

Microwave-assisted transesterification of sour cherry kernel oil for biodiesel production: comparison with ultrasonic bath-, ultrasonic probe-, and ohmic-assisted transesterification methods

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SUMMARY: In this study, sour cherry kernel oil was converted to biodiesel by microwave-assisted transesterification. Evaluations were made of several variables, namely, reaction time (1, 2, 3, 4, and 5 min), microwave power (100, 200, 300, 400, and 500 W), methanol/oil mole ratio (3, 6, 9, 12, and 15), and catalyst (KOH) concentration (0.3%, 0.6%, 0.9%, 1.2%, and 1.5%). The efficiency of fatty acid methyl esters increased in response to lengthier reaction times, greater microwave power, higher methanol/oil mole ratio, and higher catalyst concentrations up to the optimal level. The optimal reaction conditions for microwave-assisted transesterification were 300 W microwave power, 1.2% catalyst concentration, a methanol/oil mole ratio of 1:2, and a reaction time of 4 min. Microwave-assisted transesterification was more effective than ohmic-, magnetic stirrer-, ultrasonic probe-, and ultrasonic bath-assisted transesterification methods. In conclusion, microwave-assisted transesterification can be suggested as a fast, efficient, and economical method compared to other transesterification methods.

KEYWORDS: Biodiesel; Microwave; Sour cherry kernel oil; Transesterification.

RESUMEN: *Transesterificación asistida por microondas de aceite de semilla de cereza ácida para la producción de biodiesel: comparación con métodos de transesterificación asistida por baño ultrasónico, sonda ultrasónica y óhmica.* En este estudio, el aceite de semilla de cereza ácida se convirtió en biodiesel mediante transesterificación asistida por microondas. Se realizaron evaluaciones de varias variables, como tiempo de reacción (1, 2, 3, 4 y 5 min), potencia de microondas (100, 200, 300, 400 y 500 W), relación molar metanol/aceite (3, 6, 9, 12 y 15) y concentración de catalizador (KOH) (0,3%, 0,6%, 0,9%, 1,2% y 1,5%). La eficiencia de los ésteres metílicos de ácidos grasos aumentó en respuesta a tiempos de reacción más prolongados, mayor potencia de microondas, mayor relación molar metanol/aceite y mayores concentraciones de catalizador hasta el nivel óptimo. La condición de reacción óptima de la transesterificación asistida por microondas fue una potencia de microondas de 300 W, una concentración de catalizador del 1,2%, una relación molar de metanol/aceite de 12 y un tiempo de reacción de 4 min. La transesterificación asistida por microondas fue más efectiva que los métodos de transesterificación asistida por baño ultrasónico, óhmico, con agitador magnético y con sonda ultrasónica. En conclusión, la transesterificación asistida por microondas puede sugerirse como un método rápido, eficiente y económico en comparación con otros métodos de transesterificación.

PALABRAS CLAVE: Aceite de semilla de cereza ácida; Biodiesel; Microonda; Transesterificación.

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1. INTRODUCTION

Many sour cherry cultivars have a characteristic tart taste since their acid/sugar ratios are higher in comparison with the sweet cherry cultivars. The strong tartness of sour cherry cultivars limits the fresh consumption of sour cherries (Yilmaz *et al.*, 2019). Thus, most sour cherries are industrially processed and consumed products to make canned or frozen food, jam, and juice. The global sour cherry production in 2019 was about 1.5 million tons (Almasi *et al.*, 2021). The largest sour cherry harvests occur in Europe, accounting for 62% of the total worldwide production. Sour cherry by-products consist of pomace and kernel. Sour cherry kernel comprises 7-15% of the whole fruit and consists of two main parts: shell (75-80%) and kernel (20-25%). The sour cherry kernel is made of 7.2% moisture, 4.4% ash, 46.6% carbohydrates, 29.3% protein, and 17-36% oil (Yilmaz *et al.*, 2019). Thus, sour cherry kernel oil (SCKO) is an attractive and valuable source for biodiesel production (Almasi *et al.*, 2021).

Biodiesel is an alternative fuel for diesel engines and is made from renewable biological sources such as vegetable oils and animal fats (Zhang *et al.*, 2010). However, since edible oils are more globally needed for food security, non-edible oils would be ideally considered for biodiesel production (Mahlin-da *et al.*, 2017). Biodiesel is more environmentally friendly than diesel because of its many advantages, such as biodegradability, renewability, low toxicity, secure usability and storage, adaptability to existing engines, and good blending ability with petroleum-based diesel fuels (Zhang *et al.*, 2012). The most commonly used method of biodiesel production is the transesterification of vegetable oils and animal fats (Ma and Hanna, 1999). Biodiesel production processes are based on either conventional or novel heating methods.

The heating method employed in transesterification is a crucial factor in biodiesel production. Conventional heating methods such as magnetic stirrer, hot plate, and water bath require longer reaction times with higher energy inputs that usually render them inefficient (Lin and Chen, 2017; Dehghan *et al.*, 2019). Meanwhile, novel heating methods such as membrane reactors, reactive distillation columns, reactive absorption, ultrasonic, and microwave ra-

diation significantly influence the final conversion, efficiency, and the quality of the product in particular (Talebian-Kiakalaieh *et al.*, 2013). An alternative heating system is “microwave radiation”, which has recently gained popularity as a method of conducting chemical reactions. When a reaction is carried out under microwaves, the reaction is efficiently accelerated in a short reaction time by the effect of microwaves. This usually results in a drastic reduction in the quantity of by-products and a short separation time (Azcan and Danisman, 2008).

The current research aimed at evaluating several variables of the reaction conditions, namely, microwave power, methanol/oil mole ratio, catalyst concentration, and reaction time in the microwave-assisted transesterification (MAT) of SCKO. The MAT of SCKO under optimal condition was compared to the performance of ohmic-, magnetic stirrer-, ultrasonic probe-, and ultrasonic bath-assisted transesterification methods (OAT, MSAT, UPAT, and UBAT, respectively).

2. MATERIALS AND METHODS

2.1. Materials

Potassium hydroxide, ethanol, hydrochloric acid, sodium sulfate, sodium chloride, TBHQ, sulfuric acid, chloroform, sodium thiosulfate, methanol, acetyl chloride, potassium iodide, methyl laurate, phenolphthalein, hexane, and acetic acid were of analytical grade and were purchased from Sigma-Aldrich (St. Louis, MO) and Merck (Darmstadt, Germany). SCKO was purchased from Mahya Company (Shiraz, Iran).

