and lipids molecules, causing more lipids' extraction.

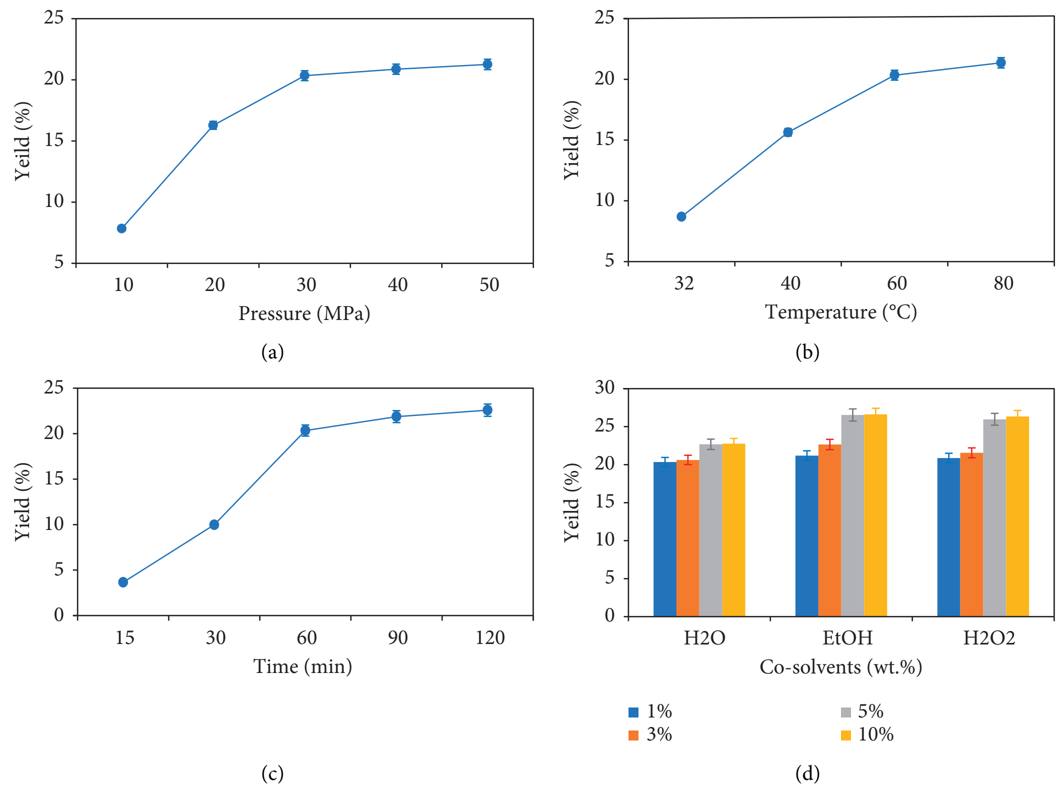

Figure 1: Lipids' extraction from municipal sewage sludge using $scCO_2$. (a) Effects of pressure, experimental conditions: temperature of 60°C and treatment time of 60 min. (b) Effects of temperature, experimental conditions: pressure of 30 MPa and treatment time of 60 min. (c) Effects of treatment times, experimental conditions: pressure of 30 MPa and temperature of 60°C. (d) Effect of cosolvents, experimental conditions: pressure of 30 MPa, temperature of 60°C, and treatment time of 60 min.

Moreover, the increase in temperature increases the fluidity of CO_2, which increases the solubility of lipids in CO_2, and therefore, lipids' extraction increases [25, 27]. Besides, the lipids' extraction increases with increasing treatment time because it requires sufficient treatment time to interact between the fluid CO_2 and lipids molecules. However, extraction percentages were negligible over $scCO_2$ pressure of 30 MPa, the temperature of 60°C, and treatment time of 60 min, which might be due to the saturation of solvent power of the fluid CO_2 with the further increase of $scCO_2$ pressure and temperature [26]. Besides, the nonpolar and lipophilic nature of fluid CO_2 might make it unable to extract polar fatty acids [17, 26]; therefore, extraction percentage declined when $scCO_2$ pressure increased at temperatures of over 30 MPa and 60°C, respectively.

