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Microwave Irradiation Aided Transesterification for Biodiesel Synthesis via Heterogeneous Catalysts

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Abstract:

This review paper has examined, though not exhaustively, the synthesis of biodiesel through the transesterification reaction of non-edible and waste oils utilizing chemically-based heterogeneous catalysts activated by microwave irradiation. The production of biodiesel from such feedstock oils can significantly enhance the commercialization of biodiesel, as it presents a cost-effective alternative to fresh edible oils, thereby lowering raw material expenses. Another potential reduction in costs may stem from employing heterogeneous catalysts alongside microwave heating, which utilizes less energy and necessitates a shorter transesterification reaction time, exhibiting improved reaction kinetics without compromising the overall yield of biodiesel, in contrast to traditional heating methods. The findings from the reviewed studies indicate that microwave heating may surpass conventional heating in all assessed parameters, despite the more controlled reaction conditions associated with the former. It has also been observed that the acceleration of the transesterification reaction via microwave heating cannot be directly compared to that achieved through conventional heating under otherwise identical conditions. Moreover, microwave-assisted heterogeneously catalyzed transesterification reactions are distinguished by the emergence of hot spots, superheating, and selective heating of particular species. These phenomena improve the efficiency of the heating process, resulting in a higher rate of transesterification while minimizing the generation of by-products. The efficacy of heterogeneous catalysts in facilitating transesterification reactions is remarkable, showcasing high reactivity, stability, and selectivity when integrated with microwave technology.

Keywords: Transesterification, free fatty acid, microwaves, heterogenous, impregnation.

1. Introduction

Biodiesel has emerged as a more appealing alternative to traditional fossil fuels, thanks to its environmental advantages, such as biodegradability and non-toxicity. However, the commercialization of biodiesel production through catalytic transesterification has faced several challenges that have hindered its effectiveness. These challenges include high operating costs, low production efficiency due to kinetic limitations, significant energy consumption, lengthy and complex processes for separating products from catalysts and the sustainability issues associated with raw materials. The feedstocks for biodiesel synthesis primarily consist of fresh edible oils, which include, but are not limited to, oils from barley, canola, coconut, copra, corn, cottonseed, groundnut, oat, palm, rapeseed, rice, safflower, soybean and wheat. To address these challenges, biodiesel has been produced using waste cooking oils, which are often discarded and can pose environmental issues if not properly managed. Additionally, non-edible oils, such as those from almond, babassu, jatropha curcas, palm, rice bran, sesame, salmon and tobacco seeds, have also been explored as alternative sources.

Transesterification, also known as alcoholysis, is a reversible reaction that removes glycerol from the triglycerides in the initial feedstock oil or fat, using a catalyst. This process produces fatty acid alkyl esters, commonly referred to as biodiesel, depending on the type of alcohol used (1-5). Fig.(1) illustrates a typical transesterification reaction that utilizes methanol (methanolysis) as the alcohol.

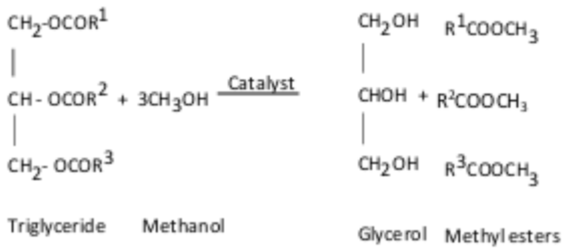

Fig. 1. A Transesterification Reaction, reproduced from (5).

For a catalytic transesterification reaction to occur, two key conditions must be met: first, a specific type of catalyst must be employed, unless the process utilizes supercritical heating, which is non-catalytic; second, the reaction temperature must be maintained according to the type of feedstock oil or fat and the catalyst used. Various catalysts have been utilized in transesterification reactions for biodiesel production, including enzymes (6), homogeneous (7) and heterogeneous catalysts(8-9). Generally, heterogeneous catalysts require extreme reaction conditions, with temperatures reaching up to 476 °C, catalyst amounts of up to 10 wt.% and alcohol-to-oil molar ratios ranging from 10:1 to 25:1 or even higher. These demanding conditions are necessary to compensate for low mass transfer rates caused by the small surface area of these catalysts, which limits their contact with the reactants. As a result, to achieve a desired biodiesel yield, the reaction time must be extended.

