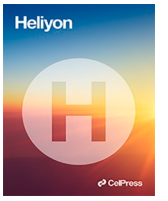
Heliyon 10 (2024) e24643

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon



Review article

A review on recent biodiesel intensification process through cavitation and microwave reactors: Yield, energy, and economic analysis

Yonas Desta Bizualem *, Amare Gashu Nurie

Department of Chemical Engineering, Kombolcha Institute of Technology, Wollo University, P.O. Box: 208, Kombolcha, Ethiopia

ARTICLE INFO

Keywords:
Biodiesel
Intensification
Cavitation
Microwave
Activation energy
Economy

ABSTRACT

The use of biodiesel as a reliable and green energy source has grown over the past few years. Biodiesel is sustainable and biodegradable because it is only made from vegetable contents and waste cooking oil. Although biodiesel has many advantages over conventional fuels, there are still a lot of technological issues that need to be addressed during the production process. The yield of biodiesel produced using conventional methods is poor and the process is time-consuming. Process enhancements like cavitation and microwave have thus been developed to address this problem. Starting with a comparison to the conventional biodiesel process, this paper has reviewed the most recent developments in the increase of mixture and transfer of heat in these two reactors. This paper examined biodiesel improvement using microwave and cavitation reactors, including biodiesel yield, by meticulously reviewing and analyzing previous works. The production of biodiesel from various raw materials using a range of catalysts, energy requirements, as well as operating factors, activation energy, and constraints also have been discussed. Additionally, the economic analysis discusses the feasibility and cost-effectiveness of implementing these technologies on a commercial scale. Overall, this review provides valuable insights into the intensification of biodiesel production using cavitation and microwave reactors while considering both the technical and economic aspects.

1. Introduction

1.1. Green energy and biomass

Green energy is described as the energy produced utilizing modern technology and renewable energy sources (such as biomass, wind, solar, and geothermal). Recently, a lot of nations decided that the primary goal of the UN Climate Summit in 2019 should be to achieve net-zero carbon dioxide emissions by 2050 [1]. Achieving the Sustainable Development Goals (SDGs) and guaranteeing a sustainable future for our planet depend heavily on green growth and the energy transition [2]. Significant environmental issues that need immediate attention include pollution, resource depletion, and climate change [3]. The International Energy Agency (IEA) reports that in 2019, energy-related carbon emissions reached a record-breaking 33.2 gigatons, adding to the mounting risk of climate change. Nonetheless, there is increasing awareness of the substantial positive effects that green development and the shift to a

* Corresponding author.
E-mail addresses: yonasdesta27@gmail.com (Y.D. Bizualem), amaregashu1000@gmail.com (A.G. Nurie).

https://doi.org/10.1016/j.heliyon.2024.e24643
Received 10 May 2023; Received in revised form 9 December 2023; Accepted 11 January 2024
Available online 20 January 2024

low-carbon economy may have on the environment, society, and economy [4].

According to an IEA assessment, by 2030, progressive climate efforts may generate 65 million new low-carbon employment and almost $26 trillion in economic benefits [5]. Because most nations rely on fossil fuels to satisfy their energy needs, green growth suffers, and environmental deterioration occurs [6]. The current state of the world economy demands a change to more environmentally friendly practices, and nations all over the world are working to achieve carbon neutrality by utilizing cutting-edge technology to support green recovery.

Green growth is a crucial metric for assessing a country's capacity to achieve long-term goals for sustainable development [6]. Innovation in green technologies can help solve environmental issues by promoting sustainable economic growth while improving environmental management [7–9]. According to Popp [10], industrialized nations have been able to attain higher environmental quality because of modern technology, which has greatly decreased pollution and enhanced environmental conditions [10]. According to Caglar et al. (2022b), using green energy can help the US lessen its environmental impact [11]. According to research by Umar et al. [12], biomass energy reduces emissions from transportation in the USA whereas fossil fuels tend to increase emissions. To manufacture biomass-based transport fuels including methanol, ethanol, bio-crude, biodiesel, and methane that can eventually replace fossil fuels, strategies need to be developed and profitable advantages should be provided [12].

Energy produced from biomass is a more sustainable and greener alternative to energy derived from fossil fuels [13,14]]. As a result of this finding, using biomass for the synthesis and manufacturing of biofuels has garnered a lot of attention lately [15]. A plentiful and sustainable source of carbon on earth is biomass [16]. Depending on the number of lipids or carbohydrates that have accumulated, biomass can be converted into biofuels such as biodiesel or bioethanol. Mineral diesel may be swapped for an alternative called biodiesel. It burns cleaner and releases less harmful substances. It is renewable [17]. The organic components found in flowers, grasses, stalks, and trees are referred to as biomass [18]. Agricultural crop residues, algae, forestry residues, and wood processing residues are the major biomass sources for the production of bio-energy [16].

While the fruits, grains, and fibers that are sold for direct consumption account for a portion of the total biomass produced by farmlands, agricultural waste such as sawdust, sugarcane bagasse, corncob, potato haulms, oil palm waste, wheat straw, sunflower residue, and rapeseed oil pressing makes up a larger portion of it. Fruit peelings, shells, seeds, and pits are examples of unconsumed food products that belong to different types of biomass. Large-scale use of biomass is highly possible as it is a carbon-neutral, sustainable, and renewable energy source. In addition, it is inexpensive, widely accessible, and biodegradable. Since the 1970s, interest in biomass as a fuel source has grown, and in the twenty-first century, this interest is intensifying. In terms of fuel economy and its applications, there have been several technical advancements and inventions. Since biomass is inexpensive, abundant, sustainable, and renewable, it is regarded as a possible alternative to fossil fuels. Since it can be transformed into ethanol for industrial use, it has a great deal of promise for use as a renewable energy source [18].

Biofuel is an environmentally beneficial energy source. Both the developed and developing nations are turning to biofuel to address the problem of power disruptions and they have also constructed the infrastructure for the production of the necessary equipment for their domestic use [19]. Conventional biofuels generated from food crops are now the most popular choice [20], although they are being phased out in the EU [16] because of concerns about land use change and other sustainability hazards [21]. These numerous biomass wastes can be utilized in the current traditional biofuel production techniques (such as spent cooking oil) [22]. However, there is currently no economically viable generation of advanced biofuels based on lignocellulosic biomass leftovers, despite their relatively great but unidentified potential [23].

> Scholars have elucidated that the adoption and use of sustainable energy sources, such as biodiesel, may almost eliminate pollution and find direct application in both household and commercial contexts [24]. The renewable nature of biodiesel and its environmental friendliness have made it a very popular green energy source among researchers worldwide [25]. All things considered, the transition to green energy and the encouragement of green growth are crucial to guaranteeing the planet's sustainability in the future. The world's overpopulation and booming economy have resulted in a need for non-renewable fossil fuels in many nations. The process of converting biomass into biofuels has received more attention and is viewed as an inventive way to achieve zero carbon emissions and minimize impacts on the environment.

As a review paper, there is no detailed yield, energy, and economic analysis that has been done yet on biodiesel intensification using cavitation and microwave reactors. Therefore, this review paper offers a summary and analysis of current developments in cavitation and microwave reactor-based biodiesel production techniques. It explains the basic concepts and mechanisms of these technologies as well as how they may improve the production of biodiesel. Furthermore, this work advances our knowledge of how cavitation and microwave reactors could intensify the production of biodiesel. In addition, it provides details on how to optimize process parameters, energy efficiency, and the financial sustainability of these technologies, opening up opportunities for further developments in the processing of biodiesel. In general, researchers, engineers, and business experts involved in the production of biodiesel will find this review to be an insightful tool. It provides a thorough analysis of current scientific developments in microwave reactors and cavitation for the production of biodiesel. Assessing the yield increase, energy efficiency, and financial viability of various intensification processes, advances our understanding and guides academics, industry experts, scientists, and business experts in the direction of more economical and environmentally friendly methods of producing biodiesel.

1.2. Biodiesel

Fossil fuels have accounted for about 88 % of the world's energy in recent years and have integrated into nearly every aspect of everyday life [26]. A good level of living and rapid technological advancement, particularly in the field of transportation, have both

been made possible by the use of fossil fuels [27]. Among all social areas today, transportation is devoted as the biggest energy user. The transportation industry accounted for 64.8 % of world oil usage in 2017, according to the International Energy Agency [28]. Most megacities around the world have experienced air pollution and climate change as a result of the indiscriminate use of fossil fuels. The non-renewability of fossil fuels will also be a major barrier to societies' healthy growth. Governments have been forced to create new energy sources due to the greater percentage of fossil fuel usage in the transportation sector and its detrimental environmental effects. As a result, using biofuels in cars can dramatically cut on how much conventional gasoline is used and how much pollution is released [29].

However, fossil fuels are non-renewable energy sources that are constantly linked to severe environmental problems like global warming [30]. People have started looking for alternative fuels because of the pollution that fossil fuels create and the fact that they are an infinite source of energy. Furthermore, renewable fuels are more in demand than ever in today's society due to the volatility of natural fuel prices. Despite the fact that fossil fuels like coal, natural gas, and other types of fuel are still used today, their dependence is gradually growing [31–33]. One of the main forms of green or alternative fossil fuels is biofuels. To address issues related to natural fuels, significant progress has been made in the production of biofuels in recent years. Without regard to their finish, the most significant qualities of biofuels are their renewability and friendliness [34]. One of the different renewable fuels that have drawn significant attention from industry and society is biodiesel [35].

One of the most suitable biofuels is biodiesel, which can serve as a viable substitute for common liquid fuels like diesel due to its high molecular similarity to petroleum diesel [36–38]. The primary benefits of biodiesel are that it is biodegradable [39], emits fewer greenhouse emissions than gasoline fuels [40], is non-toxic, and provides the same energy durability [41,42]. Typically, organic oils like sunflower, soybean, and canola oil are used to make biodiesel. However, the problems surrounding the food versus fuel issue make the ongoing production of biodiesel from edible oil unsustainable [43]. A fuel called biodiesel is made from long-chain monoalkyl esters of vegetable or animal lipids [44–46]. Biodiesel is usually produced chemically from waste or organic sources, such as food oils, animal fats, and even used frying oils, and is composed of long-chain fatty acid methyl esters [47–51]. Cleanliness and renewability are two benefits of biodiesel fuel, and it can be used in compressor combustion engines without significantly altering performance [52].

1.2.1. Sources for biodiesel production

Various feed sources for oil extraction have been investigated, including veggie, animal fat, and waste cooking oil. In addition to these oil resources, microbial and algal oils are gaining attention due to their high oil concentration and rapid biomass production [53].

Table 1
Different feedstocks oil quantity and composition.