Since CO_2 is a nonpolar solvent, it is limited in the solubility of polar fatty acid components [16, 23]. However, the inclusion of the cosolvent as a chemical modifier would enhance the lipids' extraction because of the increase in the solubility of lipids [19]. In the current study, the influence of cosolvents on MSS lipids' extraction using $scCO_2$ is determined by adding H_2O, EtOH, and H_2O_2 as cosolvents at cosolvents amounts of 1wt.% to 10 wt.%, the pressure of 30 MPa, temperature of 60°C, and treatment time of 60 min, as shown in Figure 1(d). It was found that the addition of cosolvents potentially increased the percentage of lipids' extraction from 1 wt.% to 5 wt.%; thereafter, the percentage of lipids extracted was negligible with a further increase of cosolvent from 5 wt.% to 10 wt.%. However, EtOH and H_2O_2 had shown almost similar results in lipids' extraction from MSS using $scCO_2$. The highest lipids' extraction obtained was about 27%, 26%, and 23% using EtOH, H_2O_2, and H_2O as cosolvents, respectively. Similarly, Jafarian et al. [28] reported that the inclusion of 5% EtOH as a cosolvent increased the $scCO_2$ extraction of tocopherols and phytosterols from rapeseed oil waste.

3.2. Mathematical Modeling for $scCO_2$ Extraction of Lipids from MSS. The modified Gompertz equation was utilized to assess the $scCO_2$ extraction of lipids from MSS with varying pressure (10–40 MPa) and temperature (32–80°C) as a function of treatment time as presented in Figure 2. The lipids' extraction curves, obtained from the modified Gompertz mathematical model, were alienated into three distinct phases, namely, the extraction phase, lag phase (λ), and stationary phase. Figure 2(a) shows the influences of the $scCO_2$ pressure with a treatment time of 0–180 min, at the constant temperature of 32°C and EtOH loading of 5 wt.%. The extraction of lipids was increased with increasing pressure and reached the asymptote (time required to reach the optimal lipids' extraction) at a treatment time of 105 min, 90 min, 75 min, and 60 min for the pressure of 10 MPa, 20 MPa, 30 MPa, and 40 MPa, respectively. The estimation of

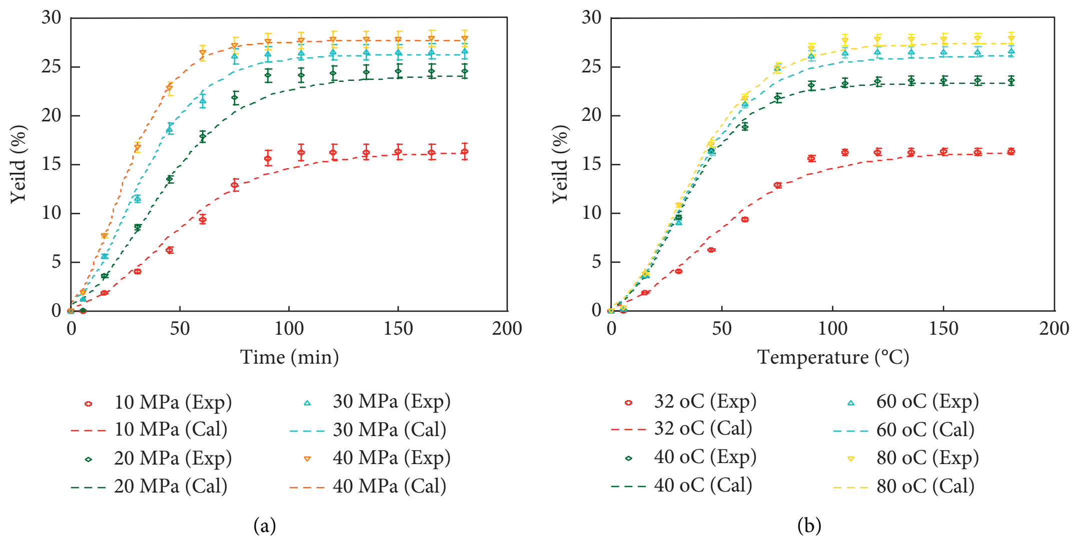

Figure 2: Effect of $scCO_2$ pressure (a) and temperature (b) on the extraction lipids from municipal sewage sludge. Exp: experimental data, Cal: calculated values by fitting the modified Gompertz equation to experimental data.

Table 1: Estimated the kinetics parameters of the modified Gompertz equation for the extraction of lipids from municipal sewage sludge (MSS), with varying $scCO_2$ pressures.

Pressure (MPa)	A (%)	k_m ($\min^{-1}$)	λ (min)	t_t (min)	R^2
10	16.32	0.184	8.7	97.39	0.9938
20	24.16	0.319	7.6	83.33	0.9921
30	26.36	0.369	4.9	76.34	0.9877
40	27.78	0.454	3.6	64.79	0.9863

Table 2: Estimated kinetics parameters of the modified Gompertz equation for MSS lipids' extraction at various $scCO_2$ temperatures.