Furthermore, using heterogeneous catalysts for transesterification reactions can lead to several issues, including poisoning, sintering, coking and leaching, all of which can compromise the catalyst's reactivity. Additionally, the high cost and challenges associated with filtering out small catalyst particles from the produced biodiesel can limit the use of these catalysts in this process. However, heterogeneous catalysts are generally more tolerant of oils with high levels of free fatty acids and water, such as those found in waste feedstock oils, which helps prevent the formation of undesirable soap during biodiesel synthesis. On the other hand; nevertheless, the use of heterogeneous catalysts in biodiesel production can help prevent corrosion of the equipment involved. Also, these catalysts are known for their high reactivity, stability, selectivity and long lifespan, especially when designed with solid supports like alumina or silica. Additionally, they can be regenerated for future use with minimal or no loss in catalytic performance. Furthermore, employing heterogeneous catalysts can significantly reduce the costs and complexities associated with biodiesel purification (9).

Equally important is maintaining the specific temperature throughout the transesterification reaction to ensure its progress. The type of feedstock oil or fat, along with the catalyst used, influences the temperature required for the reaction. To achieve the necessary temperature, heat must be supplied to the transesterification mixture. This heating can be accomplished through conventional methods, supercritical techniques, or non-conventional approaches. Non-conventional methods include ultrasonic, plasma and microwave (dielectric) heating. This review focuses specifically on microwaves among the various heating methods. In conventional heating (wall heating), as previously noted, a specific type of catalyst is necessary, which typically requires a separation process unless it is heterogeneous. The temperature for the transesterification reaction ranges from 60 to 476 °C, and atmospheric pressure is adequate. Heat loss is a significant concern, as heat dissipates into the environment through conduction and convection while transferring through the reactor's walls and the reactants, respectively (10-11). One drawback of conventional heating is its tendency to produce uneven temperature distribution within the heated medium. Additionally, the efficiency of heating is significantly influenced by the properties of the medium, such as density, heat capacity and thermal conductivity. In contrast, supercritical heating does not require a catalyst, eliminating the need for catalyst removal. However, this method compensates for the absence of catalysts by operating under extreme conditions, with pressures reaching up to 60 bar and temperatures as high as 400 °C. These conditions can pose safety risks and entail substantial capital costs. Unlike supercritical heating, microwave heating still necessitates the use of a catalyst under specific pressure and temperature conditions, similar to conventional heating.

However, heat loss is minimal because the reactor's wall does not require heating, and the molecules throughout the entire liquid in the heated medium are exposed to microwaves, which create electric and magnetic fields that interact differently with the molecules being heated (11). This process is influenced by ionic conduction and a type of dipolar polarization, which can involve displacement, orientation or interfacial polarization. In microwave heating, approximately 65% of electrical energy can be converted into heat using microwave equipment (12). Furthermore, microwave heating offers several advantages over conventional and supercritical heating methods, including shorter reaction times (13), higher process efficiency and cleaner products (11,14-18).

In pursuit of these goals, microwaves have been employed in a variety of applications, including biodiesel synthesis, methane conversion, coal and biomass processing, desulfurization and carbon dioxide separation, as well as materials synthesis (12).

This paper aims to review research on biodiesel production from various non-edible and waste oils through transesterification using different heterogeneous catalysts under microwave irradiation. Additionally, the paper briefly discusses the use of conventional heating for comparison.