Source Oil	Content of oil (wt %)	12:00	14:00	16:00	17:00	18:00	18:10	18:20	18:30	References
Canola oil (edible oil)	41–46.5	–	–	5.7	–	2.6	71.78	19.12	–	[57]
Corn oil	3.2–.6	–	–	10.87	–	2.1	28.80	54.77	2.26	[58]
Coconut oil	65–68	46–55	17–22	6–9	–	3–5	6–11	1–3.4	–	[59]
Olive oil	15.2–35.3	–	–	10–11	–	3–4	71–83	11–16	–	[59]
Palm oil	21–46	–	0.6–3	38–47	–	5–7	35–47	10–13	–	[59]
Peanut oil	44.-51	–	–	9–10	–	3–4	48–35	23–33	–	[59]
Rice bran oil	16–22	–	0.40	21.7	–	2.0	42.9	28.30	1.4	[60]
Soybean oil	19–21	–	–	8–12	–	3–6	19–31	51–62	6–10	[59]
Sunflower oil	36–51	–	–	4–7	–	3–7	16–38	28–71	4–6	[59]
Castor oil (non-edible)	46–51	–	–	1.0	–	2	4	5	–	[61]
Cotton seed oil	19–24	–	–	27–27	–	0.9–1.0	21.87–27.8	–	0.3	[59]
Jojoba oil	44–56	–	0.08	1.60	–	4.33	39.78	33.54	–	[62]
Jatropha oil	21–61	–	13.2–16.4	0–14	–	–	35.1–43.6	14.2–16.1	0–0.3	[59]
Karanja	22–51	–	–	3.8–8.1	–	2.5–9.6	42.8–69.7	11.8–17.4	–	[59]
Kusum oil	11–66	0.41	0.33	9.1	–	2.4	43	5.6	–	[63]
Linseed oil	34–46	–	–	5–9	–	2–6	26–42	36–42	24–58	[59]
Neem seed oil	21–31	–	–	13.2–16.3	–	–	48.4–63.3	–	–	[59]
Mahua oil	36–51	–	–	25.0	–	22.8	57.2	11.5	1.8	[64]
Moringa oil	32–43	–	0.09	6.20	–	5.33	68.8	0.61	0.15	[65]
Rapeseed oil	21	–	0.11	13.33	–	7.38	38.48	18.64	4.90	[66]
Rubber tree oil	41–61	–	2.3	11.00	–	8.1	23.7	40.0	15.7	[59]
Chicken fat (waste oil)	–	–	–	18.74	–	7.00	35.73	31.41	1.38	[67]
Tallow oil	–	–	4.2	24.0	–	13.60	46.50	1.78	1.0	[67]
Lard oil	–	–	1.4	24.4	–	12.0	42.0	14	–	[68]
Yellow grease	–	–	2.40	24.25	–	13.24	42.88	6.66	0.58	[69]
Brown grease	–	–	1.78	21.21	–	11.87	43.06	12.00	1.2	[69]
Botryococcus braunii oil	24–76	0.51	1.56	18.68	1.44	7.20	35.44	6.10	7.33	[70]
Chlorella sp.	29–33	–	–	45.3	5.72	1.07	2.00	26.1	13.31	[71]
Schizochytrium sp.	49–78	0.0–0.6	9–16	23–26	–	0.6–0.8	–	–	–	[72]

1.2.2. Edible and inedible plant oils

According to Bankovi-Ili et al. [53], dietary oils are used in almost 95 % of the methods used to produce biodiesel [53]. There have been reports of using different edible oils (such as sunflower, maize, palm, soybean, canola, rice cereal, and coconut oils) in the production of biodiesel [54] (Table 1). An estimate places feedstock costs at 70 % of the expense of biodiesel [55]. There have also been reports of the use of non-edible oils like cotton, castor, jatropha, rubber, neem, and tobacco in the synthesis of biodiesel. Vegetable oils are used depending on where they are readily available, such as canola in Europe and, Southeast Asia's palm oil, India's jatropha, the Philippines' coconut oil, Brazil's, and the United States' soybean are common [56]. Around 5000 kg of oil is produced from palm trees per acre, with canola (1000 kg, 20 wt%) and sunflower (375 kg, 37–50 %) following [53].

Jatropha oil is regarded as the prime basic material for synthesis of biodiesel because it can be grown in any environment and with minimal effort [56].

2. General overview of applications of microwaves

Many areas use microwaves, including the culinary, telecommunications, medicinal, and chemical sectors. Previous investigations have also shown the possibilities of applying microwaves in biological, hydrothermal depolymerization, or carbonization processes from a non-thermal perspective [73–77]. Magnetrons, with an efficiency of over 70 % and a power capacity of at least 1 kW, are used to generate the microwave [78]. Rapid electrical field direction change occurs 2450 million times per second for a household microwave with a frequency of 2450 MHz. A rapid oscillation of the substance's free ions and dipole molecules produces a tremendous quantity of thermal energy, which the substance absorbs. The energy emitted by a substance as a result of alterations to the electrical structure of molecules is represented by fast-moving fields known as electromagnetic waves or electromagnetic radiation [79,80].

Through a transesterification reaction, microwave heating has demonstrated potential applications in the manufacturing of biodiesel [81], pyrolysis-based syngas production [82–84], drying of food [85,86] production of plastic polymers, and reinforcing composite [87], extraction [88] as well as biogas production [89–91]. To accelerate any process's rate of heating more quickly than with conventional heating, microwave irradiation is utilized [92]. Heat is produced by microwaves through the movement of charged protons and electrons, which emit electromagnetic waves [93]. The interactions of the substance and the electric field have an impact on a microwave-heated reaction mixture. Without having to heat the entire reactor, the substance is penetrated by microwave radiation at the molecular level, which transmits accumulated energy into the molecules [94]. When compared to conventional heating, the usage of a microwave minimizes the amount of time needed. For the synthesis of biodiesel, Lin et al. [95] achieved time and energy savings of 10 and 13 times, respectively, when compared to normal/conventional heating [95]. As a result, it would be possible to achieve low by-product flow, quick residence time, high product conversion and return, and effective energy [89–91,96]. In addition to that, in comparison to conventional approaches, Patil [97] reported a 23 times reduction in energy use [97].

2.1. Microwave heating over conventional heating

To use microwave heating, it is essential to understand the dielectric characteristics of the materials that undergo microwave reactions [98]. When exposed to an external electric field, a substance's molecular properties measure its capacity to prevent electron movement and, as a result, produce internal polarizations. Any variations in the oil's dielectric constant could indicate that the oil has absorbed water, that the additive has oxidized or weakened, or that the oil's chemistry has changed [99,100]. The effectiveness of microwave heating in a reaction is greatly influenced by a solvent's or material's dielectric properties, which rely on frequency and temperature [95]. Dipolar and ion polarizations are the two primary mechanisms by which microwave irradiation produces heat. Dipole-dipole interactions occur between the polar compounds in the reaction mixture, whereas ionic polarisation affects the free ions in a sample. The sample's dipole molecules or ions are oriented in the applied electric field at microwave frequencies. Energy is dissipated as heat as a result of molecule friction and dielectric loss as the dipole or ion field attempts to reconnect with an electric field as an applied field oscillates [101].

Since localized heating occurs with microwave heating rather than conventional heating through conduction and convection, it uses considerably less energy. The internal reactor wall's conductivity and the temperature difference between it and the reaction mixture determine the conventional heating. Conduction heating is influenced by the material's characteristics, the temperature difference, the reactor's cross-section, and its thickness [102]. When the fluid close to the top of the wall is hot, convection heating begins. The molecules subsequently acquire energy from both internal energy and heat of the reaction. When a moving fluid is given energy, it expands, and its density falls, which makes it rise. This cycle repeats until the thermal equilibrium is achieved [103]. The summary of the comparison between microwave and conventional reactors in Biodiesel synthesis is presented in Table 2.

Table 2
Comparison between microwave and conventional reactors [102].

Features	Conventional	Microwave
Period of reaction	More prolonged processing periods	Very quick, immediate heating
Amount of solvent	Little solvent	No or little liquid/solvent
Quality of product	Vary	Better
Product output	Vary	Higher
Separation period	Very long time	Very little time

2.2. Esterification processes through microwave reactors

According to Bogdal [104], when methanol tries to realign under an electrical field that is continually changing, it cannot maintain phase with the applied field, which leads to collisions and the conversion of the absorbed energy into heat. In ionic conduction, heat is produced when moving ions collide, change direction, and slowdown in an oscillating electromagnetic field. The catalyst's ability to absorb heat allows oil esterification to proceed and significantly shortens the processing time [104]. When compared to conventional heating, the non-thermal action of microwaves led to reductions in the activation energy, an improvement in the pre-exponential factor, and a reduction in the Gibbs' free energy change [105,106]. Oil of free fatty acids is converted into their methyl ester during the esterification process. The mechanism of microwave heating is similar to that of conventional heating because it does not alter the bond at the molecular level but instead excites electrons. However, compared to conventional heating, localized superheating brought on by ionic conduction and dipole moments accelerates the reaction rate [96]. The esterification of oil with a high content of free fatty acids can be accomplished with the help of hetero poly acids (HPAs) or polyoxometalates as catalysts. In contrast to conventional acid catalysts, they exhibit homogenous acid sites and a high Brønsted acidity [107].

2.3. Intensification of biodiesel production on microwave reactors

At present, synthesis of biodiesel frequently uses microwave irradiation. Oil extraction from certain feedstock [108,109] and the transesterification process of oil into biodiesel are the two primary ways that microwave energy can facilitate the production of biodiesel. Dipole reorientation is the mechanism that generates thermal energy [110]. In this scenario, when polar molecules are subjected to microwave irradiations, atomic or electronic polarisation, or the movement of electrons around atoms or nuclei, occurs trillions of times per second. Because of the friction created by revolving molecules, heat is produced. The Maxwell-Wagner and conduction systems are the other two methods of microwave heating [110,111].

Researchers have been examining the microwave intensification application in the synthesis of biodiesel from various basic materials. Nayak et al. [112] carried out kinetic, thermal, and parametric analyses of Kusum oil microwave-assisted esterification. A statistical study of the effect of the methanol-to-oil molar ratio, temperature, catalyst quantity, and duration was performed to obtain an acceptable conversion of free fatty acid. According to the study findings, a 9:1 molecular ratio, 65 °C, 3.6 wt % catalysts, and a reaction period of 13 min resulted in 92 % conversion of free fatty acids. Using a pre-optimized 9:1 M ratio of methanol to oil and 3.6 wt percent of silicotungstic acid for varying times, the kinetic analysis was carried out [112]. Given that the activation energy is smaller and the pre-exponential component is higher, the kinetic investigation demonstrates that microwave heating is not thermal [112,113]. Due to the presence of the OH group, this offers polar properties as well as anchoring behavior, methanol functions best as an acyl acceptor for the synthesis of biodiesel using microwaves [114]. As a result, methanol molecules rotate more locally, which increases their capacity to superheat. In comparison to other alcohols, such as ethanol, this enables for more immediate reaction, higher

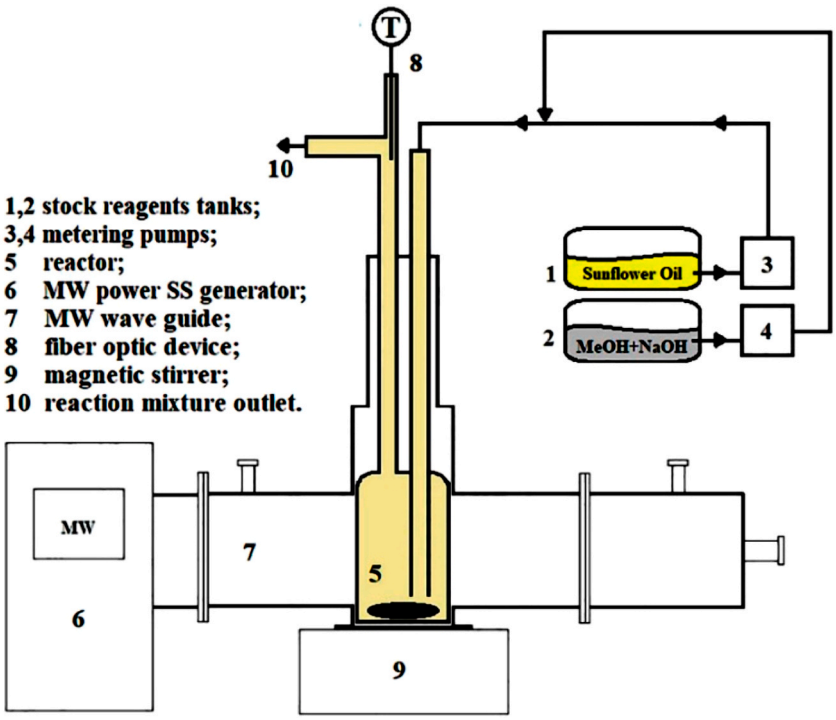


Fig. 1. Microwave mono-mode reactor schematic for the production of biodiesel [121].

performance, and reduced costs [115]. A comparison between the electrical energy requirements of the microwave generator and mixers used in the biodiesel production process and the power provided by the combustion of the biodiesel produced allowed us to determine if the system using microwaves was sustainable [116].

Scares et al. [117] *trans*-esterified soybean oil in a continuous flow microwave reactor at optimal conditions (1 wt% NaOH, 9:1 ethanol-to-oil molar ratio, 42.5 L/h flow rate, 56.4 °C, 33 s, 1000 W microwave power), obtaining an ethyl ester yield of 84 % [117]. The enzymatic microwave aid in the synthesis of biodiesel from waste cooking oil and dimethyl carbonate was also studied by Panadare and Rathod [118]. A yield of up to 94 % of biodiesel was produced after 4 h of reaction time [118]. A combination of *Calophyllum inophyllum* and waste cooking oil was effectively transesterified by Giuntoli [119] utilizing an Anton Paar Monowave 400 high-performance microwave reactor (0.77 wt percent KOH, 59.6 wt percent methanol-to-oil ratio, 100 °C, 600 rpm and 7.15 min) [119]. A high conversion yield of 99.5 % was also attained by Thirugnanasambandham and Sivakumar [120] by transesterifying cotton seed oil in the presence of an unknown quantity of KOH (17:1 ethanol-to-oil molar ratio, 380 rpm, 70 °C, 12 min, and 270 W microwave power) [120].