2.2. Microwave-assisted transesterification (MAT)

2.2.1. Experimental procedure

The MAT of SCKO was carried out in methanol/oil mole ratios of 3, 6, 9, 12, and 15, along with KOH catalyst concentrations of 0.3, 0.6, 0.9, 1.2, and 1.5%, as well as microwave power values of 100, 200, 300, 400, and 500 W. The reaction time was either 1, 2, 3, 4, or 5 min. All experiments were designed based on changing one variable at a time and keeping the rest of the variables constant at their center point (i.e. microwave power of 300 W, methanol/oil mole ratio of 9, catalyst concentration of 0.9%, and reaction time of 3 min). Effects of each variable on the

weight efficiency, purity, and final efficiency of the production of fatty acid methyl esters (FAME) were investigated and the optimal level for each parameter was determined. Eq. (1) was used for determining the amount of oil in each test.

$$MW_{oil} = 3 \times \sum (MW_i \times X_i) + 38 \quad \text{Eq. (1)}$$

MW_{oil} : Molecular weight of oil; MW_i : Molecular weight of fatty acids in oil; X_i : Mass ratio of fatty acids in oil

A known quantity of catalyst (KOH) was initially dissolved in methanol and the resultant solution was then added to the SCKO. The reaction was carried out in a microwave oven (Samsung, 2450 MHz, model ME3410W), equipped with a condenser. The reaction was captured immediately by immersing the glass reactor in an ice bath. As the reaction was stopped, the product was kept in a separating funnel overnight, when biodiesel was separated from glycerol. The crude FAME remained in the upper phase, while the catalyst and unreacted methanol were situated in the lower glycerol phase, meaning that small amounts of catalyst, methanol, and glycerol were present in the upper phase (Dehghan *et al.*, 2021). Excess methanol in the methyl ester phase was evaporated by a magnetic stirrer equipped with a condenser at 80 °C for 30 min at 600 rpm (Azcan and Danisman, 2008). After separating the biodiesel phase, it was further washed with water to ensure a complete removal of glycerol, catalyst, and other contaminants. Then, a magnetic stirrer at the agitation speed of 400 rpm for 1 h was used to remove the remaining moisture at 60 °C (Alishahi *et al.*, 2021). To determine the purity of the FAME, methyl laurate was used as internal standard. The weight efficiency, purity, and final efficiency of the resultant FAME were determined according to the following equations:

$$\text{Weight efficiency (\%)} = \frac{\text{Gross methyl ester (g)}}{\text{Consumable primary oil (g)}} \times 100 \quad \text{Eq. (2)}$$

$$\text{Purity (\%)} = \left[\frac{\text{Area of methyl ester peak}}{\text{Area of standard peak}} \times \frac{\text{Standard weight}}{\text{Methyl ester weight}} \right] \times 100 \quad \text{Eq. (3)}$$

$$\text{Final efficiency (\%)} = \frac{\text{Purity of the methyl ester} \times \text{Weight efficiency of methyl ester}}{100} \quad \text{Eq. (4)}$$

2.2.2. Physicochemical properties of FAME

The kinematic viscosity, refractive index, and density of biodiesel were measured according to the guidelines of the American Society for Testing Materials (ASTM; D445), the AOCS Cc7-25 Official Method, and the AOCS 1a-64 Official Method, respectively (AOCS, 2000; ASTM, 2013; Golmakani *et al.*, 2022). The fatty acid (FA) composition and color attributes of biodiesel were evaluated using a method described by Dehghan *et al.* (2019).

2.3. Comparison of different transesterification methods

The OAT, MSAT, UPAT, and UBAT methods were compared to the optimal conditions of MAT. The weight efficiency, purity, and final efficiency of FAME produced by different transesterification methods were determined according to Eq. (2), Eq. (3), and Eq. (4), respectively.

The reaction conditions in the MSAT, OAT, UPAT, and UBAT methods were similar to those of MAT (300 W power value, methanol/oil mole ratio of 12, reaction time of 4 min, and KOH concentration of 1.2%) unless otherwise stated. In the MSAT method, a magnetic stirrer (Labinco model L81, DG Breda, Netherlands) operated at 600 rpm for 140 min. In the OAT method, an ohmic reactant entered a 50-mL glass balloon and two holes (2 cm in diameter) were made on the sides of the balloon for the entry of electrodes. The applied voltage and salt concentration in this study were 200 V and 0.25%, respectively. In the UPAT method, an ultrasonic probe was used (Bandelin HD 3200, Bandelin Electronics, Berlin, Germany). The substrates were sonicated in a high-grade titanium tip (TT13, 13 mm diameter) with a constant horn depth of 2 cm. In the UBAT method, an ultrasonic bath was used (Bandelin, DT 255H).

2.3.1. Physicochemical properties

The kinematic viscosity, refractive index, density, fatty acid composition, and color attributes of the resultant FAME, produced with different transesterification methods, were measured according to section 2.2.2.

2.3.2. Thermal properties of SCKO esters

Cloud, flash, fire, and pour points were calculated according to the American Society for Testing Materials (ASTM, 2013). Also, a laser thermometer

(TM-939, Lutron, Taiwan) was used for measuring the temperature.

2.3.3. Energy consumption

The amounts of energy used in each step of the reactions per transesterification method, separation of methanol, washing, and drying were monitored using a digital electric energy meter (a watt-hour meter) at the entrance of the electrical power supply. The amount of energy (power consumption (W)) was determined and then multiplied by time to get the total energy consumption (Wh) (Eq. (5)) (Motasemi and Ani, 2012). The energy consumed in all stages was added together and by applying Eq. (6), the amount of energy consumed to produce 1 g of FAME was calculated as the relative energy consumption.

$$\text{Total energy consumption (Wh)} = \text{Power consumption (W)} \times \text{Time (h)} \quad \text{Eq. (5)}$$

$$\text{Relative energy consumption (Wh/g)} = \text{Total energy consumption (Wh)} / \text{Final methyl ester weight (g)} \quad \text{Eq. (6)}$$

For producing 1 kWh of energy, 800 g of CO₂ entered the environment. CO₂ production and relative CO₂ production were measured according to the following equations:

$$\text{CO}_2 \text{ production (g)} = \text{Energy consumption (Wh)} \times 0.8 \text{ (g/Wh)} \quad \text{Eq. (7)}$$

$$\text{Relative CO}_2 \text{ production} = \text{CO}_2 \text{ production (g)} / \text{Final methyl ester weight (g)} \quad \text{Eq. (8)}$$

2.4. Statistical analysis

All experiments were done in three repetitions. Their mean values and standard deviations were calculated. The mean comparison was made to determine the differences among the mean values via SAS software (Statistical Analysis Software, version 9.1; SAS Institute Inc. Cary, NC).

3. RESULTS AND DISCUSSION

The physicochemical properties of SCKO are shown in Table 1. The amount of free fatty acid (FFA) for alkaline transesterification should be less than 5% and the moisture content should be less than 0.5% (Cavalcante *et al.*, 2010). According to the pre-

TABLE 1. Physicochemical properties of pre-esterified inedible sour cherry kernel oil.

Physicochemical property	value
Free fatty acids (% as oleic acid)	3.5
Refractive index	1.479
Saponification value (mg KOH/g)	163.812
Acid value (mg KOH/g)	6.965
Density (kg/m ³)	869.6
Moisture and volatile matters (%)	0.34
Viscosity at 40 °C (mm ² /s)	28.16
Equivalent saponification value	1027.39
Color attribute	
L*	89.33
a*	-2.00
b*	35.33
Fatty acid composition (%)	
Myristic acid	0.67
Palmitic acid	10.59
Palmitoleic acid	0.63
Stearic acid	1.43
Oleic acid	40.43
Linoleic acid	44.14
α-Linolenic acid	1.05
Eleostearic acid	0.71
Arachidic acid	0.33
Saturated fatty acid (SFA)	13.02
Unsaturated fatty acid (UFA)	86.98
Polyunsaturated fatty acid (PUFA)	45.90

liminary experiments, SCKO showed the necessary characteristics to participate in the transesterification reaction. Oleic acid (C18:1) and linoleic acid (C18:2) were the main unsaturated fatty acids in SCKO. Our findings are consistent with the results of Popa *et al.* (2011), Gornas *et al.* (2016) and Korlesky *et al.* (2016) regarding the properties of SCKO.