2. Microwave Irradiation Aided Transesterification for Biodiesel Synthesis via Heterogeneous Catalysts

Several basic and acidic heterogeneous catalysts have been developed using both chemical materials and, more recently, waste materials. This paper emphasizes the use of these heterogeneous catalysts for the transesterification of various non-edible and waste oils through microwave heating. Microwaves are a type of electromagnetic wave created when electric and magnetic fields interact perpendicularly. They occupy a position in the electromagnetic spectrum between radio waves and infrared waves. The wavelengths of microwaves range from 0.01 to 1 m, and their frequencies are quite broad, spanning from 0.300 to 300 GHz. However, the most commonly used frequencies in industrial applications fall between 0.915 and 2.450 GHz. Therefore, an effective heterogeneous catalyst should be able to absorb microwaves at these frequencies beyond its skin depth. In terms of frequency, wavelength and energy content, microwaves with higher frequencies have shorter wavelengths and greater energy content. Additionally, the way materials respond to microwave exposure differs from one material to another, depending on factors such as polarity, viscosity, density, temperature, concentration and molecular weight (12). To avoid digression, further information on the principles, theories and mechanisms of microwave heating, as well as the necessary equipment for microwave heating and microwave-assisted organic reactions, is left for the reader to explore in other sources (19-20).

To improve the biodiesel synthesis process, Kord, et al. studied the transesterification reaction of castor oil using microwave irradiation, with methanol as the alcohol and KOH as a heterogeneous catalyst. Both the alcohol and the catalyst components possess high dielectric properties, which significantly enhance microwave absorption. This method achieved a biodiesel yield of 92.15% in just two minutes (21). In a separate study, Yuan et al. also explored biodiesel production from castor oil under microwave irradiation, evaluating the effectiveness of two acid homogeneous catalysts and one heterogeneous base catalyst in facilitating the transesterification reaction with methanol. The acid homogeneous catalysts employed were $NaHSO_4 \cdot H_2O$ and $AlCl_3$, while the heterogeneous base catalyst used was Na_2CO_3. The necessary temperature for the transesterification reaction was achieved through both conventional and microwave heating methods. Among the various heating techniques and catalysts tested, the combination of microwave heating with the Na_2CO_3 catalyst resulted in the highest biodiesel yield, reaching 90%. Additionally, microwave heating proved to be more energy-efficient than conventional heating across all experiments conducted (22). In a separate study conducted by Zhang and colleagues, a biodiesel yield exceeding 96% was achieved in just 10 minutes through microwave-assisted transesterification of yellow horn oil. This process utilized 1 wt.% of heteropolyacid as a catalyst and methanol as the alcohol (23).

Employing the same alcohol, Hsiao et al. and Patil et al. studied the transesterification of soybean oil and camelina sativa oil using powders of CaO and BaO, CaO, MgO and SrO, respectively. Both studies conducted experiments using conventional heating and microwave heating. The results showed that under microwave heating, the biodiesel yields were 95% and 94% for the first and second studies, respectively (24-25). In the second study, BaO and SrO outperformed CaO and MgO in terms of yield. Additionally, the rate of the transesterification reaction under microwave heating was two orders of magnitude faster than that achieved with conventional heating (25). Also, research was conducted on microwave-assisted transesterification of pongamia pinnata seed oil to produce biodiesel. The process utilized methanol as the alcohol and two alkali heterogeneous catalysts, NaOH and KOH, for the transesterification reaction. A biodiesel yield of 96% was achieved with both catalysts after just 5 minutes of reaction time (26). Additionally, Kamath, H. V. and Saidutta, R. M. B. synthesized biodiesel from karanja oil using methanol and KOH as the catalyst, employing microwave heating for 150 seconds. However, this process required a pretreatment step involving an esterification reaction lasting for 190 seconds to lower the free fatty acid content of the oil to between 1.04% and 1.18%. This approach resulted in a satisfactory biodiesel yield of 90% (27).