Temperature (°C)	A (%)	k_m ($\min^{-1}$)	λ (min)	t_t (min)	R^2
32	16.32	0.164	8.7	108.21	0.9938
40	23.42	0.213	8.1	102.05	0.9294
60	26.18	0.314	7.8	91.17	0.9573
80	27.53	0.365	7.2	82.624	0.9984

kinetics parameters of the modified Gompertz equation for the extracted MSS lipids at different $scCO_2$ pressures and treatment times of 0–180 min at the constant temperature of 32°C and EtOH loading of 5 wt.% is shown in Table 1. It was found that the λ value was diminished by increasing pressure from 10 to 40 MPa. Conversely, the lipids' extraction rate (km) increased by increasing pressure from 10 to 40 MPa. The R^2 values obtained were over 0.98, demonstrating the good agreement between experimental data and estimated values for the extraction of lipids from MSS. The calculated total extraction times (t_t) for the lipids' extraction reached to the asymptote were close to the experimental values of lipids' extraction time for obtaining the asymptote.

Figure 2(b) shows the influence of temperature on MSS lipids at varying treatment times of 0–180 min at $scCO_2$ pressure of 10 MPa and EtOH loading of 5 wt.%. The extraction of lipids increased with enhancing temperature from 32°C to 80°C. The required treatment time to reach asymptote decreases with increasing temperature and reached the asymptote at a treatment time of 105 min, 105 min, 90 min, and 90 min for the $scCO_2$ temperature of 32°C, 40°C, 60°C, and 80°C, respectively. Table 2 displays the estimated kinetics parameters of the modified Gompertz equation for the extraction of MSS lipids at different $scCO_2$ temperatures at pressure 10 MPa and EtOH loading of 5 wt.%. The km values were increased from 0.164 min to 1 to 0.365 $\min^{-1}$ with increasing temperature from 32°C to 80°C. Instead, the λ value was decreased from 8.7 min to 7.2 min with increasing temperature from 32°C to 80°C. The estimation of R^2 values (0.9573–0.9984) indicated that the experimental data were fitted with estimated data for the lipids' extraction from MSS. The calculated t_t values (time required to reach optimal lipids' extraction) were close to those of experimental data.

3.3. Analyses' Dependence of Temperature Using Arrhenius Equation.

3.3. Analyses' Dependence of Temperature Using Arrhenius Equation. The dependence of temperature on the extraction of lipids from MSS was determined using the Arrhenius equation, as shown in equations (7) and (8).

$$k_m = a.e^{-E_a/RT}, \tag{18}$$

$$\ln k_m = \ln a - \frac{E_a}{RT}, \tag{19}$$

where E_a denotes the activation energy (kJ/mol), T indicates the absolute temperature, a indicates the preexponential factor ($\min^{-1}$), and R is the ideal gas constant (8.314 J/mole. K). The dependence of temperature for the extraction of lipids from MSS using $scCO_2$ is shown in Figure 3. From Figure 3, the estimated E_a value was determined to be 14.82 kJ/mole for the extraction of lipids from MSS using $scCO_2$. Kassim et al. [29] determined the activation energy of

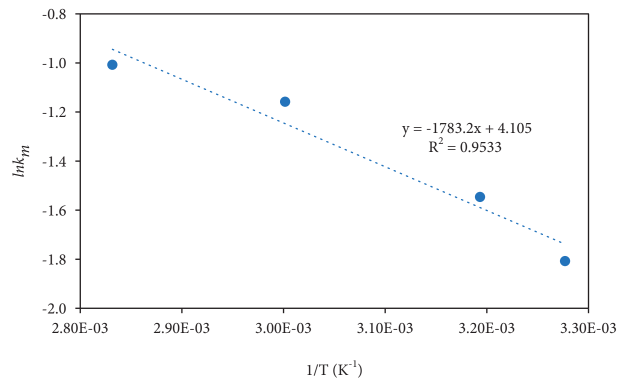

FIGURE 3: Dependence on temperature for the extraction of lipids from municipal sewage sludge (MSS) with $scCO_2$ at pressure of 10 MPa.

TABLE 3: Physicochemical properties of $ScCO_2$ extracted lipids from municipal sewage sludge (MSS) and sewage sludge biodiesel.

Properties	Unit	Lipids	Biodiesel	ASTM D6751	EN 14214
Yield	%	26.54 ± 0.21	84 ± 2	—	—
FFAs	%	0.81 ± 0.16	0.16 ± 0.06	—	—
Kinematic viscosity at 40 ℃	mm^2/s	6.18 ± 0.21	4.10 ± 0.14	1.9–6.0	3.5–5.0
Density at 15 ℃	kg/m^3	840 ± 6	865 ± 4	880	860–900
Saponification value	mgKOH/g	196 ± 2.54	158 ± 2.54	—	—
Acid value	mgKOH/g	0.50 ± 0.04	0.20 ± 0.02	≤0.5	≤0.5
Heating value	MJ/kg	39.20 ± 1.4	39.64 ± 2.86	—	—
Cetane number	—	56.10 ± 2.7	56 ± 2	≥47	≥51
Pour point	℃	8.5 ± 0.5	−10.50 ± 0.65	−15 to 16	—
Cloud point	℃	12.5 ± 0.5	−2.50 ± 0.14	−3 to 12	—
Heating value	MJ/kg	39.20 ± 1.4	39.64 ± 2.86	—	—
Iodine number	g I^2/100 g	69.10 ± 2.80	75.9 ± 2.34	—	≤120
Flash point	℃	166 ± 2.10	140 ± 4	≥130	≥101

TABLE 4: Fatty acid compositions of $scCO_2$ extracted lipids from municipal sewage sludge (MSS) and sewage sludge biodiesel.