3.1. Effects of influential parameters on biodiesel efficiency of MAT

3.1.1. Reaction time

Figure 1a shows variations in weight efficiency, purity, and final efficiency with respect to the reaction time. Within the first 4 min, the weight efficiency, purity, and final efficiency increased with the extension of the transesterification time. After 4 min (microwave power of 300 W, methanol/oil mole

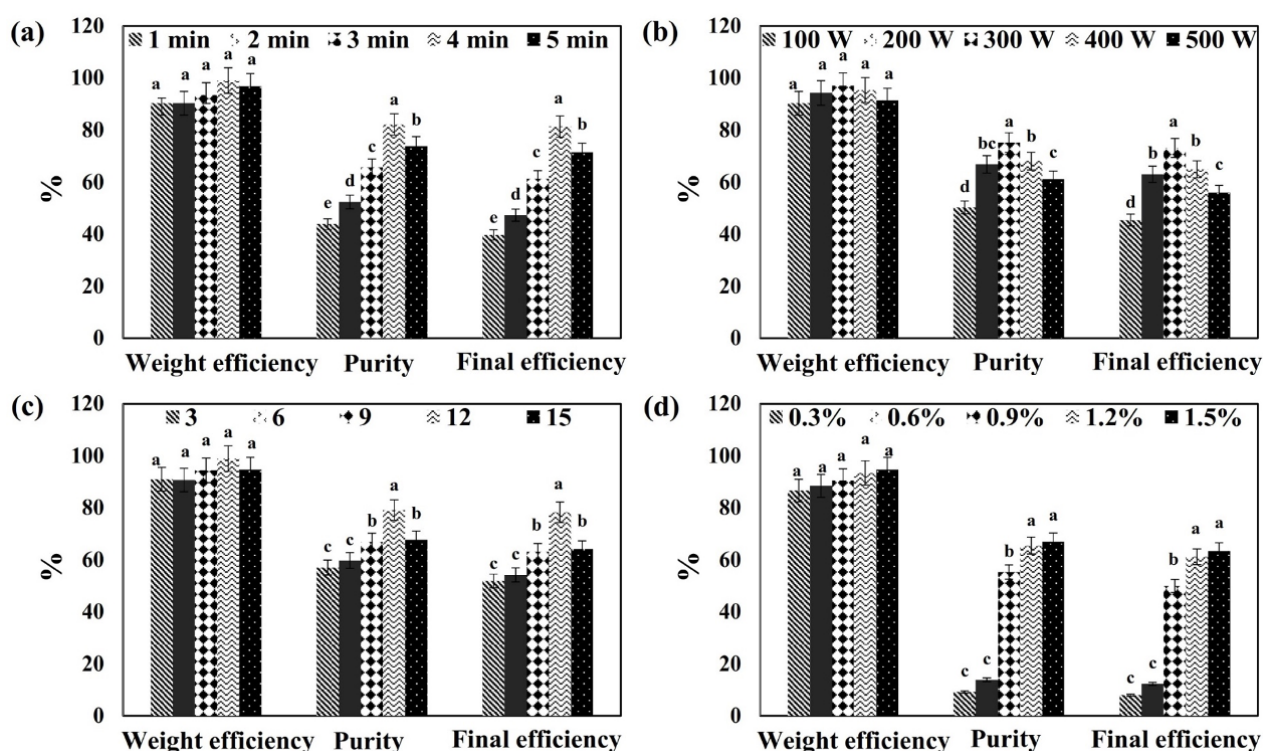


FIGURE 1. Effects of (a) reaction time, (b) microwave power, (c) methanol/oil mole ratio, and (d) catalyst concentration on microwave-assisted transesterification of sour cherry kernel oil; Mean $\pm$ SD ($n = 3$); Statistical test: ANOVA and multiple comparison of means using Duncan's multiple range test; ($P < 0.05$); Each factor was optimized by considering an intermediate value (center point) of other factors (i.e., microwave power of 300 W, methanol/oil mole ratio of 9, catalyst concentration of 0.9%, and reaction time of 3 min).

ratio of 9, and catalyst concentration of 0.9%), the weight efficiency, purity, and final efficiency decreased. Thus, 4 min was considered as an optimal reaction time. At the beginning of the process, due to the non-uniform distribution of methanol in the oil, the reaction was slow. However, the reaction rate increased with time. This means that in the initial stages, while the reactants had the least contact with the microwaves, FAME production was low in purity and efficiency (Sajjadi *et al.*, 2014). Prolonging the reaction time above the optimal one led to a decrease in weight efficiency, purity, and final efficiency from several angles. Over time, the reversibility of the transesterification reaction caused an increase in the solubility of glycerol and the reaction slightly changed in the reverse direction, thereby resulting in by-products and reducing the production of FAME. Also, the long reaction time caused the reactants to overheat. Methanol evaporated from the reaction medium after reaching the boiling point and reduced the efficiency of FAME production. In addition, by increasing the reaction time, the costs related to the amount of energy required to carry out the reaction

will also increase (Chen *et al.*, 2012; Leung *et al.*, 2010; Patil *et al.*, 2011). Similarly, Azkan and Yilmaz (2013) reported the effects of reaction time on the final efficiency of FAME production from waste from frying oil.

3.1.2. Microwave power

Figure 1b shows variations in weight efficiency, purity, and final efficiency with respect to microwave power. The weight efficiency, purity, and final efficiency increased in response to the increase in microwave power up to 300 W (reaction time of 3 min, methanol/oil mole ratio of 9, and catalyst concentration of 0.9%). Maximum weight efficiency, purity, and final efficiency reached 97.14, 75.26, and 73.11%, respectively, when biodiesel production from the SCKO operated at 300 W. This can be justified by the fact that the increase in microwave power accelerated the electromagnetic wave transfer through the molecular components of the mixture and their energy spread at a higher rate within the reactant mixture. Thus, the final efficiency increased. However, by increasing the microwave

power to above 300 W, the reactant mixture and the structure of organic compounds became susceptible to damage. Triglycerides broke down and were converted to FFA. An excessive increase in power rendered an intense and chaotic interaction between molecules, thereby reducing the formation rate of the final, intended product. Similarly, Zu *et al.* (2009) produced biodiesel using yellow horn (*Xanthoceras sorbifolia* Bunge.) oil and reported that at irradiation power of 500 W the highest efficiency was achieved in 6 min. However, when the power of 700 W was applied, the conversion efficiency of FAME began declining, because different raw materials have different appropriate irradiation power.

3.1.3. Methanol/oil mole ratio

Figure 1c shows the variations in weight efficiency, purity, and final efficiency with respect to the methanol/oil mole ratio. The weight efficiency, purity, and final efficiency increased in response to the increase in methanol/oil mole ratio from 3 to 12 (reaction time of 3 min, microwave power of 300 W, and catalyst concentration of 0.9%). However, the weight efficiency, purity, and final efficiency decreased when the methanol/oil mole ratio increased from 12 to 15. Thus, the methanol/oil mole ratio of 12 was considered optimal. The highest weight efficiency, purity, and final efficiency of FAME (98.90, 80.52, and 79.63%, respectively) were obtained at the mole ratio of 12. An excessive increase in methanol in several aspects reduced its production efficiency to esterify the triglycerides to FAME. Since methanol is highly capable of absorbing microwaves, increasing its ratio causes a higher absorption of waves when sufficient amounts of methanol exist. The temperature of the reaction mixture increased with less intensity (Lin *et al.*, 2014), while excess methanol made catalyst separation difficult at the end of the reaction. Increasing the methanol/oil mole ratio beyond a certain value increased the glycerol solubility and led to foam formation, thereby lowering the efficiency (Sharma *et al.*, 2019). In addition, an excess of glycerol drove the shifted equilibrium towards the reactants, and, thus, lowered the efficiency of biodiesel conversion when glycerol remained in the solution (Mahlinda *et al.*, 2017). In a similar study, Zhang *et al.* (2010) produced biodiesel using yellow horn oil and reported that the transesterification could be

accelerated by increasing the amounts of methanol. The high mole ratio of methanol to oil could enhance the conversion efficiency of FAME. On the other hand, excessive methanol amounts reduced the concentrations of catalyst and reactant, which retarded the reaction and aggravated the recovery of the solvents.