Silitonga et al. synthesized biodiesel from ceiba pentandra oil using a microwave-assisted transesterification process. They employed methanol as the alcohol and KOH as the catalyst, continuously agitating the reactants to enhance the reaction rate and reduce the reaction time. This method allowed to achieve an average biodiesel yield of 95.42% in a short period, while maintaining energy efficiency and minimizing production costs (28). In another word, Lin, J. J. and Chen, W. C. utilized this alcohol and catalyst with agitation for the transesterification of jatropha seed oil, employing both conventional and microwave heating under mild conditions. The transesterification reaction rate achieved with microwave heating was significantly faster than that obtained using a conventional heating reactor (29). Pongamia pinnata oil, widely found in India, has been processed using both conventional and microwave heating methods to synthesize biodiesel, utilizing the same alcohol and catalyst as previously reported. Given the high levels of free fatty acids in the oil, a pretreatment step was essential to achieve biodiesel with a low acid value. The results indicated that microwave heating significantly enhanced the yield, reduced reaction time and shortened processing time compared to conventional heating methods (30). Also, in a study conducted by Choedkiatsakul and colleagues, a biodiesel yield of 99.40% was achieved in just 1.75 minutes during the transesterification of palm oil. This process utilized methanol and only 1 wt. % of NaOH as a heterogeneous catalyst under microwave conditions (31).

Using methanol as an alcohol and waste cooking oil, biodiesel was synthesized via several catalysts using microwave irradiation. Gupta, A.R. and Rathod, V.K. obtained biodiesel from a waste cooking oil in the presence of microwave irradiation and calcium diglyceride as a catalyst. The highest biodiesel yield reported is 94.86% obtained in 15 min (32). To enhance biodiesel yield from waste cooking oil, Chen and colleagues experimented with CH_3NaO and NaOH as catalysts, and again using methanol as the alcohol and a microwave heating system. Their findings indicated that increasing the reaction power up to 750 W led to higher biodiesel yields. However, higher power levels negatively affected the reactant molecules. When both catalysts were used at a concentration of 0.75 wt.%, CH_3NaO produced a greater biodiesel yield compared to NaOH. The reaction time was as short as 3 minutes (33).

In a separate study, Hsiao and colleagues compared the effectiveness of a traditional water-heating bath system with a microwave heating system for the transesterification of waste cooking oil. Methanol served as the alcohol, and a novel alkaline solid surface-modified CaO was used as the catalyst. The modified CaO demonstrated high thermal stability. The results showed that the microwave heating system significantly reduced the reaction time compared to the traditional water bath. Biodiesel conversion reached 98.20% with microwave irradiation, in contrast to just 53.66% with the water bath, even though the reaction time nearly doubled from 75 to 140 minutes. In both setups, the reaction temperature was maintained at 65 °C, the methanol-to-oil molar ratio was 8:1 and the concentration of CaO was 4 wt.% (34). In another study, Hsiao and colleagues conducted a similar experiment using a low-quality oil with a high acid value of 4.84 mg KOH/g to synthesize biodiesel through microwave heating. They utilized NaOH as a catalyst instead of CaO, achieving a reported biodiesel conversion rate of up to 98.20% (35).

Table (1) summarizes the details of many of the studies mentioned above, along with additional research on microwave-assisted transesterification of various non-edible and waste oil feedstocks using different chemical heterogeneous catalysts. For comparison, Table 2 presents details from some previously reviewed studies on the transesterification of various feedstocks using conventional heating methods.

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Table 1. A summary of some investigations on microwave- assisted transesterification of different non-edible and waste oil feedstocks.