Fatty acids	Carbon group	Concentration (%)	
		Lipids	Biodiesel
Lauric acid	(C12: 0)	0.52 ± 0.02	0.24 ± 0.02
Myristic acid	(C14: 0)	1.22 ± 0.06	0.81 ± 0.04
Palmitic acid	(C16: 0)	37.61 ± 2.18	30.20 ± 2.14
Palmitoleic acid	(C16: 1)	0.34 ± 0.01	0.26 ± 0.01
Stearic acid	(C18: 0)	4.20 ± 0.22	4.62 ± 0.17
Oleic acid	(C18: 1)	38.55 ± 3.64	38.62 ± 2.58
Linoleic acid	(C18: 2)	14.68 ± 1.08	23.81 ± 1.56
Linolenic acid	(C18: 3)	1.92 ± 0.12	0.31 ± 0.01
Arachidic acid	(C20: 0)	0.32 ± 0.02	0.40 ± 0.02
Eicosenoic acid	(C20: 1)	0.21 ± 0.01	0.20 ± 0.01
∑Saturated fatty acids		43.87 ± 2.58	36.27 ± 2.16
∑ Unsaturated fatty acids		55.7 ± 2.62	63.20 ± 2.38

301.70 kJ/mol to extract lipids from *Chlorella* sp. using the pyrolysis process. Ashokkumar et al. [30] obtained the activation energy of 36.72 kJ/mol for solvent lipids' extraction from microalgae with methanol/chloroform as solvent. The minimal E_a value obtained in the present study reveals that the $scCO_2$ is a less dependent technology for MSS lipids' extraction. Similar to this, Ahmadkelayeh et al. [26] referred to the fact that the $scCO_2$ is indeed a high-pressure extraction type of technology, which is highly dependent on the pressure as compared to temperature, for the extraction of lipids.

3.4. Characterization of Municipal Sewage Sludge Lipid and Biodiesel. A biodiesel amount of about 84 ± 2 wt.% was obtained by extracting lipids from the sewage sludge, with

Table 5: Comparison of the physicochemical properties of sewage sludge biodiesel with other biodiesel obtained from edible and nonedible Feedstock.

Biodiesel	Density at 15°C (kg/m^3)	Viscosity at 40°C (mm^2/s)	Acid value mg (KOH/g)	Cloud point (°C)	Pour point (°C)	Heating value (MJ/Kg)	Flashpoint (°C)	Iodine number g I_2/100 g	Cetane number	Reference
Palm	880	4.52	0.25	14.25	14.33	34.41	175	50.5		[34]
Soybean	883	6.75	0.11	N/A	−7.0	N/A	120	N/A	54.60	[35]
Sunflower	860	4.72	0.07	4.0	−5.0	N/A	183	N/A	N/A	[36]
Canola	852	4.74	0.56	—	—	—	217	N/A	N/A	[37]
Jatropha curcas L.	867	4.01	0.04	N/A	N/A	36.66	165	N/A	40.01	[38]
Animal fat	870	4.82	0.07	N/A	−2.0	N/A	149	77.7	N/A	[39]
Waste cooking oil	876	3.66	N/A	N/A	N/A	39.76	160	N/A	63.88	[34]
Algae	872	5.82	0.40	N/A	−16	40.80	N/A	N/A	50.54	[40]
Chicken fat	875	4.60	0.43	2.0	−5.0	N/A	168	N/A	N/A	[41]
Jojoba	868	24.84	0.71	N/A	N/A	46.47	285	50.2	58.25	[21]
MSS	875	4.10	0.50	−2.5	−10.50	39.64	140	75.9	N/A	Present study

*N/A: not available.

$scCO_2$ through the alkaline catalytic transesterification process, utilizing NaOH as a catalyst at lipid-to-methanol mixture of 1 : 6, catalyst loading of 1wt %, reaction temperature 60°C, and reaction time of 4 h. However, Patiño et al. [31] obtained about 33% biodiesel from the secondary sewage sludge lipids using Amberlite IR-120 IR120 as a catalyst. Zhu et al. [21] obtained approximately 86% of biodiesel from the MSS lipids via a catalytic transesterification process. Table 3 shows the physicochemical properties of $scCO_2$ extracted lipids from sewage sludge and the biodiesel produced. Moreover, biodiesel physicochemical properties were compared to other standards of biodiesel, including ASTM D 6751 and EN 14214.