3.1.4. Catalyst concentration

Figure 1d shows variations in weight efficiency, purity, and final efficiency with respect to catalyst concentration. Weight efficiency, purity, and final efficiency increased when the amount of catalyst concentration increased from 0.3 to 1.2% (reaction time of 3 min, microwave power of 300 W, and methanol/oil mole ratio of 9). A higher catalyst concentration caused proper physical contact between the reactants that led to an increase in purity and final efficiency. Since increasing the catalyst concentration from 1.2 to 1.5% had no considerable impact on the efficiency and purity of FAME, the catalyst concentration of 1.2% was considered optimal. High amounts of alkaline catalyst increased the possibility of soap formation, which caused an emulsion to form between soap and water molecules. This emulsion entraps FAME and makes their separation difficult, so that some of them remain unrecovered (Atapour and Kariminia, 2011). An excessive increase in the catalyst concentration increased the kinematic viscosity of the mixture, created a gel, and led to problems in separating the glycerol phase (Sajjadi *et al.*, 2014). In a similar study, Sharma *et al.* (2019) produced biodiesel using waste cotton-seed cooking oil, and reported that the excessive amount of heterogeneous catalyst increased washing time and decreased the formation of biodiesel as the reactant mixture became more viscous and thus, increased resistance to mass transfer. A suitable amount of catalyst reduces catalyst waste and avoids pollution in bodies of water.

3.2. Investigation of the FAME produced by MAT

3.2.1. Fatty acid composition

Table 2 shows variations in the fatty acid composition of SCKO FAME with respect to different MAT variables. It seems that different microwave conditions had no significant effect on the transesterification of different fatty acids in terms of chain

TABLE 2. Effect of reaction time, microwave power, methanol/oil mole ratio, and catalyst concentration on fatty acid composition (%) of sour cherry kernel oil methyl esters.

Transesterification variable	Fatty acids								
	Myristic acid	Palmitic acid	Palmitoleic acid	Stearic acid	Oleic acid	Linoleic acid	α -Linolenic acid	Eleostearic acid	Arachidic acid
Reaction time (min)									
1	0.35 $\pm$ 0.31*	8.88 $\pm$ 0.44	0.53 $\pm$ 0.03	0.61 $\pm$ 0.03	41.95 $\pm$ 2.10	46.05 $\pm$ 2.30	0.48 $\pm$ 0.02	0.79 $\pm$ 0.04	0.36 $\pm$ 0.02
2	0.51 $\pm$ 0.03	9.25 $\pm$ 0.46	0.70 $\pm$ 0.04	1.50 $\pm$ 0.08	39.83 $\pm$ 1.99	46.80 $\pm$ 2.34	0.39 $\pm$ 0.02	0.70 $\pm$ 0.04	0.32 $\pm$ 0.02
3	1.33 $\pm$ 0.07	9.63 $\pm$ 0.48	0.71 $\pm$ 0.04	1.24 $\pm$ 0.06	39.85 $\pm$ 1.98	45.71 $\pm$ 2.29	0.61 $\pm$ 0.03	0.66 $\pm$ 0.03	0.27 $\pm$ 0.01
4	0.26 $\pm$ 0.01	7.51 $\pm$ 0.38	0.42 $\pm$ 0.02	1.33 $\pm$ 0.05	42.76 $\pm$ 2.14	46.70 $\pm$ 2.39	0.21 $\pm$ 0.01	0.48 $\pm$ 0.02	0.33 $\pm$ 0.02
5	0.18 $\pm$ 0.1	8.86 $\pm$ 0.44	0.64 $\pm$ 0.03	1.50 $\pm$ 0.07	41.87 $\pm$ 2.09	45.46 $\pm$ 2.26	0.50 $\pm$ 0.02	0.67 $\pm$ 0.03	0.32 $\pm$ 0.02
Microwave power (W)									
100	0.28 $\pm$ 0.01	9.02 $\pm$ 0.45	0.63 $\pm$ 0.02	1.90 $\pm$ 0.09	39.58 $\pm$ 1.98	47.31 $\pm$ 2.37	0.70 $\pm$ 0.04	0.43 $\pm$ 0.02	0.15 $\pm$ 0.01
200	1.09 $\pm$ 0.05	10.18 $\pm$ 0.51	0.57 $\pm$ 0.03	1.62 $\pm$ 0.08	38.21 $\pm$ 1.91	45.47 $\pm$ 2.27	0.67 $\pm$ 0.03	1.69 $\pm$ 0.08	0.29 $\pm$ 0.01
300	1.14 $\pm$ 0.06	9.07 $\pm$ 0.45	0.68 $\pm$ 0.03	1.42 $\pm$ 0.07	38.84 $\pm$ 1.94	46.78 $\pm$ 2.34	0.55 $\pm$ 0.03	0.35 $\pm$ 0.02	1.17 $\pm$ 0.06
400	1.24 $\pm$ 0.06	6.84 $\pm$ 0.34	0.90 $\pm$ 0.00	1.94 $\pm$ 0.10	38.04 $\pm$ 1.89	46.24 $\pm$ 2.31	0.32 $\pm$ 0.02	1.93 $\pm$ 0.10	2.55 $\pm$ 0.13
500	0.77 $\pm$ 0.04	8.87 $\pm$ 0.44	0.57 $\pm$ 0.03	1.75 $\pm$ 0.09	40.18 $\pm$ 2.01	45.43 $\pm$ 2.27	0.57 $\pm$ 0.03	1.15 $\pm$ 0.06	0.71 $\pm$ 0.04
Mole ratio (methanol/oil)									
3	0.80 $\pm$ 0.00	9.05 $\pm$ 0.44	0.48 $\pm$ 0.02	1.19 $\pm$ 0.06	40.03 $\pm$ 2.00	46.48 $\pm$ 2.32	0.39 $\pm$ 0.02	1.58 $\pm$ 0.07	0.45 $\pm$ 0.02
6	0.59 $\pm$ 0.03	10.17 $\pm$ 0.51	1.46 $\pm$ 0.07	1.49 $\pm$ 0.07	38.83 $\pm$ 1.93	44.87 $\pm$ 2.23	0.98 $\pm$ 0.05	1.05 $\pm$ 0.05	0.67 $\pm$ 0.03
9	0.82 $\pm$ 0.04	9.87 $\pm$ 0.49	1.11 $\pm$ 0.06	1.36 $\pm$ 0.07	38.06 $\pm$ 1.88	45.33 $\pm$ 2.26	0.70 $\pm$ 0.03	1.97 $\pm$ 0.10	0.79 $\pm$ 0.03
12	0.71 $\pm$ 0.04	9.04 $\pm$ 0.45	0.56 $\pm$ 0.03	1.87 $\pm$ 0.09	40.86 $\pm$ 2.04	44.68 $\pm$ 2.22	0.48 $\pm$ 0.02	1.36 $\pm$ 0.06	0.44 $\pm$ 0.02
15	1.79 $\pm$ 0.09	8.63 $\pm$ 0.43	0.59 $\pm$ 0.03	1.55 $\pm$ 0.07	39.50 $\pm$ 1.98	45.68 $\pm$ 2.27	0.67 $\pm$ 0.03	1.12 $\pm$ 0.05	0.47 $\pm$ 0.02
Catalyst concentration (%)									
0.3	1.24 $\pm$ 0.06	8.97 $\pm$ 0.43	0.45 $\pm$ 0.02	1.49 $\pm$ 0.07	39.91 $\pm$ 1.97	44.47 $\pm$ 2.20	1.04 $\pm$ 0.05	1.24 $\pm$ 0.06	1.19 $\pm$ 0.06
0.6	1.03 $\pm$ 0.05	9.08 $\pm$ 0.45	0.61 $\pm$ 0.03	1.47 $\pm$ 0.07	39.12 $\pm$ 1.92	46.3 $\pm$ 2.32	0.84 $\pm$ 0.13	0.50 $\pm$ 0.00	1.05 $\pm$ 0.04
0.9	1.63 $\pm$ 0.08	7.46 $\pm$ 0.37	0.30 $\pm$ 0.02	0.27 $\pm$ 0.01	40.07 $\pm$ 1.98	46.12 $\pm$ 2.30	1.45 $\pm$ 0.07	1.06 $\pm$ 0.05	1.65 $\pm$ 0.08
1.2	1.01 $\pm$ 0.04	9.61 $\pm$ 0.47	0.47 $\pm$ 0.02	1.04 $\pm$ 0.05	39.33 $\pm$ 1.94	45.87 $\pm$ 2.28	0.25 $\pm$ 0.01	0.95 $\pm$ 0.04	1.48 $\pm$ 0.06
1.5	0.71 $\pm$ 0.04	9.07 $\pm$ 0.45	0.57 $\pm$ 0.03	0.28 $\pm$ 0.01	39.83 $\pm$ 1.99	46.78 $\pm$ 2.34	1.42 $\pm$ 0.02	1.05 $\pm$ 0.05	0.29 $\pm$ 0.01