Feedstock Oil	Catalyst	Transesterification Reaction Parameters				Biodiesel yield/conversion, %	Reference
		Reaction temperature, °C	Maximum reaction time, min	Maximum catalyst concentration	Methanol to oil molar ratio		
Yellow horn oil	Heteropolyacid	-	10	1 wt.%	12:1	Y= 96.22	23
Palm oil	NaOH	70	1.75	1 wt.%	12:1	Y= 99.40	31
Pongamia pinnata seeds oil	NaOH	60	5	0.5 wt.%	1:6	Y= 96	26
Pongamia pinnata seeds oil	KOH	60	5	1 wt.%	1:6	Y= 96	26
Jatropha oil	Potassium fluoride modified hydrotalcite	-	30	10 wt.%	2:10	Y= 97	36
Jatropha oil	KF- modified natural halloysite	-		Catalyst/oil:1/30	8:1	Y= 83.77	42
Jatropha curcas oil	20% KOH impregnated on CaO	-	68	3.17 wt.%	8.42:1	Y= 97.10	37
Soybean oil	Nano powder calcium oxide	60	60	3 wt.%	7:1	Y= 96.60	24
Soybean oil	Alumina/silica loaded with potassium sodium tartrate	65	45	8 wt.%	13:1	Y= 96.50	38
Soybean oil	KOH impregnated alumina	65	35	3 wt.%	12:1	Y= 97.30	39
Soybean oil	Amorphous SiO_2 loaded with 10 wt.% of silfonic groups	-	-	1 wt.%	1:10	-	41
Wet Microalgal Biomass	Ionic liquid	-	25	-	4:1	Y= 42.22	40
Camelina Sativa Oil	BaO	-	4	1.5 wt.%	9:1	Y= 94	25
Chlorella vulgaris lipid	SiC- NaOH/GO	85	5	4 wt.%	48:1	Y= 81	49
Canola oil	$ZnO/La_2O_2CO_3$	85	5	1 wt.%	12:1	Y> 95	50
Corn oil	Diphenylammonium salt	150	20	20 mol. %	5:2 g/g	Y= 100	44
Castor oil	55% H_2SO_4/C	58	2	1.44 wt.%	7.12:1	Y= 92.15	21
Castor oil	H_2SO_4 immobilised in SiO_2	60	30	10 wt.%	6:1	C= 90	45
Rapeseed oil	KSF montmorillonite	170	60	10 wt.%	9:1	Y= 51	46
Waste cooking oil	Heterogeneous base catalyst-calcium diglyceroxide 62	62	15	1.03 wt.%	7.46:1	Y= 94.86	32
Waste cotton seed and cooking oil	CaO	-	9.7	1.33 wt.%	9.6:1	Y= 89.94	43
Wate lard fat	35% CaO/zeolite	-	1.25	8 w/v	30:1	90.89	48
Free fatty acid stearic acid	Macroporous styrene chelate resin, with $NHCH_2PO_3H_2$ functional groups	80	420	9 wt.%	11:1	C= 90	47

Table 2. A summary of some investigations on transesterification of different oil feedstocks under conventional heating:

Catalyst	Transesterification Reaction Parameters				Biodiesel yield/conversion, %	Reference
	Reaction temperature, °C	Maximum reaction time, min	Maximum catalyst concentration	Methanol to oil molar ratio		
Sulfated zirconia	150	240	7.61 wt.%	9.88:1	Y= 90	51
KOH	65	120	1 wt.%	9:1	Y= 95	52
Sulfated zirconia and KOH	63.50	-	1.44 wt.%	7.47:1	Y= 84.51	53
Sulfonated poly(vinyl alcohol) and zirconium sulfate	65	120	4 wt.%	12:1	Y= 95.1	54
Tungstophosphoric acid impregnated on four different supports including hydrous zirconia, silica, alumina and activated carbon	200	-	3 wt.%	9:1	Y= 90	55
$AlCl_3$	100	1080	5 wt.%	24:1	C= 98	56
Zeolite	65	-	10 wt.%	16:1	Y= 84	57
Ion exchanger using natural zeolite	60	120	100 g KOH/ 100 ml	-	Y= 95.24	58