A continuous flow method for the process intensification of FAME synthesis employing microwave was examined by Chipurici et al. [121] (Fig. 1).

A Mini-flow, a mono-mode device, was employed by Bucciol et al. [122]. The reactants enter the reactor, are mixed there, and then come out of the reactor through the top outlet. To maintain a temperature of 40 °C, the heat input is automatically and continually controlled, while the flow rate alters the residence duration. According to the findings, the catalyst concentration has to be around 0.25 % for the microwave strengthening effect to be very significant. However, a stationary time of 180 s is required [122].

In a multimode-enhanced microwave System (EMS) with instantaneous cooling, Ergan et al. [123] investigated the production of biodiesel using canola oil and methanol in the presence of a dolomite catalyst under constant temperatures and steady, continuous microwave power conditions. The experiments were conducted in the EMS using the one variable at a time method to determine the ideal values of 5 experiment parameters: the methanol-to-oil molar ratio, the catalyst amount, the temperature, the reaction time, and the absorbed MW power. These parameters' optimal values were 9, 5 %, 65 °C, 120 min, and 48 W, respectively. After the EMS study, an experiment was run under optimal conditions in the conventional heating system (CHS). As a result, it was reported that EMS's (99.1 %) yield of biodiesel during the same time was 30.2 % higher than CHS's (76 %). Compared to the CHS, faster, better-quality, and more affordable biodiesel output was achieved. In EMS, a 58.2 % reduction in energy and production costs and a 30.4 % increase in output rate was achieved. Additionally, the active catalyst and various methyl ester concentrations benefited from the powerful vibratory effect of MW on dipoles and the specific and uniform heating effect on the local surface temperature of the catalyst [123]. Table 3 presents a comprehensive overview of the various flow types used aided by microwave reactors for the production of biodiesel.

To produce biodiesel, Yari et al. [128], used a microwave-assisted transesterification method. Calculations resulted in 48.839 MJ L^{-1} of total output energy and 50.866 MJ L^{-1} of total input energy. In the production of microwave-assisted biodiesel, the energy was determined to be 1.0415 MJ, meaning that 0.0178 kg of biodiesel could be produced for every MJ of energy utilized [128]. Table 4 provides a summary of the comparison between equivalent energy input and output during the production of biodiesel.

Rapeseed oil and oleic acid that contained 20 % free fatty acid (FFA) were microwave transesterified and esterified using the heterogeneous catalyst silicon carbide/sodium hydroxide oxide-graphene oxide (SiC/NaOH-GO), which was effectively designed and characterized by Loy et al. [137]. The reaction conditions were optimized using the Central Composite Design (CCD) coupled response surface methodology. The optimal conditions for the reaction were a 13:1 mass ratio of SiC/NaOH to GO, a catalyst input of 5 %, a reaction temperature of 65 °C, and a 6-min reaction time, which produced 96 % transesterification and 92 % esterification. Additionally, the researcher used the SiC/NaOH-GO bi-functional heterogeneous catalyst to synthesize biodiesel from microalgae lipids that had been microwave-intensified while central composite design (CCD) was used to optimize the reaction conditions. The study found that a methanol to lipid molecular ratio of 48, a reaction period of 5 min, a catalyst content of 4 wt percent, and a reaction temperature of 85 °C were the optimal conditions for generating fatty acid methyl ester content (FAME). In these conditions, 81 % of FAME and 92 % of the FFA in the algal lipid were converted [137]. The transesterification of refined sunflower oil by microwave-irradiated acid was optimized by Moina Athar et al. [138] using a central composite design coupled response surface technique. At the optimal reaction conditions of 76 °C reaction temperature, 30 min of reaction time, 0.09 wt% catalyst, and 9.0 methanol to oil molar ratio, an entire conversion occurred [138].

Table 5 provides a general summary of the above-discussed biodiesel intensification process using a microwave reactor and additional findings from the literature.

Table 3
Biodiesel production methods aided by microwave reactor.

System	Raw material	Catalyst Load	Methanol: Oil	Conversion	Ref.
Batch and flow	Vegetable oil	KOH 1.0 %	6:1	98.9	[124]
Flow	Palm oil	NaOH 1.0 %	12:1	99.4	[125]
Flow	Palm oil	NaOH 1.0 %	6:1	97.8	[126]
Flow	Palm oil	NaOH	9.1	99.8	[127]
Flow	Sunflower oil	KOH 1.0 %	6:1	96.5	[121]

Table 4
Equivalent energy input and output for the production of biodiesel.

Outputs and inputs	Energy equivalent (MJ per unit)	Ref.
Inputs (h)	1.89	[129]
Residual fish oil (kg)	38.6	[130]
Methanol (solvent) (kg)	23.0	[131]
KOH (catalyst) (kg)	18.21	[132]
Electricity (energy) (kWh)	3.8	[133]
Machine (hour)	63.0	[134]
Outputs (kg)	41.8	[135]
Methanol (solvent) (kg)	23.2	[131]
KOH) (catalyst) (kg)	18.3	[132]
Clean glucose (kg)	26.4	[136].

3. Simultaneous supercritical/subcritical microwave approach

Supercritical transesterification is catalytic-free, which simplifies the process and eliminates the need for pre-treatment or purification steps. It also produces no wastewater during the process [148,149] (Fig. 2). However, high temperatures and high pressures are needed to perform both supercritical and subcritical reactions, which means they both use a lot of energy. Water was used as a common solvent under subcritical conditions to improve oil extraction from wet Jatropha seed by making the sample more porous and weakening its internal structure [77]. Additionally, lipid hydrolysis became more practical as a result; at a gentler setting of 523 K and 13 MPa, transesterification of FAME was completed with less activation energy. Go et al. [77] used methyl alcohol and ethanoic acid as solvents to achieve a 65.1 % yield in 105 min. Without using a microwave, it took 40–45 min to reach 523 K [77]. According to other research, when rapeseed oil and methyl acetate were transesterified without the use of a catalyst under supercritical conditions, a molar ratio of 1:42 resulted in a 97 % yield in 45 min at 320 °C and 20 MPa [150].

In two stages, Mohamad Aziz et al. [102] first produced fatty acids using ethanoic acid and oil and subsequently converted FAME in a milder condition using supercritical methanol. After 5 min at 300 °C and 20 MPa and 15 min at 270 °C, the yield was 96 %. This has significantly reduced the overall process time [102]. However, a one-step biodiesel production method using methyl alcohol with ethanoic acid and CO_2 present under milder conditions has been suggested [151]. With the application of CO_2, the reaction was processed at 280 °C, and 97.8 % yield in 90 min. In 20 min of reaction time, a yield of 98.8 % at 265 °C was achieved using a ratio of oil to methyl alcohol of 1:25 [152]. Research on the combined microwave transesterification of palm oil was conducted using dimethyl carbonate as the solvent [149]. With a molar ratio of 1: 9.5 for the oil to DMC, 86 % of the biodiesel yield was produced in 2.5 h at 167 °C and 5 bars. While it might take longer to react in milder operating conditions, there are more energy savings and fewer hazards. At 300 °C, 20 MPa, 1:42 oil-to-DMC ratio, and 20 min, Ilham & Saka [153], achieved 97.4 % FAME yield for palm oil-based biodiesel under standard supercritical conditions [153].

According to some researchers, polar substances lose polarity or their dielectric constant as the temperature rises [154,155]. To

Table 5
Transesterification of biodiesel assisted by microwave.

Temperature (°C)	Catalyst Load	Molar Ratio of Reactant	Product	Yield (%)	Conversion (%)	Ref.
50.0	1.0 % KOH	methyl alcohol: oil (6:1)	Ethyl ester	97.00	NA	[113]
70	dolomite	methyl alcohol: oil (9:1)	Methyl pentadecanoate	98.20 in 121min		[123]
65	1.0 % CH_3ONa	methyl alcohol: Oil (6:1)	Methyl pentadecanoate	99.80 in 6 min	99.10	[139]
70	2.0 % potassium hydroxide	ethyl alcohol: Oil (10:1)	Ethyl acetate	81.20 in 12 min	NA	[140]
70	1.0 % sodium hydroxide and 2 % potassium hydroxide	methyl alcohol: Oil (6:1)	Methyl pentadecanoate	98.40 in 12 min	NA	[141]
70	Heteropoly acid	methyl alcohol: water beech oil (12:1)	Methyl pentadecanoate	97.30 in 12 min	NA	[142]
75	4 % CaO	methyl alcohol: Soybean oil (7:1)	Methyl pentadecanoate	NA	97.8 in 65 min	[143]
80	305 mg Novozym 398	OC $(OCH_3)_2$ (DMC): propylene glycol (3:1)	Propylene carbonate	NA	94 in 7 h	[144]
90	5 % zirconium tungstate	methyl alcohol: Oil (45:1)	Methyl pentadecanoate	NA	60.00 in 20 min	[145]
100	4 % Sulfuric acid	methyl alcohol: Oil (8:1)	Methyl pentadecanoate	87.50 in 33 min	NA	[142]
110	2 % CH_3ONa	Oil: methyl alcohol (1:6)	Methyl pentadecanoate	NA	95.89 in 32 s	[146]
165	9 % montmoril-lonite	Rapeseed oil: methyl alcohol (1:18)	Methyl pentadecanoate	58 in 62 min	NA	[147]

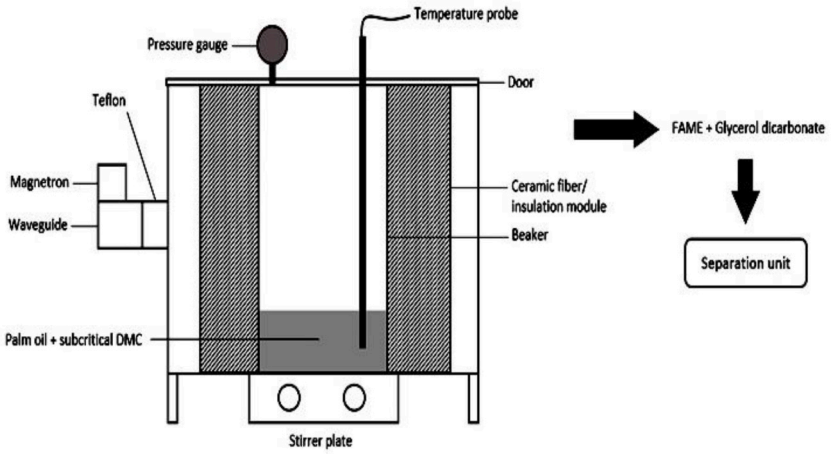


Fig. 2. Transesterification of palm oil triglycerides using a microwave and subcritical dimethyl carbonate [150].

intensify the heating, Patil et al. [156] used microwave irradiation to introduce heat because of the alteration of the dielectric properties of methyl or ethyl alcohol during the reaction process. Microwave heating uses less than 10 % of the energy required by conventional heating to produce the same amount of biodiesel, according to research by Patil et al. [156]. Based on the kinetic analysis of transesterification, the activation energy of the microwave-assisted process is lower (13–28 kJ mol^{-1}) than that of conventional approaches (34–50 kJ. $mole^{-1}$) [156].

In a single stage of transesterification of biodiesel from algae using a microwave, conditions were: 265 °C, 80 bar, a reaction duration of 20 min, and a ratio of 1:9 (wt/vol) of ethyl alcohol [157]. Under extreme temperatures and pressures, the system's existence of moisture from a wet algae material boosted the solubility of non-polar molecules of organic matter, which further sped up the process. The absence of a combination method is justified by the fact that supercritical and subcritical conditions depend on a complex reactor that can endure conditions of high pressure and high temperature [102]. Table 6 provides a summary of the previously mentioned works.

Table 6
Transesterification of various raw materials with supercritical/subcritical solvent using or without using microwave reactors.