* Mean $\pm$ SD ($n = 3$); Statistical test: ANOVA and multiple comparison of means using Duncan's multiple range test; Constant condition: Microwave power of 300 W, reaction time of 3 min, catalyst concentration of 0.9%, and methanol/oil mole ratio of 9.

length and saturation degree. Thus, strong similarities existed between the percentages of fatty acids in the FAME produced under different MAT conditions.

3.2.2. Physical properties

Table 3 shows variations in the physical properties of SCKO FAME with respect to different MAT variables. The kinematic viscosity of SCKO was measured as 28.16 mm²/s in this study. The kinematic viscosity of the final FAME should be 1.9-6.0 centistokes (mm²/s), according to the ASTM 6751 (American Standard) and should be 3.5-5.0 centistokes (mm²/s),

according to the EN 14214 (European standard) (Kantikar *et al.*, 2011). As can be seen, there were significant differences among the viscosities of FAME produced at different microwave reaction times. Samples exposed to 1- and 2-min reaction times were more than 6.0 mm²/s and were outside the aforementioned limits. In contrast, other reaction times were within the permissible range of the defined standards. The best result (i.e. the lowest kinematic viscosity of 3.78 mm²/s) was obtained after 4 min of reaction time. By increasing the reaction time and increasing the purity of the produced FAME (i.e. decreasing the molecular weight), the process of kinematic viscosity changes declined and reached the lowest value after 4 min, but

with a further increase in the reaction time and due to the purity reduction and an increase in the molecular weight, the kinematic viscosity increased. There was a negative correlation between kinematic viscosity and final efficiency (kinematic viscosity = $(-0.069 \times \text{final efficiency}) + 9.11$, $R^2 = 0.93$ for reaction time; kinematic viscosity = $(-0.086 \times \text{final efficiency}) + 9.90$, $R^2 = 0.90$ for microwave power; kinematic viscosity = $(-0.11 \times \text{final efficiency}) + 11.72$, $R^2 = 0.91$ for mole ratio; kinematic viscosity = $(-0.43 \times \text{final efficiency}) + 30.30$, $R^2 = 0.98$ for catalyst concentration).

The density of SCKO was 869.6 kg/m^3 and increased after transesterification (Table 3). According to the EN standard, the density of FAME at 15°C should be in the range of $860\text{--}900 \text{ kg/m}^3$. All FAME were within the permitted range of the EN

standard. The unsaturation degree had no significant effect on the transesterification reaction of the produced FAME. However, due to the conversion of primary triglycerides to FAME, the molecular weight of the final product decreased, whereas the density increased compared to the primary SCKO. There was a significant positive correlation between the density and the final efficiency (density = $(0.59 \times \text{final efficiency}) + 853.16$, $R^2 = 0.91$ for reaction time; density = $(0.62 \times \text{final efficiency}) + 849.66$, $R^2 = 0.90$ for microwave power; density = $(0.68 \times \text{final efficiency}) + 844.67$, $R^2 = 0.94$ for mole ratio; density = $(0.22 \times \text{final efficiency}) + 870.82$, $R^2 = 0.98$ for catalyst concentration). Therefore, the highest density of 900.01 kg/m^3 was obtained after 4 min microwave power of 300

TABLE 3. Effects of microwave-assisted transesterification on physical properties of sour cherry kernel oil fatty acid methyl esters.

Transesterification variable	Viscosity (mm ² /s)	Refractive index	Density (kg/m ³)	Color attribute		
				L*	a*	b*
Time (min)						
1	6.43±0.32 ^a	1.487±0.073 ^a	878.43±43.92 ^c	82.00±4.36 ^b	-4.00±1.00 ^b	48.67±0.58 ^a
2	6.05±0.30 ^b	1.486±0.073 ^a	880.28±44.01 ^c	81.33±3.06 ^b	-5.00±1.00 ^c	48.00±1.00 ^a
3	4.37±0.22 ^c	1.461±0.073 ^b	884.13±44.21 ^b	82.00±3.00 ^b	-3.00±1.00 ^b	46.00±1.00 ^b
4	3.78±0.19 ^c	1.468±0.073 ^b	900.01±45.00 ^a	89.67±1.53 ^a	-3.67±0.58 ^b	34.67±2.52 ^c
5	3.97±0.20 ^d	1.459±0.073 ^b	899.68±44.98 ^a	88.67±8.02 ^a	-2.33±1.53 ^a	46.33±1.15 ^b
Power (W)						
100	6.20±0.30 ^a	1.486±0.073 ^a	880.16±44.00 ^c	84.33±3.51 ^b	-2.33±0.58 ^b	44.67±1.53 ^a
200	4.10±0.20 ^c	1.471±0.073 ^c	885.93±44.29 ^c	83.33±7.37 ^b	-2.00±0.00 ^b	43.33±3.79 ^a
300	4.00±0.20 ^c	1.469±0.073 ^c	889.70±44.98 ^a	90.67±4.51 ^a	-1.67±0.57 ^a	34.67±6.35 ^d
400	4.00±0.20 ^c	1.460±0.073 ^d	887.19±44.35 ^b	87.67±10.02 ^a	-2.33±0.58 ^b	37.33±11.02 ^c
500	5.10±0.30 ^b	1.472±0.073 ^b	883.47±44.17 ^d	87.67±4.93 ^a	-2.67±1.53 ^c	38.33±3.51 ^b
Mole ratio (Methanol/oil)						
3	5.70±0.28 ^a	1.483±0.073 ^a	882.07±44.10 ^d	87.00±07.94 ^a	-3.00±1.00 ^b	48.67±0.58 ^a
6	5.70±0.28 ^a	1.483±0.073 ^a	882.11±44.10 ^d	87.67±4.93 ^a	-2.33±0.58 ^a	48.00±1.00 ^a
9	4.10±0.20 ^b	1.471±0.073 ^b	886.19±44.30 ^c	89.00±1.00 ^a	-2.00±0.00 ^a	46.00±1.00 ^b
12	3.80±0.19 ^d	1.469±0.073 ^c	899.98±44.99 ^a	90.33±2.08 ^a	-1.67±0.58 ^a	42.00±4.00 ^c
15	4.00±0.20 ^c	1.460±0.073 ^c	887.12±44.35 ^b	85.67±3.06 ^a	-3.00±1.00 ^b	46.33±1.15 ^b
Catalyst concentration (%)						
0.3	26.40±1.32 ^a	1.486±0.074 ^a	872.90±43.64 ^d	87.33±2.08 ^a	-3.33±0.58 ^d	37.67±3.06 ^b
0.6	26.10±1.30 ^a	1.481±0.074 ^a	873.45±43.67 ^d	82.00±1.00 ^b	-2.67±0.58 ^c	35.33±5.13 ^c
0.9	6.01±0.30 ^b	1.473±0.073 ^b	881.98±44.09 ^c	88.67±2.52 ^a	-2.67±0.58 ^c	40.00±3.00 ^a
1.2	4.46±0.22 ^c	1.462±0.073 ^c	883.99±44.19 ^b	89.67±3.51 ^a	-2.00±1.00 ^b	35.33±7.77 ^c
1.5	4.05±0.20 ^d	1.460±0.073 ^d	886.24±44.31 ^a	90.00±3.00 ^a	-1.33±0.58 ^a	35.00±3.61 ^c