3. Performance of Microwave Irradiation Aided Transesterification for Biodiesel Synthesis via Heterogeneous Catalysts:

While satisfactory biodiesel yields have been achieved using various efficient chemical heterogeneous catalysts under conventional heating, as shown in Table (2), the conditions for the transesterification reaction had to be intensified in all the studies referenced. The reaction temperature was raised to 476 °C, and a significant catalyst amount of 10 wt.% was employed, along with high methanol-to-oil molar ratios, reaching up to 24:1, which requires substantial methanol consumption. Additionally, the duration of the transesterification reaction varied from two to eighteen hours. Unfortunately, these factors make the transesterification process using different chemical heterogeneous catalysts with conventional heating both energy-intensive and costly.

Based on the investigations mentioned earlier and shown in Table 1, it is evident that microwave heating offers advantages over conventional heating. Specifically, it results in a higher biodiesel yield and reduces the time needed for the transesterification reaction, while other reaction conditions are kept moderate. The required reaction temperature, catalyst amount and methanol-to-oil molar ratio are significantly lower than those used in conventional transesterification processes. Furthermore, as previously noted, heterogeneous catalysts are characterized by their high reactivity, stability and selectivity. These features can be enhanced by microwaves, leading to improved reaction rates, extended catalyst lifespans and greater production selectivity. The catalytic reactivity of a heterogeneous catalyst reflects the strength of the chemical bonds between its surface and the reactants involved in the reaction. This reactivity is influenced by the structure and composition of the catalyst's surface sites. Microwaves, combined with the polarity of the reactant molecules, facilitate faster molecular rotation, resulting in increased reaction rates. Additionally, one reason methanol is commonly used in transesterification reactions is its high polarity and greater dielectric constant compared to other alcohols, making it the quickest alcohol to heat enhancing its ability to absorb microwaves (60). Microwave irradiation can enhance the transesterification reaction, which, as previously noted, is influenced by ionic conduction and dipolar polarization (11). Additionally, it has been suggested that microwave heating can slow down catalyst deactivation caused by factors such as poisoning, sintering, coking and leaching, thereby extending the catalyst's lifespan. The effect of microwave heating on the selectivity of a heterogeneous catalyst can be attributed to the rapid heating rates and high temperatures that concentrate on specific areas of the catalyst's surface. This results in a non-uniform distribution of the electromagnetic field, particularly due to the presence of certain metals that are impregnated on the catalyst's surface. Consequently, this leads to increased product selectivity through the swift activation of reactants (12), while also minimizing the formation of by-products, which simplifies and shortens the downstream separation process (61-62).

In contrast to traditional heating methods, microwave heating is associated with phenomena such as the formation of hot spots, superheating and selective heating of specific species. These effects enhance the efficiency of the heating process and increase the rate of the transesterification reaction, leading to a higher yield of biodiesel in a shorter reaction time. This is due to the non-uniform distribution of electromagnetic field on the surface of the heterogeneous catalyst, hot spot zones form alignments, resulting in a temperature gradient ranging from 15 to 200 °C. The strength of the temperature gradient created is primarily influenced by the thermal conductivity of the catalyst employed. This results in localized high temperatures in that area, which enhances the formation of biodiesel by increasing the reaction rate. Additionally, because of the temperature gradient, the products generated on the active sites of the heterogeneous catalyst must migrate back to the bulk, where the temperature is consistently lower. Another study revealed that the intensity of the electric field is highest at the point of contact between two neighboring catalyst particles (63). The formation of hot-spot zones is enhanced when the heterogeneous catalyst used in the transesterification reaction contains metal(s) deposited on its surface. Additionally, the interaction between microwaves and the metal(s) generates local micro-plasmas and electrical arcs at the metal sites. This phenomenon positively influences the reaction by creating an additional temperature gradient within the catalyst, specifically between the catalyst body and the metal sites (64). Additionally, the geometry and morphology of heterogeneous catalyst particles, along with the presence of electrically conductive particles in their matrix, contribute to the development of hot-spot zones. Research indicated that a spiked heterogeneous catalyst demonstrated superior dielectric properties compared to a cubed one. It is clear that the inclusion of conductive particles in the matrix of a heterogeneous catalyst facilitates the formation of these hot-spot zones (65). Moreover, the minimal heat loss associated with microwave heating makes it an excellent method for heating. Additionally, the selective heating of specific species through microwaves can be attributed to the varying responses of metals present on the surface of the heterogeneous catalyst when exposed to microwave irradiation. These differing responses result in certain parts of the heterogeneous catalyst (the selective species) being heated more than others, which in turn enhances the reaction rate (12).