Source of oil	Operating Condition	Ester Content/yield	Energy Assessment	Ref.
Palm: Solvent to dimethyl carbonate	Dimethyl carbonate to oil 9.4:1168 °C 2.4 h, 6 bar	86.2 %	With Microwave (44.88 kJ/mol)	[149]
Waste cooking: Solvent to methyl alcohol ratio	Methanol to oil 38:2 without a microwave 527.0 K, 197.4 bar, 15.1 min	91.1 %	No microwave	[152]
Whole kernel: Solvent to methyl alcohol and ethanoic acid ratio	487 K, 2.4 MPa, 16.1 min Second step: methyl alcohol and ethanoic acid 523 K, 14 MPa, 103 min	66.1 %	No microwave	[77]
Algae: Solvent to ethyl alcohol ratio	1.0: 9.0 ratio of ethanol, 538 K, 81 bar, 22 min	31 %	With microwave (1560 kJ)	[157]
Microalgae: Solvent to methyl alcohol and methylating agent ratio	Algae: Methylating agent (1:10) 245 - 370 ^{O}C, 21 MPa, 11–78 min	>91 % with methyl alcohol 53 % with dimethyl carbonate 42 % with a methylating agent	No microwave	[158]
Rapeseed: Solvent to dimethyl carbonate ratio	Dimethyl carbonate: oil (41:1), 573 K, 21 MPa, 18 min	96.5 %	No microwave	[153]
Soybean: Solvent to supercritical methyl alcohol, CO_2 and ethanoic acid ratio	Methyl alcohol to oil ratio (58: 1), ethanoic acid to oil ratio (3:1) 553 K, 20 MPa, 92 min	98.0 %	No microwave	[159]
Rapeseed: Solvent: subcritical ethanoic acid and supercritical methyl alcohol	Ethanoic acid to oil ratio (53:1) 573 K, 21 MPa, 32 min Second step: to methanol ratio 1.0:1.7 543 K, 18 MPa, 16 min	97 % yield	Without microwave	[151]

4. Cavitation-assisted biodiesel production

4.1. Ultrasonic/acoustic cavitation assisted biodiesel production

One of the best and greatest potential technologies to replace conventional reactors is ultrasonic cavitation [160]. Due to pressure fluctuations, ultrasound vibrations travel through the reaction mixture in this process, causing numerous small bubbles to form. The expansion and contraction of these bubbles create the cavitation effect, which accelerates the transfer of masses between the oil and alcohol phases and lowers response time. The decreased response temperature results in lower energy consumption [161]. Additionally, the utilization of catalysts and the molecular ratio of alcohol to oil is reduced in sonochemical reactors [162].

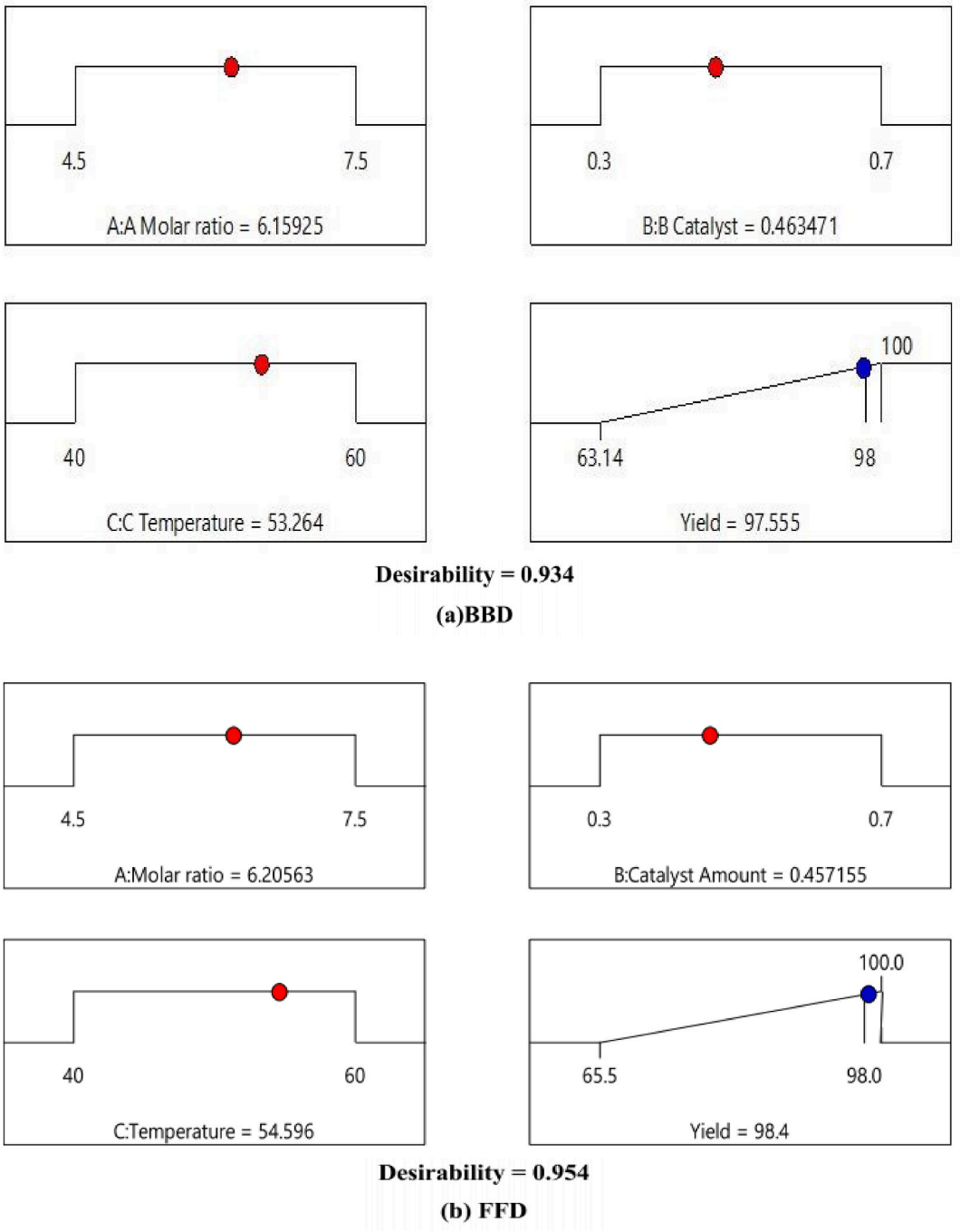


Fig. 3. The ultrasound-assisted optimum reaction condition for (a) BBD and (b) FFD [167].

In general, free fatty acids can be transesterified through heterogeneous or homogeneous enzymes in the existence of alcohol to produce biodiesel [163]. For transesterification, homogeneous catalysts with strong enzymatic activity include NaOH, KOH, and CH_3ONa [164]. However, since it necessitates involved cleaning procedures to cleanse the end products, there are several disadvantages in the production of biodiesel with homogeneous catalysts. Furthermore, a homogeneous catalyst is not generable and might result in equipment rusting [165]. The development of heterogeneous catalysts to replace the use of homogeneous catalysts has been prompted by the increasing severity of environmental and economic problems. Heterogeneous catalysts have a high catalytic performance, a high conversion of triglycerides to fatty acid methyl esters, and are easy to recover, which could address the issue with homogeneous catalysts [166].

Oza et al. [167] used Box-Behnken design (BBD) and full factorial design (FFD) response surface methodology (RSM) analytical tools to optimize the process parameters of transesterification of waste cottonseed cooking oil enhanced through the ultrasonic technique. At 6.160 methyl alcohol-to-oil molar ratio, 0.464 wt% KOH, and 53.274 °C temperature for 10 min reaction time, the BBD analytical tool achieved 98 % experimentally confirmed yield and 97.57 % optimal expected yield (Fig. 3a). At 6.206 methyl alcohol-to-oil molar ratio, 0.464 wt% KOH, and 54.596 °C temperature for 10 min reaction duration, the FFD analytical instrument obtained 98 % actual yield and 98.4 % optimal expected yield (Fig. 3b). The actual optimal yield for both models was close to the expected optimum yield. However, BBD has a better R-value (R = 0.993) than FFD (R = 0.991) [167]. Face-cantered central composite design (FCCD) linked to RSM was used to optimize the ultrasound-assisted biodiesel production process from Annona squamosa seed oil catalyzed by KOH. ANOVA was used to evaluate the experimental data, and a quadratic mathematical model was used to fit it. The model identified the following optimal reaction conditions: oil-to-methanol ratio of 5.04 mL/mL, 1.12 %wt KOH, temperature of 57 °C, and sonication period of 113 min. The optimal predicted biodiesel yield under these conditions was found to be 97.61 %. This result was empirically tested and found to be 98.4 %, indicating the model's fit [168]. The effects of methoxide catalyst weight, volumetric flow rate, ultrasonic mixing duration, Aegle Marmelos Correa seed oil-to-methanol molar ratio, and operating temperature on ultrasonic enhanced continuous flow microreactor biodiesel production were explored. These process parameters were optimized using central composite design (CCD) linked RSM. The highest yield of 98 % was obtained for the 0.3 mm microreactor under the operating conditions of 6.8 mL/min flow rate, 1.3 wt% sodium methoxide, 48 °C reaction temperature, 83s ultrasonic mixing time, and 1:9 oil-to-methanol molar ratio [169].

4.2. *Hydrodynamic cavitation technique for biodiesel production*

Even though the research investigation of a combination of hydrodynamic cavitation (HC) and microwave is still in its early stages, the use of a standalone hydrodynamic cavitation reactor resulted in a 98.1 % conversion of methyl pentadecanoater produced from waste cooking oil and methyl alcohol in 15 min [170]. By moving the oil-alcohol reaction combination through a constriction-like aperture plate and venturi tubes during the biodiesel production using HC, cavitation is formed, which causes pressure expansion [171]. Cavities develop when the local pressure falls below the vapor pressure of an oil-alcohol mixture, producing boundary layer separation and wake formation. These cavities enlarge and compress, releasing a massive quantity of energy nearby in the form of shock waves [172]. When the holes close, shear forces are created in the nearby bulk fluids that break molecular bonds [34]. This

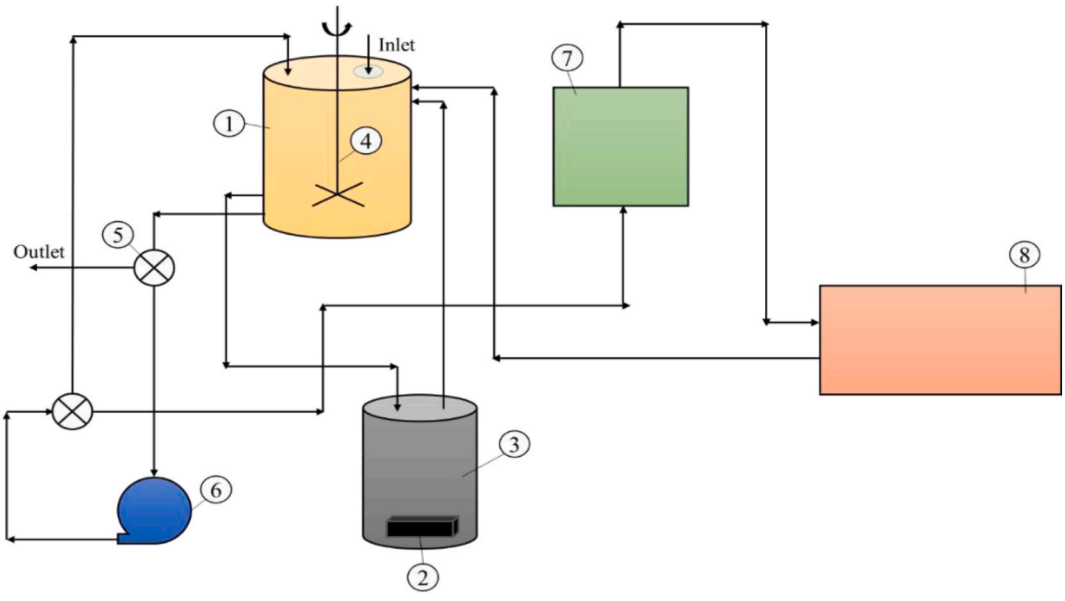


Fig. 4. Biodiesel synthesis schematic illustrated using successive ultrasound and microwave [181].
1) Oil container/tanker, 2) Heater, 3) Water tank, 4) Mixer, 5) valve, 6) Pump, 7) Ultrasound, 8) Microwave [181].

mixing phenomenon is not realized in the conventional technique, demonstrating the importance and uniqueness of hydrodynamic cavitation in biodiesel synthesis [173].