The kinematic viscosity of $scCO_2$ extracted lipids from MSS and biodiesel was $6.18 \pm 0.21\,mm^2/sec$ and $4.10 \pm 0.14\,mm^2/sec$, respectively, wherein the density of lipids and biodiesel was 840 ± 6 and $865 \pm 4\,kg/m^3$, respectively. It was found that the density of sewage sludge biodiesel complied with stipulated standard limits set by EN 14214. Lipids and biodiesel acid levels are determined as 0.50 ± 0.04 mg KOH/g and 0.32 ± 0.02 mgKOH/g, respectively. However, the acid value of the MSS biodiesel sewage sludge biodiesel was below standard limits set by EN 14214 and ASTM D 6751. The percentage of FFAs content in lipids and biodiesel was $0.25 \pm 0.11\%$ and 0.16 ± 0.06, respectively. Abdulhussein Alsaedi et al. [32] reported that the acid value for biodiesel derived from soxhlet extracted lipids from MSS was 2.60 mg KOH/g, which was higher than the ASTM standard. Thus, it can be postulated that the $scCO_2$ extraction method has privileged over soxhlet extraction for the extraction of lipids from MSS with lower FFAs and acid values. Saponification values of both sewage sludge lipids and biodiesel were 196 ± 2.54 mgKOH/g and 158 ± 2 mgKOH/g, respectively. Iodine numbers for sewage sludge lipids and biodiesel were found to be 76.83 ± 5.68 g I2/100 g and 75.9 ± 2.34 g I2/100 g, respectively. But iodine number for sewage sludge biodiesel was lower than the concentration reported by EN14214. Flashpoints, cloud points, and pour points complied with standard limitations of biodiesel reported by EN 14214 and ASTM D6751 standards. Sewage sludge biodiesel cetane number was 56 ± 2, higher than the standard specifications of EN 14214 and ASTM D6751, indicating that biodiesel will burn more quietly and smoothly in a diesel engine than petroleum diesel.

Fatty acid properties analyses of $scCO_2$ extracted lipids from MSS and sewage sludge biodiesel were conducted using GC-FID, as shown in Table 4. Both $scCO_2$ extracted lipids and sewage sludge biodiesel contain more quantity of unsaturated fatty acids than saturated fatty acids. The major fatty acids determined in $scCO_2$ extracted lipids and sewage sludge biodiesel were palmitic acid (C16 : 0), oleic acid (C18 : 1), linoleic acid (C18 : 2), and stearic acid (C18 : 0). Similarly, D'Ambrosio and others [33] found that stearic acid, palmitic acid, linoleic acid, and oleic acid were the major fatty acids detected in lipids extracted from MSS using the solvent of ethyl butyrate. The total identified fatty acids for lipid extracted by $scCO_2$ was 99.57 compared with Abdulhussein Alsaedi et al. [32] that showed total identified fatty acids for sewage sludge from soxhlet extraction at 98.78. This result proves the superiority and efficiency of $scCO_2$ to extract lipids from MSS, which is higher than the soxhlet extraction method by 0.80%. Those findings were confirmed by Pradhan et al. [33] found that the $scCO_2$ extraction method was better with a total identified component of fatty acids at 96.8%, compared to solvent extraction and screw press of 92.5% and 95%, respectively.

Table 5 compares the physicochemical properties of sewage sludge biodiesel with biodiesel obtained from edible and nonedible feedstocks, such as animal fat, palm oil, soybean oil, canola oil, waste cooking oil, algal oil, and jojoba oil. It was observed that the MSS biodiesel physicochemical properties, such as density, acid value, pour point, heating value, iodine number, and cetane number, were almost similar to biodiesel obtained from edible and nonedible feedstocks. The current study findings reveal that MSS has the possibility to be used as a lipids feedstock for the production of biodiesel. Implementation of $scCO_2$ is a green approach for lipids' extraction that does not generate wastewater and residual waste. Besides, using MSS lipids for biodiesel production would be employed for the beneficial purposes of (i) obtaining a cheap source of biodiesel feedstock, (ii) defining an alternative and sustainable feedstock for biodiesel, (iii) minimizing the volume of solid waste disposed of in landfills, (iv) minimizing pollution of the environment, and (v) enhancing the sustainable usage of environmental solid waste materials.