4. Comparison of Conventional and Microwave-Aided Transesterification Reactions of Various Feedstock Oils:

Microwave-aided transesterification reactions consistently yield higher conversions than traditional transesterification methods using the same feedstock oils while various catalysts. However, the yield values from both methods are relatively close. In contrast, when examining catalyst concentrations, methanol-to-oil molar ratios, reaction temperatures and reaction durations, significant differences emerge. Conventional heating methods typically require much higher values for these parameters compared to those used in microwave-assisted transesterification. Numerical values that support this argument are displayed in Table (3).

Table 3. Comparison of conventional and microwave-aided transesterification reactions of various feedstock oils:

Feedstock oil	Conventional Heating						Microwave Heating					
	Catalyst	Catalyst concentration, wt.%	Molar ratio	Reaction temperature, °C	Reaction time, min	Yield/conversion, %	Catalyst	Catalyst concentration, wt.%	Molar ratio	Reaction temperature, °C	Reaction time, min	Yield, %
Canola oil	AlCl	5	24:1	100	1080	C= 98	$ZnO/La_2O_2CO_3$	1	12:1	85	5	> 95
Jatropha curcas oil	Sulfated zirconia	7.61	9.88:1	150	240	Y= 90	KOH	3.17	8.42:1	-	68	97.1
Waste oil	zeolite	10	16:1	65	-	Y= 84	Calcium diglyceroxide	1.03	7.46:1	62	15	94.86

5. Conclusions

High energy consumption and, consequently, elevated operating costs have posed significant challenges to the commercialization of biodiesel production via catalytic transesterification using heterogeneous catalysts. However, these issues may be alleviated if the transesterification reaction is facilitated by microwaves. This approach can also reduce the time needed for product-catalyst separation, thanks to the advantageous properties of heterogeneous catalysts. Additionally, the cost of raw materials for biodiesel production can be lowered by using waste or non-edible oils instead of fresh edible oils. Research reviewed in this paper, indicates that the yield of biodiesel from waste and non-edible oils remains comparable to that derived from fresh edible oils. However, transesterification reactions catalyzed heterogeneously and heated through conventional methods face challenges such as the requirement for high temperatures, heat loss and uneven temperature distribution.

In heterogeneously-catalyzed transesterification reactions enhanced by microwaves, the reaction conditions are optimized, resulting in minimal heat loss and reduced reaction times while achieving high process efficiency. The shortened reaction time and increased efficiency can be attributed to the improved reaction kinetics associated with microwave heating compared to traditional heating methods. This enhancement arises from the effective combination of microwaves with the high reactivity, stability and selectivity of the heterogeneous catalyst. This synergy leads to faster movement of reacted molecules, reduced catalyst deactivation, and rapid heating rates that concentrate on specific sites on the catalyst's surface. Furthermore, the polarity and high dielectric constant of the alcohol used in the transesterification reaction may enhance the reaction kinetics. This could explain why all the studies examined have utilized methanol as the alcohol for their transesterification processes. Moreover, microwave-assisted heterogeneously-catalyzed transesterification reactions are characterized by the creation of hot spots, superheating and selective heating of species. These phenomena improve the efficiency of the heating process, thereby increasing the rate of the transesterification reaction while reducing the formation of by-products.

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