* Mean $\pm$ SD ($n = 3$); Statistical test: ANOVA and multiple comparison of means using Duncan's multiple range test; In each column and for each variable, means with different lowercase letters are significantly different ($P < 0.05$); Each factor was optimized by considering an intermediate value (center point) of other factors (microwave power of 300 W, methanol/oil mole ratio of 9, catalyst concentration of 0.9%, and reaction time of 3 min).

W, which is consistent with the results of Talebi-an-Kiakalaieh *et al.* (2013) regarding the FAME density of several types of vegetable oils.

The refractive index of SCKO was 1.479 and decreased after transesterification (Table 3). The lowest refractive index (1.460) was acquired and a strong negative correlation existed between the refractive index and the final efficiency (refractive index = $(-0.0002 \times \text{final efficiency}) + 1.4725$, $R^2 = 0.90$ for reaction time; refractive index = $(-0.0002 \times \text{final efficiency}) + 1.4774$, $R^2 = 0.90$ for microwave power; refractive index = $(-0.0002 \times \text{final efficiency}) + 1.14$, $R^2 = 0.90$ for mole ratio; refractive index = $(-0.0002 \times \text{final efficiency}) + 1.47$, $R^2 = 0.94$ for catalyst concentration). The obtained results are consistent with the research of Azcan and Yilmaz (2013) They reported the refractive index of waste frying oil to be 1.4710 and the resulting FAME to be 1.4575.

The highest purity and efficiency of FAME production were reflected in L^* (89.67), a^* (-3.67), and b^* (34.67) values (Table 3). Initially, increasing the microwave power decreased the a^* value (an increase in greenness or a decrease in redness) and b^* values (a decrease in yellowness), but after the optimal point, both a^* and b^* values increased.

3.3. Comparison of different transesterification methods

By comparing the mixture of FAME produced by the MSAT, MAT, OAT, UPAT, and UBAT methods, the MAT method showed the highest weight efficiency, purity, and final efficiency, compared to the other transesterification methods. Then, OAT, UPAT, and UBAT showed the highest weight efficiency, purity, and final efficiency, respectively. Weight efficiency, purity, and final efficiency of the MSAT method were the lowest in comparison with other transesterification methods.

3.3.1. Weight efficiency, purity, final efficiency, and fatty acid composition

The highest weight efficiency, purity, and final efficiency of FAME production from SCKO were 99.03, 82.21, and 81.41, respectively, using MAT at an operating power of 300 W, methanol/oil mole ratio of 12, catalyst concentration of 1.2%, and reaction time of 4 min (Figure 2a).

The purities of FAME produced by different transesterification methods are shown in Figure 2b. It can

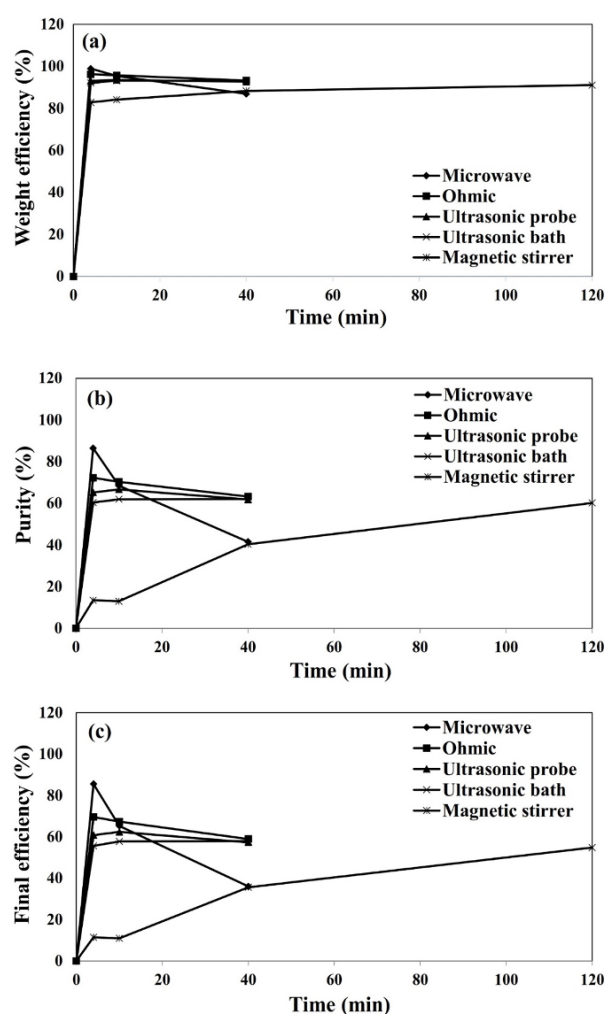


FIGURE 2. Effects of different transesterification methods on (a) weight efficiency, (b) purity, and (c) final efficiency of sour cherry kernel oil fatty acid methyl esters; Mean $\pm$ SD ($n = 3$); Statistical test: ANOVA and multiple comparison of means using Duncan's multiple range test; ($P < 0.05$); Constant condition: methanol/oil mole ratio of 12 and catalyst concentration of 1.2%; microwave power of 300 W, ohmic voltage of 200 V, salt concentration of 0.25%, and ultrasonic probe power of 150 W.

be clearly seen that the highest purity was obtained after 4, 10, 40, and 120 min of MAT (86.47%), OAT (70.30%), UBAT (57.72%), and MSAT (60.16%) methods, respectively.

Figure 2c compares the efficiency of different transesterification methods. The process of changes in the efficiency correlated significantly with changes in purity. The highest efficiencies of different transesterification methods were 85.52% after 4 min MAT, 69.60% after 4 min OAT, 62.38% after 10 min UPAT, 57.88% after 40 min UBAT, and 54.79% after 120 min MSAT. The highest efficiency in the MSAT method was obtained after 120 min (54.79%), but

TABLE 4. Fatty acid methyl ester composition (%) of sour cherry kernel oil produced by different transesterification methods.