Many scholars have used HC intensification to eliminate the diffusion resistance of immiscible oil and alcohol since it has a quicker response and less energy consumption than conventional stirring [174]. One of the most energy-effective processes for producing biodiesel, effluent remediation, and chemical synthesis is hydrodynamic cavitation (HC) [175,176]. Within 15–60 min, the hydrodynamic cavitation method can produce enhanced outcomes with greater biodiesel yields of up to 90 % [177]. The activating circumstances are comparable to ultrasonic capitations, but the intensity is different. Cavitation can be produced using the hydrodynamic technique by passing the reaction mixture through small limitations such as orifice plates and venturi tubes [178]. The reaction mixture flashes and intense cavitation occurs when the system's overall pressure is lower than the reaction mixture's vapor pressure. While regaining pressure and temperature, a huge quantity of energy is discharged [179]. This causes the immiscible reaction mixture to combine properly and boosts the transesterification process [170,180].

Using an intensification method, Gupta et al. [181] examined the synthesis of biodiesel from used cooking oil. Using a successive ultrasonic and microwave method for biodiesel production, the transesterification of used heating oil using KOH as a catalyst was investigated. The transesterification procedure was carried out in an oil tank equipped with a condenser and thermocouple, with a batch capacity of 4500 ml (Fig. 4). During the synthesis, the catalyst concentration ranged from 0.9 to 1.2 wt%, the methanol: oil molar ratio ranged from 4.5:1 to 12:1, the temperature ranged from 52 to 62 °C, and the reaction duration ranged from 5 to 15 min used**.** The findings indicate that the biodiesel production was 96.9 % in 5 min at the optimum process conditions of 7:1 methyl alcohol to oil molar ratio, 0.9 wt% catalyst concentration, and 62 °C temperature of the reaction. The study offers insight into the advancement of biodiesel production methods in terms of not only synergistic effects and possible energy and cost reductions, but also time, resilience, safety, and environmental effects [181].

Other scholars, Patil and Baral [182] investigated biofuel production using hydrodynamic cavitation (HC) using process intensification. This study examined the effects of operating factors such as the molar ratio of thumba oil to methyl alcohol (1:4–1:8), the concentration of TiO_2 (1–1.4 % by weight of oil), and the operating temperature of 50–70 °C [182].

The HC reactor that Patil and Baral [182] used is shown in Fig. 5. This closed system has a 25 L tank and a 2.23 kW reciprocating pump with ball valves and pressure gauges. The construction material is a plate made of stainless steel (SS-304) with a thickness of 3 mm. The tank's outer diameter measured 30.5 cm. The tank was 35 cm tall. A 10-bar internal pressure and a 3-bar exterior pressure were the specifications for the entire tank. To regulate the temperature, a cooling jacket encircles the tank. The flow pathways and entire construction of HC are illustrated in Fig. 5a. The geometric, systematic distribution pattern of the chosen venturi tube and orifice plates is shown in Fig. 5(b) and (c), respectively [182].

With a thumba oil to methyl alcohol ratio of 1:6, a TiO_2 content of 1.2 % w/w, and a working temperature of 60 °C in HC reactor, the highest triglyceride conversion of 71.8 % was achieved in 1hr at 5 bars. In comparison to the conventional technique, the cavitation output for HC was 9.3×10^{-6} mol L/J, or nearly 27 % more.

Gholami et al. [183], produced biodiesel from chicken fat or tallow using a hydrodynamic cavitation reactor. The transesterification yield for poultry fat or tallow containing up to 2.5 wt percent FFA was 97 %, while the average yield was 95 % for FFA

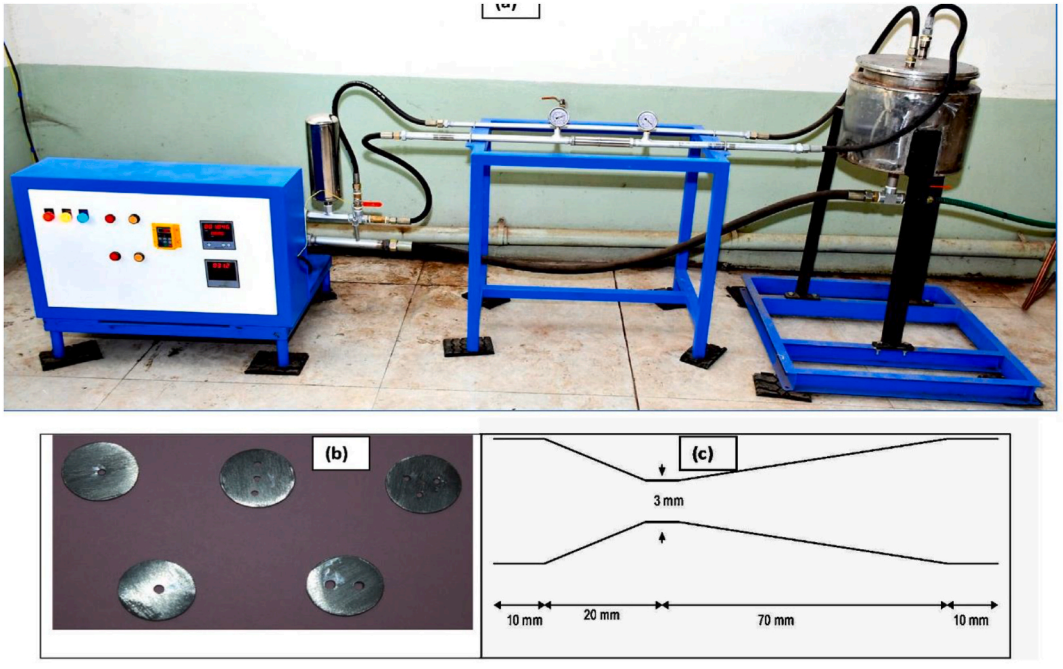


Fig. 5. (a) Set up hydrodynamic cavitation of; (b) Cavity generation device using orifice plates and (c) Venturi [182].

levels between 2.5 and 3.5 %. A conversion reactor with 99.9 % effectiveness was used in this research to simulate the HC process. The methyl alcohol to oil molar ratio was 4.7 to 1, the temperature was 25 °C, and the pressure was 100 kPa over the transesterification process. The catalyst concentration was 0.75 % [183].

Khan et al. [184] conducted another research on the synthesis of biodiesel from cannabis sativa oil using enhanced HC. An induction motor, pressure compressors, pressure gauge, temperature indicator, flow meter, nozzle spray cannon, control valves, throttle valve, and connections are included in the hydrodynamic cavitation system (Fig. 6). In this research, a nozzle spray cannon is mounted with an optimal shape aperture plate with 7 holes that are 3 mm in diameter [184].

The effects of the oil to methyl alcohol molar ratio (3:1–7:1), catalyst load (0.5–1.25 wt%), and reaction temperature between 50 and 65 °C have all been studied in this investigation using an optimized plate with seven 3 mm diameter perforations in a 10L HC reactor. An optimum yield of 97.5 % was completely accomplished in 20 min in a cavitation reactor with a 6:1 M ratio of oil to methyl alcohol, 1 wt percent of catalyst, 3 bar of operating pressure, and 60 °C of reaction temperature [184]. Additionally, Pal et al. [171] studied the homogeneous catalyst NaOH's alcoholysis with CH_3OH in hydrodynamic cavitation vessels for biodiesel production. In this research, non-edible thumba oil was alcoholized using CH_3OH at a 1:4.5 oil-to-alcohol ratio. Within 30 min, a triglyceride reduction of nearly 96 % had been accomplished [171]. According to Ghayal et al. [185], a hydrodynamic cavitation reactor was used to produce biodiesel using frying oil and alcohol, and KOH as a homogeneous catalyst. A 10L container and a centrifugal pump were attached in a closed loop as part of the setup. Using KOH as a catalyst, approximately 97 % reduction was accomplished in just 20 min [185]. Choedkiatsakul et al. [186] demonstrated the alcoholysis of waste cooking oil in a hydrodynamic cavitation reactor with a homogeneous catalyst, KOH. The superiority of potassium hydroxide in transesterifying waste oil resulted in a rapid increase in output within 30 min [186].

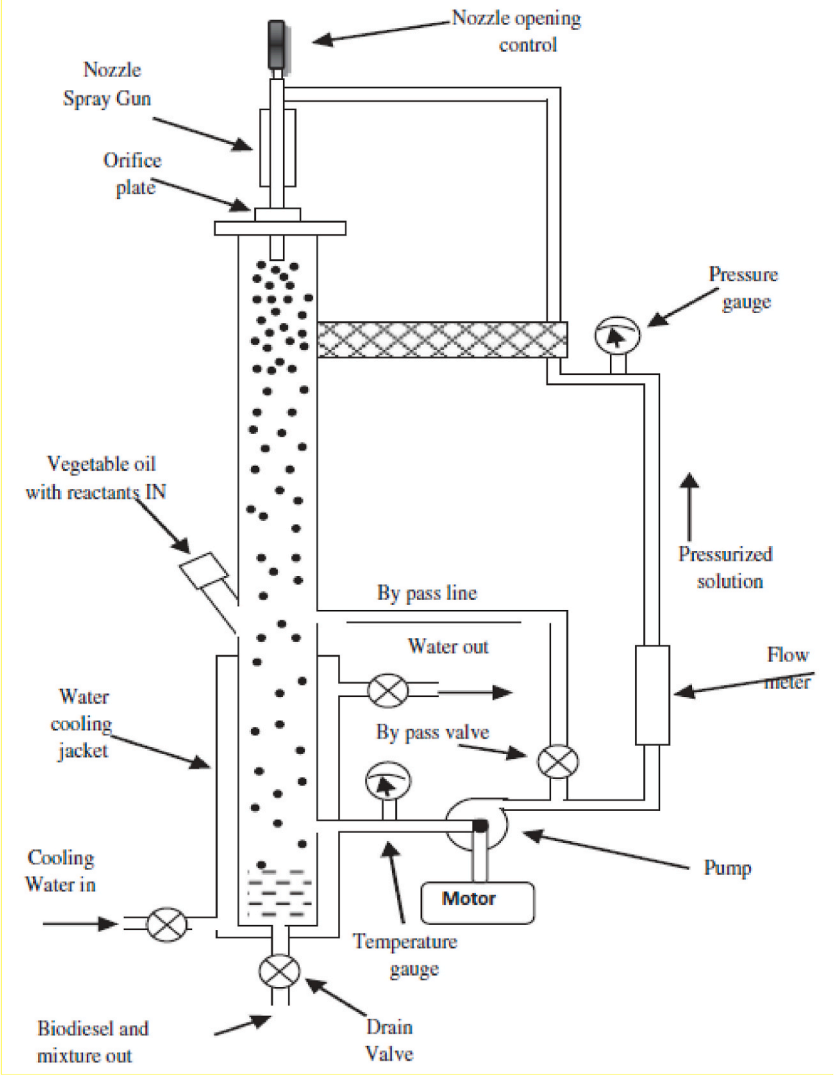


Fig. 6. Setup of hydraulic cavitation in a line illustration [184].

Mahshid et al. [187] observed the potential of potassium hydroxide in hydrodynamic cavitation for transesterifying palm oil. In this research, a yield of 96.5 % was achieved with only a 1.00 % potassium hydroxide concentration [187]. Bargole et al. [188] studied the alcoholysis of waste cooking oil using hydrodynamic cavitation by increasing the hole perimeter to area ratio. An orifice plate with the greatest number of openings and optimal size yielded approximately 99 % biodiesel output [188]. Mohod et al. [36] proposed a new method of the hydrodynamic cavitation device as a high-speed mixer for enhanced biodiesel synthesis from waste oil and fresh cooking oil [36]. Kolhe et al. [172] explained the alcoholysis of cooking oil using a molar ratio of 1:4.5 and a 0.55 % (w/w) oil concentration of sodium hydroxide. In this research, nearly 93.5 % conversion was obtained in 60 min [172]. Samani et al. [189] utilized the Box-Behnken design (BBD), a response surface methodology (RSM) analytical tool, to optimize the biodiesel process for producing it from safflower oil enhanced by hydrodynamic cavitation. The optimal expected to and experimentally measured optimum biodiesel yields were 89.11 % (Fig. 7) and 88.18 %, respectively, for the optimal reaction conditions of 63.88s reaction time, 0.94 wt% KOH catalyst, 8.36:1 methanol-to-oil molar ratio, and 1.53 cm rotor-stator clearance. The optimum outcomes are acceptable because these findings were really near to one another [189].