4. Conclusions

In the present study, lipids were extracted from MSS using $scCO_2$ with varying temperature (32–80°C), pressure (10–50 MPa), treatment time (15–120 min), and addition of 1–10 wt.% of cosolvents. Maximum lipids' extraction obtained was about 27% at the $scCO_2$ pressure of 30 MPa, temperature of 60°C, treatment time of 60 min, and the addition of 5 wt.% of EtOH as a cosolvent. The modified Gompertz mathematical model equation was adequately fitted with experimental data for the extraction of lipids from MSS using $scCO_2$. The estimated E_a value was 14.82 kJ/mole, indicating that the $scCO_2$ extraction technology for the extraction of lipids from MSS is highly dependent on pressure than temperature. About 84% biodiesel was isolated from $scCO_2$ extracted lipids using methanol as a solvent and NaOH as a catalyst at lipids-to-methanol molar ratio of 1 : 6, temperature of 60°C, and reaction time of 4 h. It was found that the physicochemical properties of sewage sludge biodiesel comply with EN 14214 and ASTM D6751 standards. Oleic acid, palmitic acid, linoleic acid, and stearic acid were the major fatty acids determined in $scCO_2$ extracted lipids and sewage sludge biodiesel. Moreover, the physicochemical properties of sewage sludge biodiesel were almost similar to the biodiesel obtained from edible and nonedible feedstocks. The present study findings revealed that MSS has the potential to be used as a promising lipids feedstock for biodiesel production. The implication of the sewage sludge lipids for biodiesel would determine an alternative and low-cost lipids feedstock for biodiesel, which will substantially minimize environmental pollution, minimize solid waste disposal in landfills, and enhance sustainable utilization of environmental solid waste materials.

Data Availability

The data used to support the findings of this study can be obtained from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

The authors would like to acknowledge and thank the authorities at the wastewater treatment plant of Indah Water Konsortium, Lebuh Permai, Pulau Pinang, Malaysia. The authors would also like to extend their gratitude to the Ministry of Higher Education (MOHE), Malaysia, for financial support through the Fundamental Research Grant Scheme (FRGS/1/2019/TK10/USM/02/7). The authors are also grateful to the Researchers Supporting Project number (RSP-2021/8), King Saud University, Riyadh, Saudi Arabia, for the financial support.

References

[1] S. Chozhavendhan, M. Vijay Pradhap Singh, B. Fransila, R. Praveen Kumar, and G. Karthiga Devi, "A review on influencing parameters of biodiesel production and purification processes," *Current Research in Green and Sustainable Chemistry*, vol. 1-2, pp. 1–6, 2020.

[2] M. A. Shaah, F. Allafi, M. S. Hossain et al., "Candlenut oil: review on oil properties and future liquid biofuel prospects," *International Journal of Energy Research*, vol. 45, no. 12, pp. 17057–17079, 2021.

[3] A. N. Syimir Fizal, M. S. Hossain, M. Zulkifli, N. A. Khalil, H. Abd Hamid, and A. N. Ahmad Yahaya, "Implementation of the supercritical CO_2 technology for the extraction of candlenut oil as a promising feedstock for biodiesel production: potential and limitations," *International Journal of Green Energy*, vol. 19, no. 1, pp. 72–83, 2022.

[4] M. A. Shaah, M. S. Hossain, F. Allafi, M. O. Ab Kadir, and M. I. Ahmad, "Biodiesel production from candlenut oil using a non-catalytic supercritical methanol transesterification process: optimization, kinetics, and thermodynamic studies," *RSC Advances*, vol. 12, no. 16, pp. 9845–9861, 2022.

[5] F. Javed, M. Aslam, N. Rashid et al., "Microalgae-based biofuels, resource recovery and wastewater treatment: a pathway towards sustainable biorefinery," *Fuel*, vol. 255, Article ID 115826, 2019.

[6] M. Rahimi, B. Aghel, M. Alitabar, A. Sepahvand, and H. R. Ghasempour, "Optimization of biodiesel production from soybean oil in a microreactor," *Energy Conversion and Management*, vol. 79, pp. 599–605, 2014.

[7] M. Abdul Hakim Shaah, M. S. Hossain, F. A. Salem Allafi et al., "A review on non-edible oil as a potential feedstock for biodiesel: physicochemical properties and production technologies," *RSC Advances*, vol. 11, no. 40, pp. 25018–25037, 2021.

[8] S. Thiruvenkatachari, C. G. Saravanan, V. Edwin Geo, M. Vikneswaran, R. Udayakumar, and F. Aloui, "Experimental investigations on the production and testing of azolla methyl esters from Azolla microphylla in a compression ignition engine," *Fuel*, vol. 287, Article ID 119448, 2021.

[9] M. A. Mujtaba, H. Muk Cho, H. H. Masjuki et al., "Critical review on sesame seed oil and its methyl ester on cold flow and oxidation stability," *Energy Reports*, vol. 6, pp. 40–54, 2020.