Method	Reaction	Fatty acid								
	time (min)	Myristic acid	Palmitic acid	Palmito- leic acid	Stearic acid	Oleic acid	Linoleic acid	α -Linolenic acid	Eleostearic acid	Arachidic acid
Microwave										
	4	0.66±0.67*	10.45±3.92	0.85±0.81	0.75±0.76	39.92±3.13	44.73±6.41	1.48±1.62	0.75±0.21	0.40±0.22
	10	0.63±0.03	9.56±0.48	0.57±0.03	0.07±0.00	41.02±2.05	46.01±2.30	1.12±0.06	0.76±0.04	0.26±0.01
	40	2.10±0.11	9.21±0.46	2.70±0.13	0.74±0.03	39.92±1.99	43.05±2.12	1.11±0.05	0.30±0.02	0.87±0.04
Ohmic										
	4	0.99±0.04	7.27±0.31	0.39±0.08	2.06±0.09	39.00±1.89	49.06±2.43	0.73±0.12	0.13±0.03	0.35±0.03
	10	1.51±0.57	7.35±0.42	0.44±0.06	2.07±0.12	38.74±2.17	46.79±2.19	0.87±0.12	0.81±1.05	1.42±1.18
	40	1.60±0.66	7.64±0.52	0.42±0.06	2.02±0.39	38.76±2.07	46.77±2.21	0.86±0.20	0.88±1.21	1.05±1.10
Ultrasonic probe										
	4	1.96±0.10	7.66±0.38	0.51±0.03	2.04±0.10	37.77±1.89	46.42±2.32	0.82±0.04	0.13±0.01	2.70±0.13
	10	1.44±0.07	6.94±0.35	0.42±0.02	1.98±0.10	37.69±1.88	46.36±2.32	0.93±0.05	1.86±0.09	2.37±0.12
	40	2.82±0.14	8.48±0.37	0.45±0.02	2.28±0.11	37.34±1.87	44.36±2.21	1.19±0.06	3.06±0.15	1.02±0.00
Ultrasonic bath										
	4	1.34±0.07	8.07±0.40	0.45±0.02	1.26±0.06	39.16±1.96	48.68±2.43	0.55±0.03	0.12±0.01	0.38±0.02
	10	1.01±0.05	8.06±0.40	0.34±0.02	2.36±0.12	40.05±2.00	46.85±2.34	0.84±0.04	0.03±0.00	0.46±0.02
	40	1.01±0.05	8.05±0.40	0.34±0.02	2.35±0.12	40.00±2.00	46.79±2.34	0.97±0.05	0.03±0.00	0.46±0.02
Magnetic stirrer										
	4	0.60±0.36	8.50±0.41	0.23±0.01	1.51±0.67	41.51±2.12	45.16±2.40	0.68±0.26	0.92±0.92	0.89±0.40
	10	1.19±0.05	9.31±0.47	0.88±0.04	1.58±0.07	38.56±1.93	45.70±2.29	0.63±0.03	1.05±0.05	1.09±0.05
	40	0.37±0.02	9.52±0.48	0.21±0.01	0.48±0.02	39.14±1.96	48.35±2.42	0.97±0.05	0.67±0.03	0.30±0.01
	120	1.20±0.06	7.21±0.36	0.07±0.00	2.09±0.10	39.39±1.97	48.78±2.44	0.75±0.04	0.25±0.01	0.35±0.02
	140	0.42±0.02	9.80±0.49	0.40±0.02	0.53±0.03	39.79±1.99	47.66±2.37	0.65±0.03	0.49±0.02	0.25±0.01

* Mean $\pm$ SD (n = 3); Statistical test: ANOVA and multiple comparison of means using Duncan's multiple range test; Constant condition: Microwave power of 300 W, methanol/oil mole ratio of 12, catalyst concentration of 1.2%, ohmic voltage of 200 V, salt concentration of 0.25%, and ultrasonic probe power of 150 W.

prolonging the duration further than 120 min caused a decrease in both purity and efficiency.

Table 4 shows variations in the fatty acid composition of SCKO FAME with respect to MAT, OAT, UPAT, UBAT, and MSAT methods. As can be seen, the FA composition of samples produced with different transesterification methods were similar. The transesterification method had no selective effect on the FA in terms of chain length or degree of saturation.

3.3.2. Physicochemical properties

Viscosity. Table 5 shows variations in the physicochemical properties of the produced FAME with respect to different transesterification methods. Except for the samples produced with the MSAT method, the properties of other transesterification methods were within the permissible limits of ASTM and

EN standards. Since the highest purity and weight efficiency of triglycerides to lower molecular weight FAME were observed in the MAT method, the lowest kinematic viscosity was also obtained in this method. Among other transesterification methods, OAT, UPAT, and UBAT showed lower kinematic viscosity values than that of the MSAT method.

Density. The density is influenced by the weight efficiency of triglycerides to FAME and increases by increasing the purity and decreasing the molecular weight. The MAT method showed the highest density (Table 5). There were no significant differences among the density of FAME produced by OAT, UPAT, and UBAT methods in their optimal conditions. The lowest density occurred as a result of the MSAT method. In addition, the densities of FAME that were produced using all transesterifica-

TABLE 5. Effects of different transesterification methods on physical properties of sour cherry kernel oil fatty acid methyl esters.

Method	Time (min)	Density (kg/m ³)	Viscosity (mm ² /s)	Refractive index	Color attribute		
					L*	a*	b*
Microwave	4	899.90±45.00 ^{a*}	3.74±0.19 ^b	1.457±0.073 ^b	87.00±6.56 ^a	2.00±0.00 ^a	37.00±6.56 ^b
	10	887.49±44.37 ^a	4.02±0.20 ^a	1.460±0.073 ^b	86.33±3.79 ^a	3.33±1.15 ^b	39.67±1.53 ^a
	40	874.53±43.73 ^a	4.03±0.20 ^a	1.468±0.073 ^a	83.67±2.08 ^a	3.33±1.15 ^b	42.33±3.79 ^a
Ohmic	4	892.99±37.12 ^a	4.08±0.30 ^a	1.460±0.060 ^a	86.67±6.66 ^b	3.33±0.58 ^a	35.00±2.65 ^a
	10	889.15±44.46 ^a	4.03±0.20 ^a	1.460±0.073 ^a	89.00±2.00 ^a	3.33±0.58 ^a	34.00±3.00 ^a
	40	883.97±44.20 ^b	4.65±0.23 ^a	1.462±0.073 ^a	87.00±2.00 ^a	4.00±1.00 ^a	32.67±4.04 ^b
Ultrasonic probe	4	884.02±36.09 ^a	4.44±0.25 ^a	1.461±0.060 ^a	89.33±3.06 ^a	3.00±0.00 ^a	34.67±1.53 ^a
	10	884.16±44.21 ^a	4.34±0.22 ^a	1.461±0.073 ^a	91.00±2.00 ^a	3.33±0.58 ^a	33.33±0.58 ^a
	40	883.75±44.19 ^a	4.83±0.24 ^a	1.462±0.073 ^a	88.00±1.73 ^a	3.67±0.58 ^a	35.00±0.00 ^a
Ultrasonic bath	4	883.09±36.06 ^a	4.43±0.46 ^a	1.463±0.060 ^a	84.00±6.08 ^a	2.00±1.73 ^a	41.67±3.21 ^a
	10	883.92±44.20 ^a	4.78±0.24 ^a	1.462±0.073 ^a	86.33±6.11 ^a	3.33±1.15 ^b	40.33±5.69 ^a
	40	883.91±44.20 ^a	4.73±0.24 ^a	1.462±0.073 ^a	88.33±3.06 ^a	2.67±0.58 ^a	39.67±2.31 ^a
Magnetic stirrer	4	871.16±35.59 ^b	23.90±7.76 ^a	1.474±0.060 ^a	89.67±6.66 ^a	-3.33±0.58 ^c	35.00±2.65 ^a
	10	871.12±43.56 ^b	26.37±1.32 ^b	1.473±0.074 ^a	89.00±2.00 ^a	-3.33±0.58 ^c	34.00±3.00 ^a
	40	875.11±43.76 ^a	6.51±0.33 ^c	1.468±0.073 ^b	87.00±2.00 ^a	-4.00±1.00 ^b	32.67±4.04 ^b
	120	882.15±44.11 ^a	5.59±0.28 ^d	1.468±0.073 ^b	86.67±2.52 ^a	-5.00±1.00 ^a	31.00±2.65 ^b
	140	878.45±43.92 ^a	6.40±0.32 ^d	1.467±0.073 ^b	91.67±1.15 ^a	-3.00±1.00 ^c	35.67±2.08 ^a

* Mean ± SD ($n = 3$); Statistical test: ANOVA and multiple comparison of means using Duncan's multiple range test; In each column and for each method, means with different lowercase letters are significantly different ($P < 0.05$). Constant condition: methanol/oil mole ratio of 12 and catalyst concentration of 1.2%; microwave power of 300 W, ohmic voltage of 200 V, salt concentration of 0.25%, and ultrasonic probe power of 150 W.

tion methods were within the allowed range of the EN standard.