5. Microwave - cavitation combined reactor for intensification process

5.1. Sonic cavitation and microwave coupling technology

In transesterification of biodiesel, multiphase reaction mixtures are employed, such as the combination of oil and alcohol for the production of biodiesel. To increase the emulsification of two incompatible liquids in the reaction medium, chemical process intensification is essential. Furthermore, the transesterification process would be accelerated if reaction mixture droplets were sufficiently small to increase the contact surface area between the reactants. Recently, a microwave-based combination of a couple of instantaneous reactor technologies has been investigated to improve mass and heat transfers while also having the potential to use less energy during the process. With either heterogeneous or homogeneous catalysis processes, ultrasonic cavitation has been extensively used to synthesize biodiesel in fast transesterification [160,190,191]. This technology describes the application of sound energy at pressure oscillation frequencies greater than 20 kHz [192]. This process can accelerate the conversion of esters at shorter reaction times and less expensive output by promoting homogenization between the reactants through ultrasonic cavitation [193]. Ultrasonic cavitation is the creation and dissolution of bubbles in liquid exposed to intense ultrasound, frequently faster than the liquid's sound velocity [194].

By using synergistic microwave-ultrasonic irradiation, Yu et al. [190] investigated the transesterification of soybean oil. With dimensions of 450, 670, and 650 cm, the Xianghu Instrument Combined Microwave-Ultrasound with Computer Controlled System for Synthesis and Solvent Extraction (mXH-300A) was employed in this study (Fig. 8). The ultrasonic horn's surface was covered with a particular cladding material in this reactor to stop the development of an electric arc. A 25 kHz frequency of ultrasound may be generated via the ultrasonic horn. A magnetic stirrer was present in the reactor in addition to an ultrasonic horn. A mechanical stirring paddle interface was also there but was not displayed. The two stirring units, however, were all located below the vapor tube but not the ultrasonic horn. Pulsed ultrasonic waves might be produced by the reactor. Three different types of ultrasonic modes were designated as 1:0, 1:2, and 2:1 (where 1:0 denotes continuous ultrasonic irradiation, 1:2, a single second of irradiation followed by 2 s of close, and 2:1, most likely, a double second of irradiation and close) [190].

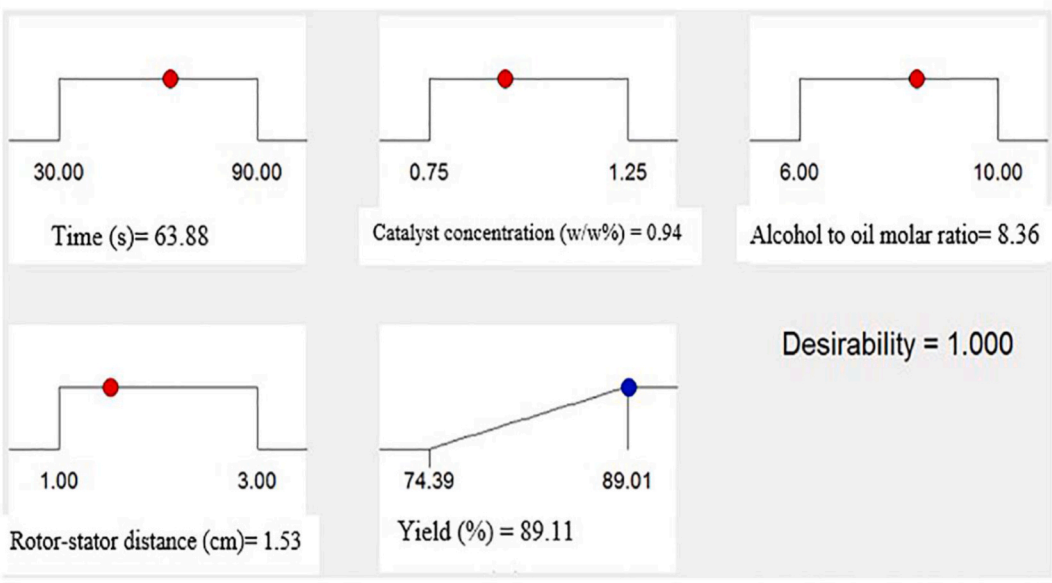


Fig. 7. Biodiesel production process optimization with BBD-linked RSM enhanced by hydrodynamic cavitation [189].

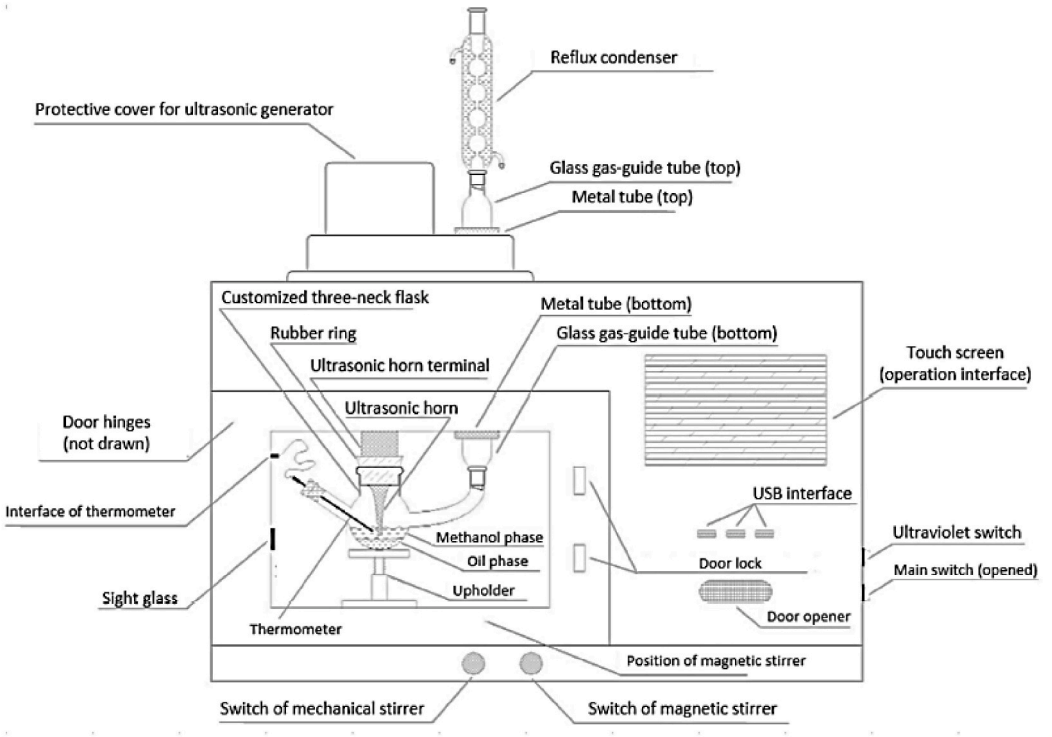


Fig. 8. Methanol and soybean oil transesterification in a microwave-ultrasonic reactor [190].

The mass transfer constraint of a material's miscibility would be reduced in the transesterification process if microwave technology was combined with either hydrodynamic or acoustic cavitation. Ultrasonic cavitation, which is caused by the creation and destruction of tiny bubbles in the shock wave, produces the accumulation of high local energy. This leads to the development of hot spots, free radicals, and liquid flows with high density and rapid turbulence. When a liquid starts to move through a constriction as a result of an increment of the velocity of flow and a drop in liquid pressure below the vapor pressure, bubbles or cavities are created. The bubbles and cavities downstream collapse when the pressure increases, causing the pressure to be altered. The intense energy produced by this quick collapse causes local heating [190].

Other Scholars, Ardebili et al. [195], also used ultrasound and microwave irradiation to produce biodiesel. This method could greatly speed up the palm oil transesterification process with optimal conditions at 58.4 °C, a molar ratio of 7:3.1 of methyl alcohol to oil, 1.1 % catalyst load, and 136 and 129 s of microwave treatment duration. The biodiesel yield was 97.5 % biodiesel [195].

In a two-step synthesis process, Gole and Gogate [196] studied the sequential effects of microwave and ultrasound and compared them to the separate ultrasound, microwave, and conventional synthesis procedures. When performing the alkaline transesterification, to prevent a saponification reaction, the initial acid value of the oil was reduced during the esterification process from 18.9 to 1.7 mg of KOH/g of oil. The esterification and transesterification steps have been optimized for the microwave, ultrasonic, and sequential approaches using the molar ratio and catalyst concentration. It has been shown that the optimum molar ratio associated with esterification is 1:2, 1:3, and 1:4 for the microwave, ultrasound, and sequential approaches, respectively, but the optimum ratio for transesterification is 1:4, 1:6, and 1:6. When utilizing ultrasound alone, the response times for esterification and transesterification were 60 and 20 min, respectively, whereas when employing ultrasound sequentially, the reaction times were only 15 and 6 min,

Table 7
Biodiesel production through transesterification using microwave-acoustic cavitation technology.

Material/Source of oil	Operating Parameters/Factors	Ester Content	Energy Assessment	Ref.
Plumeria Pudica Oil: Ratio of Catalyst to KOH	16 min for esterification and 7 min for transesterification, 110–141 W 22 kHz 118 W and molar ratio (1:2)	NA	2.4×10^2 kJ/kg	[196]
Waste cooking oils: Catalyst to NaOH ratio	3 min, 300 W and ratio of methyl alcohol to oil of 9:1 (v/v)	97.6 % biodiesel yield	NA	[200]
Palm oil: Ratio of catalyst to potassium hydroxide	2.1 min, ratio of methyl alcohol to oil of 7:3.1 (v/v), 331 K	96.8 % biodiesel yield	0.46 (MJ/L)	[195]
safflower oil: Ratio of catalyst to potassium hydroxide	7 min, 338 K and 710 W	98.40 FAME yield	NA	[190]

respectively. The primary intensification parameter is a substantial decrease in the needed alcohol excess, which can result in significant energy savings in the subsequent separations [196]. According to Gole & Gogate [196] investigations, the sequential effect has the advantages of shorter reaction times and requiring less excess methanol to achieve an equivalent equilibrium state, which can result in significant power savings.

Since the energy is transferred by microwave at a rate faster than the molecules, non-equilibrium conditions and high instantaneous temperatures are generated, which have an impact on the system's kinetics [197]. In addition to its thermal effects, the microwave's non-thermal effects also have an impact on the rate of synthesis [198], as a result of the molecules' altered vibrational frequencies and an increase in the likelihood of effective molecular collisions. These effects may also result in a change in the activation energy (the activation energy required by the microwave is 26.5 kcal/mol [199], as opposed to the conventional 42.9 kcal/mol) [124]. Microwave-acoustic cavitation technique used in transesterification to produce biodiesel is summarized in Table 7.

Additionally, Martinez-Guerra Edith et al. [96] examined how microwaves and ultrasound work together to transesterify used plant-based oils. According to the study, when methyl and ethyl alcohol were used as solvents, an equal rate of microwave and ultrasonic radiation led to greater biodiesel outputs. For both ethanol and methanol, the molar ratio of 9:1 (alcohol to oil) was optimal, yielding 98 % and 96 % biodiesel, respectively, in 2 min. Methyl and ethyl alcohol are both excellent microwave energy collectors because of their polarity, but using ethanol led to higher biodiesel outputs because of its better solubility characteristics. To increase the output and purity of biodiesel, the experts also recommended mixing the two alcohols. Martinez-Guerra Edith et al. [96] suggested that the best power density must be identified for the production of biodiesel that utilizes little energy [96]. The use of this technique for producing biodiesel is comparatively new, even though combining microwave and acoustic cavitation technologies seems promising. The synthesis of biodiesel could potentially be intensified through the use of combined microwave and acoustic cavitation [170].

6. Activation energy determination in biodiesel intensification process

The minimal amount of energy needed for the reaction to start is known as the activation energy [112]. Activation energy analysis helps in identifying the impact of microwave and cavitation reactor technologies on the biodiesel production process. It allows researchers to evaluate the effectiveness of cavitation and microwave reactors by comparing the activation energy values with traditional reaction methods. If the activation energy is lower with these advanced technologies, it indicates that they can accelerate the reaction kinetics and improve the overall efficiency of the biodiesel production process.