[10] A. Gherghel, C. Teodosiu, and S. De Gisi, "A review on wastewater sludge valorisation and its challenges in the context of circular economy," *Journal of Cleaner Production*, vol. 228, pp. 244–263, 2019.

[11] A. Ding, R. Zhang, H. H. Ngo et al., "Life cycle assessment of sewage sludge treatment and disposal based on nutrient and energy recovery: a review," *Science of the Total Environment*, vol. 769, Article ID 144451, 2021.

[12] C. Rolsky, V. Kelkar, E. Driver, and R. U. Halden, "Municipal sewage sludge as a source of microplastics in the environment," *Current Opinion in Environmental Science & Health*, vol. 14, pp. 16–22, 2020.

[13] E. E. Kwon, S. Kim, Y. J. Jeon, and H. Yi, "Biodiesel production from sewage sludge: new paradigm for mining energy from municipal hazardous material," *Environmental Science & Technology*, vol. 46, no. 18, pp. 10222–10228, 2012.

[14] J. A. Melero, R. Sánchez-Vázquez, I. A. Vasiliadou et al., "Municipal sewage sludge to biodiesel by simultaneous extraction and conversion of lipids," *Energy Conversion and Management*, vol. 103, pp. 111–118, 2015.

[15] N. A. Khalil, H. A. Hamid, A. N. S. Fizal, M. Zulkifli, M. S. Hossain, and A. N. A. Yahaya, "Utilization of supercritical carbon dioxide (SC-CO_2) in lipids extraction from sewage sludge cake: a preliminary study," *IOP Conference Series: Materials Science and Engineering*, vol. 1195, no. 1, Article ID 012054, 2021.

[16] M. S. Hossain, N. N. Norulaini, A. A. Naim, A. M. Zulkhairi, M. M. Bennama, and A. M. Omar, "Utilization of the supercritical carbon dioxide extraction technology for the production of deoiled palm kernel cake," *Journal of CO_2 Utilization*, vol. 16, pp. 121–129, 2016.

[17] M. K. M. Ilias, V. Balakrishnan, M. H. Zuknik, A. Al-Gheethi, A. A. Ghfar, and M. S. Hossain, "Supercritical CO_2 Separation of Lipids from Chicken By-Product Waste for Biodiesel Production: Optimization, Kinetics, and Thermodynamics Modeling," *Biomass Conversion and Biorefinery*, In Press, 2021.

[18] A. Patel, O. Sarkar, U. Rova, P. Christakopoulos, and L. Matsakas, "Valorization of volatile fatty acids derived from low-cost organic waste for lipogenesis in oleaginous microorganisms-A review," *Bioresource Technology*, vol. 321, Article ID 124457, 2021.

[19] P. D. Patil, K. P. R. Dandamudi, J. Wang, Q. Deng, and S. Deng, "Extraction of bio-oils from algae with supercritical carbon dioxide and co-solvents," *The Journal of Supercritical Fluids*, vol. 135, pp. 60–68, 2018.

[20] X. Liu, F. Zhu, R. Zhang, L. Zhao, and J. Qi, "Recent progress on biodiesel production from municipal sewage sludge," *Renewable and Sustainable Energy Reviews*, vol. 135, Article ID 110260, 2021.