Refractive index. Although no significant differences were observed among the FAME produced by different transesterification methods, the refractive index of the samples decreased by increasing the FAME production from triglycerides (weight efficiency), which resulted from the direct relationship between the refractive index and the length of the carbon chain. The lowest amount of FAME production and the highest refractive index were observed in samples produced by the MSAT method, whereas the highest FAME production and the lowest refractive index were observed in samples produced by the MAT method.

Color attributes. The color characteristics of FAME obtained by different transesterification

methods are listed in Table 5. Accordingly, FAME obtained from the MAT method were more visually transparent than the other transesterification methods. FAME produced by MAT had the lowest a^* and b^* values.

3.3.3. Thermal properties

Table 6 shows variations in thermal properties of the produced FAME with respect to different transesterification methods. There were no significant differences among different transesterification methods in terms of ignition and fire points (combustion points), but they differed from each other in terms of the drop and cloud points. The lower pour point of FAME produced by MAT, compared to other transesterification methods, indicates that they remained liquid at a lower tempera-

TABLE 6. Effects of different transesterification methods on heating properties of sour cherry kernel oil fatty acid methyl esters.

Heating property (°C)	Transesterification method				
	Microwave	Ohmic	Ultrasonic probe	Ultrasonic bath	Magnetic stirrer
Flash point	177.00±8.85 ^{a*}	185.00±9.25 ^a	175.00±8.75 ^a	177.00±8.85 ^a	170.00±8.50 ^a
Fire point	197.00±9.85 ^a	190.00±9.50 ^a	185.00±9.25 ^a	187.00±9.35 ^a	184.00±9.20 ^a
Cloud point	-7.00±0.35 ^a	0.00±0.00 ^d	-3.00±0.15 ^b	-2.00±0.10 ^c	0.00±0.00 ^d
Pour point	-19.00±0.95 ^a	-17.00±0.85 ^b	-15.00±0.75 ^c	-13.00±0.65 ^d	-13.00±0.65 ^d

* Mean ± SD ($n = 3$); Statistical test: ANOVA and multiple comparison of means using Duncan's multiple range test; In each row, means with different lowercase letters are significantly different ($P < 0.05$). Constant condition: methanol/oil mole ratio of 12, catalyst concentration of 1.2%, and reaction time of 4 min; microwave power of 300 W, ohmic voltage of 200 V, salt concentration of 0.25%, and ultrasonic probe power of 150 W.

ture and were pumped more easily. After MAT, FAME produced by OAT and UPAT had the lowest drop points, respectively. There were no significant differences between the drop points in the UBAT and MSAT methods. Our results are consistent with previous findings on the transesterification of soybean oil using MSAT and MAT methods. The pour point of the MAT method was -18 °C, whereas the pour point of the MSAT method was -9 °C (Kanitkar *et al.*, 2011). The lower pour point in MAT can be justified by the complete progress of the transesterification reaction as well as a kinematic viscosity reduction of the produced FAME, compared to the MSAT method. Regarding the cloud point, the optimal conditions for producing FAME by the MAT, UPAT, and UBAT methods showed the lowest crystal formation, temperature and a cloudy state, respectively. The cloud points of the produced FAME are consistent with previous results by Supalakpaniya *et al.*, which

involved measuring the cloud point of the FAME produced by MAT from crude palm oil and resulted in a cloud point at -8 °C (Supalakpanya *et al.*, 2010).

3.3.4. Energy consumption

Table 7 shows the equivalent of energy consumption in different biodiesel production methods. The highest and the lowest energy consumptions of the reaction steps were related to the MSAT (227 Wh) and MAT (20 Wh) methods, respectively. The energy consumption of the purification steps of MAT, MST, OAT, UPAT, and UBAT methods were almost equal. According to Table 7, the lowest amount of relative energy consumption was attributed to the MAT method, followed by UPAT, OAT, UBAT, and MSAT methods, respectively.

Also, the OAT method reduced the reaction time to some extent due to the homogeneous energy

TABLE 7. Effects of different transesterification methods on energy consumption of sour cherry kernel oil fatty acid methyl esters.

Energy Consumption	Transesterification method				
	Microwave	Magnetic Stirrer	Ohmic	Ultrasonic probe	Ultrasonic bath
Optimal time (min)	4	120	4	10	40
Transesterification reaction (Wh)	20	227	53	25	100
Separation of methanol (Wh)	63	63	63	63	63
Washing (Wh)	8	8	8	8	8
Drying (Wh)	71	71	71	71	71
Total (Wh)	162 ^{d*}	369 ^a	195 ^c	167 ^d	242 ^b
Relative energy consumption (Wh/g)	6.3 ^c	22.5 ^a	9.4 ^c	8.9 ^d	13.9 ^b
CO ₂ production (g)	129.6 ^d	295.2 ^a	156.2 ^c	133.6 ^d	193.6 ^b
Relative CO ₂ production	5.0 ^c	18.0 ^a	7.5 ^c	7.1 ^d	11.1 ^b

* Mean ± SD ($n = 3$); Statistical test: ANOVA and multiple comparison of means using Duncan's multiple range test; In each row, means with different lowercase letters are significantly different ($P < 0.05$). Constant condition: methanol/oil mole ratio of 12 and catalyst concentration of 1.2%; microwave power of 300 W, ohmic voltage of 200 V, salt concentration of 0.25%, and ultrasonic probe power of 150 W.

transfer. In the UPAT method, due to the direct effect of the waves on the reactants and its strong mixing effect, the reaction speed was high, and, as a result, the energy consumption was low (Motasemi and Ani, 2012). In addition, the MSAT method emitted the largest amount of CO₂ into the environment.

4. CONCLUSIONS

The main objective of this study was to investigate the effects of different variables on the transesterification of SCKO with microwaves. In turn, the effects changed the physical and chemical properties of the produced biodiesel and the best possible reaction conditions were determined. The optimal condition of MAT was a mole ratio of 12, 300 W power, KOH concentration of 1.2%, and a transesterification time of 4 min. Also, the FAME produced under optimal microwave conditions were compared to those produced by UPAT, OAT, UBAT, and MSAT methods. The weight efficiency, purity, and final efficiency of FAME produced by MAT were higher than those of other transesterification methods. In comparison with the various transesterification methods, using microwave heating for transesterification significantly reduced the reaction time, energy, and costs.

5. ACKNOWLEDGMENTS

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6. DECLARATION OF COMPETING INTEREST

The authors of this article declare that they have no financial, professional or personal conflicts of interest that could have inappropriately influenced this work.

7. REFERENCES

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