Din et al. [201] investigated Kusum oil esterification with microwave assistance from a parametric, kinetic, and thermodynamic perspective. The relationship between temperature dependence and rate constants is expressed by the Arrhenius equation [201].

$$k = Ae^{-Ea/RT} \tag{1}$$

Where E_a is the activation energy (kJ/mol), R is the gas constant (J/mol.K), T is the absolute temperature, k is the reaction rate constant, and A is the frequency factor (min^{-1}). Eq. (1) can be written as Eq. (2) by using the natural logarithm:

$$\ln k = \ln A - \frac{E_a}{RT} \tag{2}$$

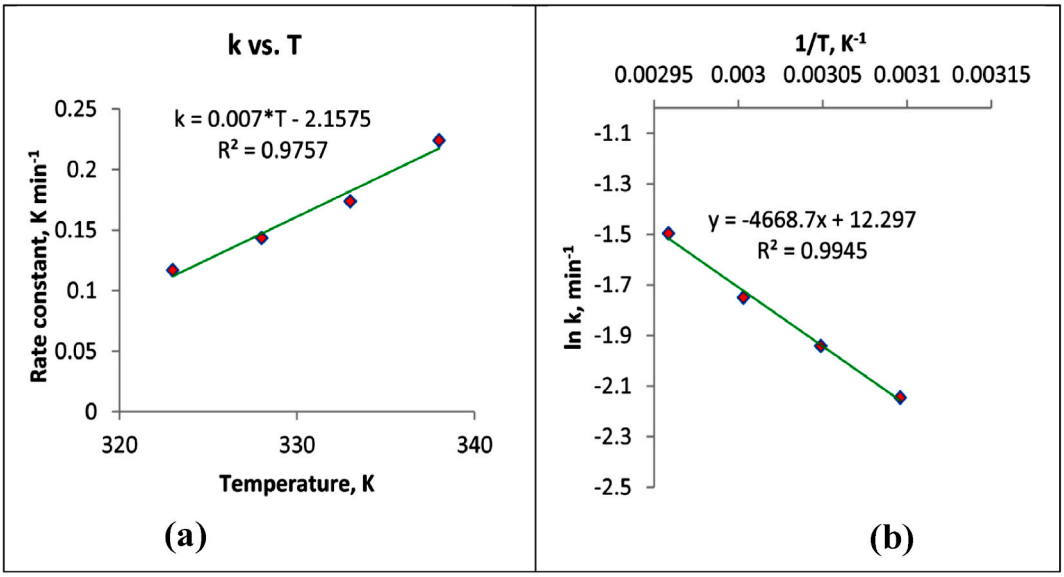


Fig. 9. Plot showing (a) rate constant, k versus temperature (K), and (b) ln k versus 1/T [112].

The temperature and rate constant k is shown in Fig. 9a. Temperature changes the rate constant in a linear progression. Additionally, the first-order kinetics of the reaction rate was supported by the R^2 value of 0.9757. The plot of ln k vs. 1/T is shown in Fig. 9b. The activation energy and frequency factor values are given by the slope and intercept.

The frequency factor is determined to be 219,037 min^{-1}, and the activation energy is 38.82 kJ mol^{-1}. Equation (3) represents the temperature dependence of the reaction rate constant [112].

$$k = 2.19*10^5 e^{-38.82/RT} \tag{3}$$

For microwave-assisted esterification, the reaction rate is demonstrated as the following (Eq. (4)).

$$-r_{FA} = \frac{dC_{FA}}{dt} = 2.19*10^5 e^{-38.82/RT} C_{FA} \tag{4}$$

Where C_{FA} is fatty acid concentration.

Depending on which chemical step makes the most use of catalysts, the reaction rate is either mass transfer limited or controlled. The range of activation energy for diffusion control is 10–15 kJ mol^{-1}, whereas the same was more than 25 kJ mol^{-1} for chemical control [202]. It demonstrates that the chemical step is controlling the rate of the reaction [112]. Catalyst usage lowers the amount of energy needed to esterify oil. By employing a typical heat source, Rani et al. [203] found that a 5 wt% sulfuric acid catalyst efficiently lowered acid value to less than 1. Process conditions were 60:1 methanol to FFA ratio, 500 rpm, 60 °C, and 60-min reaction duration. A 38.21 kJ mol^{-1} estimate of activation energy was obtained [203].

In microwave-aided esterification, the high frequency implies effective collision and severe mass transfer between the alcohol, oil, and silicotungstic acid phases. Low catalyst dosage and favorable conditions for operation are encouraged by the high-frequency factor. The reduced activation energy and high-frequency component show that microwave heating has a non-thermal impact. Mazo et al. [204] concluded that the presence of a non-thermal effect that needs less time than conventional heating is confirmed by a 10 % reduction in activation energy and a 182 % rise in the pre-exponential factor when employing a microwave heat source [204].

Sharma et al. [156] evaluated the activity of the biodiesel produced from waste cooking oil under MW irradiation to that of

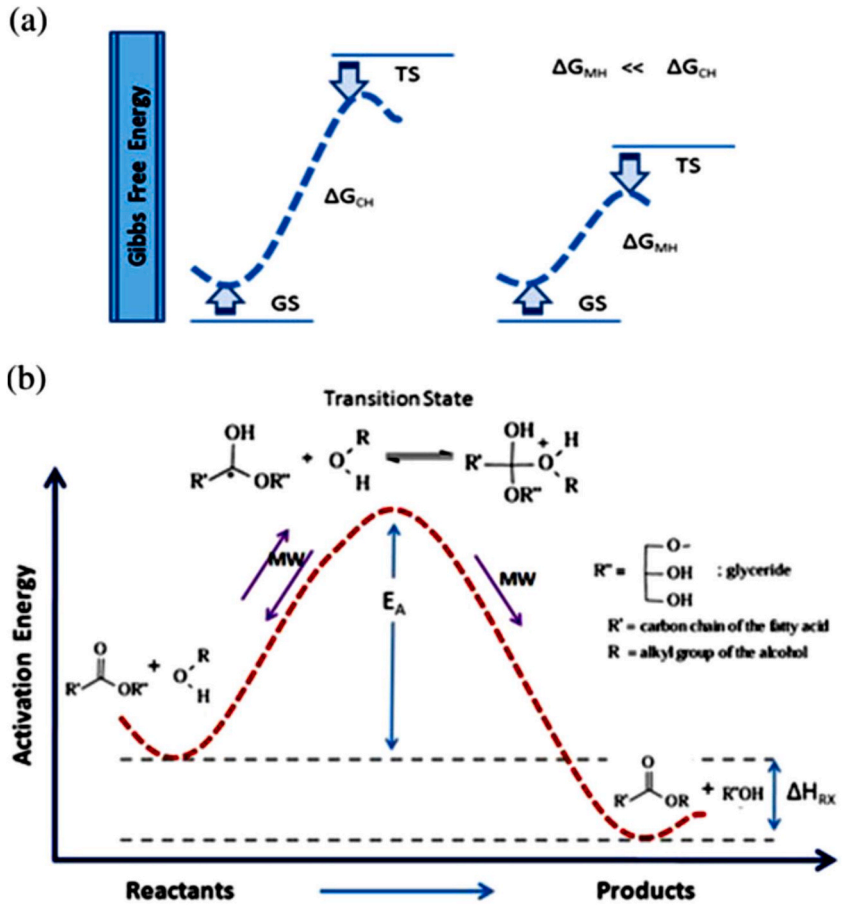


Fig. 10. a) difference in Gibb's free energy between conventional and microwave heating, b) decrease in activation energy during an acid-catalyzed transesterification process [205,207].

potassium hydroxide. The catalyst loading, reaction time, and methanol-to-oil ratio were all optimized. Additionally, by repeating the process at three different temperatures (45, 50, and 55 °C), the activation energies of the various catalysts were calculated. According to expectations, KOH is more active than CaO, having an activation energy of 13.05 kJ/mol compared to 28.93 kJ/mol. The activation energies of both materials, 34.5 and 50.4 kJ/mol, respectively, were reported to be much greater than in comparable conventional studies and to be efficiently activated by MW. 9.6:1 alcohol/oil ratio, 1.33 wt percent of catalyst, and 9.7 min were the optimal CaO conditions that produced a yield of 90.4 % [156]. When polarity increases throughout the reaction from the ground state towards the transition state in microwave-aided biodiesel generation, unique microwave effects may be anticipated for the polar mechanism. The medium and the response mechanism mostly determine how things turn out. If stabilization of the transition state is more successful than stabilization of the ground state, this increases reactivity by lowering activation energy (Fig. 10a) [205]. Jermolovicius et al. [206] observed that the esterification kinetics changed when exposed to microwave radiation [206].

The primary solvent utilized in biodiesel transesterification processes is methanol. Methanol is an organic solvent with strong polarity and has become known for its high microwave absorption capability. It follows that microwave interactions can increase the transesterification process involving the oil-methanol catalyst through dipolar polarisation and ionic conduction. Since water molecules have a dipole moment, microwave-aided supercritical reactions in biodiesel operations using water as the feedstock can cause the water to serve as an organic solvent. A dipole will try to rotate to align itself with the field since it is sensitive to external electrical fields, which can cause local superheating (Fig. 10b) [207].

Enhanced dipolar polarisation caused by microwave exposure to the reaction chemical substances leads to a significant decrease in activation energy [208]. This is accomplished by the microwaves in the reaction mixture interacting at the molecular level, causing ionic conduction and dipolar rotation [209,210]. The medium and reaction mechanism mostly determine how much of the activation energy is lowered [208].

According to Sarve et al. [211], an improved interfacial area between the oil and methanol phases resulted in a decreased activation energy of 21.75 kJ mol^{-1} during ultrasound-assisted esterification of Schleichera triguga oil. The activation energy is decreased by micro-emulsion and local cavitation between the methanol and oil phase when ultrasound is introduced. However, it takes more than an hour to convert free fatty acids by 90 % [211]. Palm fatty acid distillate esterification utilizing conventional and microwave heating was also conducted by Lokman et al. [212]. The operation parameters were a 12:1 methanol to oil molar ratio, a reaction temperature of 75 °C, and a sulfuric acid concentration of 3 %. While microwaves achieved 96 % conversion in 15 min, conventional heating took 2 h. Due to the close interaction of electromagnetic waves with the molecules of oil, methanol, and catalysts, less time and activation energy is needed compared to conventional heating. The inverted temperature gradient is brought on by microwave, which increases its effectiveness [212].

According to Ramachandran et al. [213], ultrasonic irradiation significantly improved the yield and reaction time in addition to other reaction parameters. When compared to similar findings obtained using a conventional stirring reactor system, it was discovered that the yield of biodiesel synthesized utilizing ultrasound was 30–40 % higher [213]. When comparing ultrasonic-enhanced mass transfer features to mechanically agitated systems, Choudhury et al. [214] showed that the ultrasound may improve the features of mass transport in the system with a 20 % drop in activation energy [214].

Liu et al. [215] have conducted a kinetic investigation to ascertain the catalyst's activation energy and rate of reaction when exposed to microwave radiation. Based on the value of the coefficient of determination (R^2), the statistical validity of the model was examined. Using Arrhenius equation (Eq. 2), the activation energy has been determined to be 11,969 kJ/mol. The catalyst's E_a value may be calculated using the slope of the line. At 45, 65, and 85 °C, the rate constant was 0.0943 min^{-1} [215]. Table 8 provides a summary of a kinetic investigation into the enhancement of biodiesel production using microwave and cavitation reactors, along with the associated activation energy values.

Patil and Baral [182] investigated the hydrodynamic reactor's activation energy. The bare minimum of energy required for an alcoholysis reaction to occur in an oil-and-methanol combination is called activation energy. From the Arrhenius equation (Eq. 2), the pre-exponential factor for the alcoholysis process and its activation energy were determined to be 82.26 L^2 mol^{-2}.min^{-1} and 15.44 kJ/mol, respectively. According to Patil and Baral [182], when compared to the conventional approach, the enhanced approach to the synthesis of thumba methyl ester is innovative and energy-efficient [182].

Table 8
Summary of a kinetic study of biodiesel intensification with corresponding activation energy.