[21] F. Zhu, L. Zhao, H. Jiang et al., "Comparison of the lipid content and biodiesel production from municipal sludge using three extraction methods," *Energy & Fuels*, vol. 28, no. 8, pp. 5277–5283, 2014.
[22] A. P. Bora, D. P. Gupta, and K. S. Durbha, "Sewage sludge to bio-fuel: a review on the sustainable approach of transforming sewage waste to alternative fuel," *Fuel*, vol. 259, Article ID 116262, 2020.
[23] D. E. Algapani, J. Wang, W. Qiao et al., "Improving methane production and anaerobic digestion stability of food waste by extracting lipids and mixing it with sewage sludge," *Bioresource Technology*, vol. 244, pp. 996–1005, 2017.
[24] K. S. Khoo, K. W. Chew, G. Y. Yew et al., "Recent advances in downstream processing of microalgae lipid recovery for biofuel production," *Bioresource Technology*, vol. 304, Article ID 122996, 2020.
[25] H. Sati, M. Mitra, S. Mishra, and P. Baredar, "Microalgal lipid extraction strategies for biodiesel production: a review," *Algal Research*, vol. 38, Article ID 101413, 2019.
[26] S. Ahmadkelayeh, S. K. Cheema, and K. Hawboldt, "Supercritical CO_2 extraction of lipids and astaxanthin from Atlantic shrimp by-products with static co-solvents: process optimization and mathematical modeling studies," *Journal of CO_2 Utilization*, vol. 58, Article ID 101938, 2022.
[27] P.-L. Li, H.-N. Li, K.-J. Jing, A. David, J.-R. Lin, and G. Deng, "Evaluation of lipid extraction from microalgae based on different phase regions of CO_2-expanded ethanol," *Chemical Engineering and Processing - Process Intensification*, vol. 138, pp. 1–6, 2019.
[28] P. Jafarian Asl, R. Niazmand, and M. Jahani, "Theoretical and experimental assessment of supercritical CO_2 in the extraction of phytosterols from rapeseed oil deodorizer distillates," *Journal of Food Engineering*, vol. 269, Article ID 109748, 2020.
[29] M. A. Kassim, K. Kirtania, D. De La Cruz, N. Cura, S. C. Srivatsa, and S. Bhattacharya, "Thermogravimetric analysis and kinetic characterization of lipid-extracted Tetraselmis suecica and Chlorella sp," *Algal Research*, vol. 6, pp. 39–45, 2014.
[30] V. Ashokkumar, R. Rengasamy, S. Deepalakshmi, A. Sivalingam, and P. Sivakumar, "Mass cultivation of microalgae and extraction of total hydrocarbons: a kinetic and thermodynamic study," *Fuel*, vol. 119, pp. 308–312, 2014.
[31] Y. Patiño, L. Faba, E. Díaz, and S. Ordóñez, "Biodiesel production from wastewater sludge using exchange resins as heterogeneous acid catalyst: catalyst selection and sludge pretreatments," *Journal of Water Process Engineering*, vol. 44, Article ID 102335, 2021.
[32] A. Abdulhussein Alsaedi, M. Sohrab Hossain, V. Balakrishnan et al., "Extraction and separation of lipids from municipal sewage sludge for biodiesel production: kinetics and thermodynamics modeling," *Fuel*, vol. 325, Article ID 124946, 2022.
[33] V. D'Ambrosio, L. di Bitonto, A. Angelini, A. Gallipoli, C. M. Braguglia, and C. Pastore, "Lipid extraction from sewage sludge using green biosolvent for sustainable biodiesel production," *Journal of Cleaner Production*, vol. 329, Article ID 129643, 2021.
[34] D. Singh, D. Sharma, S. L. Soni, S. Sharma, and D. Kumari, "Chemical compositions, properties, and standards for different generation biodiesels: a review," *Fuel*, vol. 253, pp. 60–71, 2019.
[35] J. Huang, Y. Zou, M. Yaseen, H. Qu, R. He, and Z. Tong, "Fabrication of hollow cage-like CaO catalyst for the enhanced biodiesel production via transesterification of soybean oil and methanol," *Fuel*, vol. 290, Article ID 119799, 2021.
[36] R. Naureen, M. Tariq, I. Yusoff, A. J. K. Chowdhury, and M. A. Ashraf, "Synthesis, spectroscopic and chromatographic studies of sunflower oil biodiesel using optimized base catalyzed methanolysis," *Saudi Journal of Biological Sciences*, vol. 22, no. 3, pp. 332–339, 2015.
[37] S. Nandi, R. Bhattacharyya, and G. Misra, "Investigation of biodiesel from canola oil deodorizer distillate using dual biocatalyst," *Asian Journal of Applied Science and Technology*, vol. 4, no. 1, pp. 131–138, 2020.
[38] A. N. Gutiérrez-López, V. Y. Mena-Cervantes, S. M. García-Solares, J. Vazquez-Arenas, and R. Hernández-Altamirano, "NaFeTiO4/Fe2O3–FeTiO3 as heterogeneous catalyst towards a cleaner and sustainable biodiesel production from Jatropha curcas L. oil," *Journal of Cleaner Production*, vol. 304, Article ID 127106, 2021.
[39] A. Cunha, V. Feddern, M. C. De Prá, M. M. Higarashi, P. G. de Abreu, and A. Coldebella, "Synthesis and characterization of ethylic biodiesel from animal fat wastes," *Fuel*, vol. 105, pp. 228–234, 2013.
[40] P. Nautiyal, K. A. Subramanian, and M. G. Dastidar, "Production and characterization of biodiesel from algae," *Fuel Processing Technology*, vol. 120, pp. 79–88, 2014.
[41] R. Foroutan, R. Mohammadi, and B. Ramavandi, "Waste glass catalyst for biodiesel production from waste chicken fat: optimization by RSM and ANNs and toxicity assessment," *Fuel*, vol. 291, Article ID 120151, 2021.
[42] R. C. Pradhan, V. Meda, P. K. Rout, S. Naik, and A. K. Dalai, "Supercritical CO_2 extraction of fatty oil from flaxseed and comparison with screw press expression and solvent extraction processes," *Journal of Food Engineering*, vol. 98, no. 4, pp. 393–397, 2010.