Source of Oil	Catalyst	Phase of Catalyst	Method of Heating	Activation Energy (kJ/mol)	Ref.
Chlorella vulgaris lipid	Heterogeneous	SiC–NaOH/GO	Microwave	30.81	[137]
Oil of Ceiba pentandra seed	Homogenous	Sulfuric acid	Microwave	53.71	[216]
Oil of Sunflower	Heterogeneous	$MgO–La_2O_3$	Conventional	77.6	[217]
Oil of Soybean	Heterogeneous	Calcium methoxide	Ultrasonic	71.25	[218]
Oil of Campto-theca seed	Homogenous	Ionic liquid and Metal sulfates	Microwave	37.6	[219]
Waste cooking oil	Conventional	Sulfuric acid	Conventional	45.93	[220]

7. Energy analysis of cavitation and microwave reactors

7.1. Ultrasonic cavitation process energy consumption

Gholami, Pourfayaz, and Maleki [221], studied on economic evaluation of rapeseed oil-based biofuel generation using ultrasonic cavitation. In this finding, even though mixing and heating the reactants in the ultrasonic cavitation process consumes more energy, the remaining operational components in this process, particularly at the transesterification step, use less energy. About three times less energy is used in the ultrasonic cavitation reactor than during the mechanical stirring procedure. Additionally, the ultrasonic cavitation process uses 26.5 % less energy during the methanol recovery stage and 1.3 % less during the biodiesel purifying stage than the mechanical stirring method. Since less methyl alcohol is entering these two distillation stages during the ultrasonic cavitation process, the decrease is caused by this. The energy and material needs are also impacted by the ultrasonic cavitation reactor, which consumes 25 % less methanol and nearly one-third less catalyst than a stirred-tank reactor [221].

7.2. Energy consumption of continuous-flow ultrasound-assisted process

The strength of the ultrasonic must be set at a high level to accomplish full blending in a batch reactor holding an enormous quantity of material, which uses additional power and greatly raises the cost of the processing. By reducing energy use and retention time, continuous processes can increase the total conversion of biodiesel. A huge amount of vegetable oil can be processed using continuous ultrasonic biodiesel synthesis in a tiny vessel capacity [222]. The continuous-flow ultrasonic reactor may demonstrate higher productivity and lower energy usage in biodiesel synthesis than batch reactors [223]. According to Stavarache et al. [222], the reactor capacity and retention time were important factors in the synthesis of biodiesel. Using ultrasonic cavitation, with a residence time of 10–30 min, the yield of biodiesel can be produced in the much smaller reactor with an operational volume of 2.62 L as compared to the larger one with an operational volume of 6.35 L [222].

The continuous base catalytic methanolysis of waste cooking oils was devised [224], combining a two-step process with 20 kHz frequency ultrasound and an input power of 1 kW. The concept of multiple frequencies and multiple transducer reactors that operate in continuous mode represents the ultrasonic reactors of future generations [223,225].

Delavari et al. [226] studied synthesizing biodiesel from waste cooking oil with methyl alcohol accelerated by catalyst sodium hydroxide using a 20 m glass helicoidal vessel combined with a hot bath and aided by ultrasound. Two ultrasound power levels of 400 and 1500 W were used in the different trial experiments to determine the reactor performance over time. The ratio of 8.6:1 M of methyl alcohol to oil, 0.5 % w/w sodium hydroxide, and a discharge rate of 1 L. min^{-1} of reactants were found in optimal conditions. The results also showed that the continuous process was effective in contrast with conventional batch methods because of the intense mingling produced by the cavitation, which achieved 90 % of the biodiesel output under this condition within 150 s [226]. Effects caused by many variables, including irradiation distance, instrument width, sound irradiation distance of 75 mm, sensor width of 28 mm, ultrasonic amplitude of 56 %, vibration pulse of 62 %, and reagent flow rate of 50 ml min^{-1} were found. Under these circumstances, this method could produce 91.12 % biodiesel while using only 102.4 W of energy [227].

7.3. Batch and continuous flow microwave-assisted reactors energy consumption

A new technology that helps to speed up chemical processes by directly providing energy to the reactants is microwave treatment in the range of frequency from 0.3 to 300 GHz [116]. As a result, microwave treatment is more effective at transferring heat than conventional heating, and reactions can be finished much more quickly (on a small scale) [228]. In comparison to the surface, the electromagnetic power intensity inside a large-scale reactor with more than 1 L of operating capacity is significantly reduced. As a result, microwave dielectric heating does not heat the materials in the reaction vessel's center; only airflow is used. Hence, the reactant's capacity grows, and more energy is needed to heat it, thereby causing greater radiation strength. Continuous-flow microwave reactors can be used to address these issues because they allow the mixture of chemicals to pass over the microwave at an acceptable flow rate without experiencing an obstacle of entry depth. According to recent research, the energy return for 1 kg of biodiesel synthesized on batch operation method with microwave assistance is approximately 1.7 kWh [116], which can be regarded as viable in real-world applications. To investigate the biodiesel production via transesterification of canola oil and sunflower oil with methyl alcohol at a 6:1 M ratio of methyl alcohol, a continuous circulating microwave system was established. The biodiesel output for a continuous-flow device was 89 % for sunflower oil and 92 % for canola oil in 7 min. Only 64 % of the biodiesel was produced when the operating capacity was 500 ml in the batch process, which produced 97 % of the biodiesel. This strongly suggests that, when producing biodiesel on a large scale, the continuous flow microwave reactor is more effective than the batch microwave reactor [229].

Using widely available microwave equipment, Barnard et al. [124] devised the continuous-flow method to perform the production of biodiesel in 4 L and 2 L volume vessels aided by microwave power of 1600W with regulated flow rates of 7.2 and 2 L min^{-1}. The approach enabled the reaction to operate under the same optimal conditions as those determined by a batch reactor. This corresponds to a production of biodiesel rate of 6.1 L min^{-1}, and the biodiesel output generated from these two reactor systems was identical at 98 %. The transesterification reaction's consumption of energy calculations for the continuous-flow microwave approach at flow rates of 7.2 L min^{-1} and 2 L min^{-1} were 60.3 and 26.0 J L^{-1}, respectively, while the estimates for the conventional heating and batch microwave reactor were 90.1 and 94.3 J L^{-1}, respectively [124]. This shows that the continuous-flow microwave method is more cost-effective than both conventional heating and batch mode methods. The method has also been used to produce biodiesel from soybean oil with butyl alcohol using potassium hydroxide and sulfuric acid as catalysts in a vessel with a 4 L working capacity. A

microwave output of 1600 W was used to assist with heating the reactor's interior as the mixture of reactants was fed through at a rate of 2.3 L min^{-1} [230].

Lertsathapornsuk et al. [231] studied on continuous flow microwave reactor system to transesterify used cooking palm oil with ethyl alcohol at a 12:1 M ratio, accelerated by NaOH (3.0 wt%). When sodium hydroxide was used to reduce and transesterify the high free fatty acid oil, which had a free fatty acid content of 4.5 wt percent, it produced 97 % biodiesel output in 30 s while operating at an 800 W microwave power [231]. Encinar et al. [232] additionally developed a similar to the previous one with microwave irradiation assistance to study the effects of temperature (50–110 °C), methanol to oil molar ratios of 3:1–12:1, KOH catalyst loading of 0.5–1.5 wt %, and microwave output power of 70–350 W on the manufacture of biodiesel through continuous-flow mode by transesterification of soybean oil with methyl alcohol. At a 12:1 methyl alcohol to oil ratio and a reaction temperature of 70 °C in 2 min with a microwave output power of 200 W, a yield of over 99 % biodiesel was obtained [232].

Choedkiatsakul et al. [125] transesterified commercial grade palm oil with methyl alcohol catalyzed by sodium hydroxide to biodiesel at a methyl alcohol to oil molar ratio of 6:1–12:1, heating power from 200 to 800 W and reaction conditions of 50–70 °C using a commercial continuous flow Teflon reactor. It was stated that an output of 99.5 % biodiesel could be produced in 1.75 min using a 12:1 methanol to oil mixture, a 400 W microwave, a reaction temperature of 70 °C, and a 1 % weight-per-weight catalyst. The rate of energy usage in the constant state of operation was also assessed. The microwave-aided continuous flow method uses 0.112 kWh of energy to make 1 L of biodiesel, which is less energy than the conventional chemical-catalyzed process [125].

The difficulty of microwave technology to permeate through huge sample sizes has been cited by several experts as one of its key drawbacks. This constraint makes it difficult for microwave applications to scale from small-scale synthesis in the lab to multi-kilogram output in industries. There are various restrictions on using microwaves to replace conventional methods. Large batch reactors have non-uniform temperature distribution and challenging measurement and control of temperature, which may replicate thermal currents used in conventional heating. According to their dielectric characteristics, microwaves may typically penetrate absorbing materials up to a few centimeters deep. As a result, in large batch-type reactors, the microwave power density substantially ranges from the sample material's surface to its inside. As a result, microwave dielectric heating does not heat the components in the reaction vessel's center; only convection is used. Additional issues develop when attempting to heat vast volumes of materials [233].

Generally, sample volume, the power of the ultrasound or microwave waves, the type of solvent used, and the depth of the reaction container all affect how much energy is needed. The findings show that, in comparison to individual and simultaneous operation, the energy needed for processing has been decreased by a factor of more than two that use the sequential method. The results of the consecutive ultrasonic and microwave methods have a great role in the synthesis of biodiesel with enhanced economic prospects and overall energy savings [181]. A comparison of the energy consumption of the various processes used to produce biodiesel is shown in Table 9.

8. Economic analysis of cavitation and microwave reactors

To determine the profitability and economic viability of the biodiesel intensification process using cavitation and microwave reactors, a comprehensive feasibility study and financial analysis would be required. Analyzing the profitability and economics of a biodiesel intensification process involves considering many factors, including capital costs, operating costs, feedstock availability, and price.

8.1. Economic analysis of cavitation

8.1.1. Economic analysis of ultrasonic cavitation

8.1.1.1. Total capital investment. The total capital investment of a biodiesel plant utilizing ultrasonic cavitation and a stirred tank reactor that has an annual output capacity of 50,000L and has been operational for 7920 h/yr was compared and contrasted by Ali Gholami et al. [221]. The size of the equipment, the length of the residence time, and the size of the plant's footprint all affect the capital investment cost for biodiesel synthesis. Capital costs for ultrasonic cavitation and stirred tank reactor were compared. The study found that because the typical stirred tank reactor had a higher purchase cost, its overall cost was 20.8 % more than that of ultrasonic cavitation. The transesterification reaction, which accounted for 39 % of stirred tank reactors and 23.5 % of ultrasonic cavitation reactions, was the source of the higher equipment acquisition costs. This was caused by the ultrasonic cavitation reactor's reduced size, which was around half that of the stirred tank reactor. The shorter residence period in the cavitation reactor was the

Table 9
Comparison of energy usage by various biodiesel production methods.

Technique/Reactor	Experimental Settings	Energy consumed (kJ/g)	Reference
Heating/Conventional	Camelina sativa oil with 10 g of oil, 14 min, 510 W	51	[234]
Ultrasonic	Vegetable oil with 54 g of oil, 30.4 min & 140 W	5.8	[235]
Microwave	Nagchampa oil with 155 W, 32 min, 21 g oil	6.4	[196]
Simultaneous (microwave & ultrasound)	Waste vegetable oil with 17 g of oil, 3 min, 110 MW	1.4	[236]
Sequential ultrasound and microwave	Waste cooking oil with 4100 g of oil, 16 min, 320 MW	2.35	[181]

cause of the reactor's reduced size. The smaller the equipment, the smaller the plant's overall footprint must be. Due to the necessity for a bigger capacity column to handle a larger amount of biodiesel, the cost of the distillation column in the downstream stages, which contributed around 23 % of the overall equipment cost, was the second greatest cost of the stirred tank reactor. Contrarily, the ultrasonic cavitation reaction's column purchase cost, which accounted for 29 % of the total, was the most expensive piece of equipment. The methanol separation stages were another piece of acquired equipment whose cost affected the purchased equipment cost. The cost of this separation column in the stirred tank reactor was higher by 11.3 % than the cost of an ultrasonic. This is because stirred tank reactors produce less unreacted methanol than ultrasonic cavitation, which results in a lower reaction yield [221].

Three biodiesel plants studied by Dongwoo Lee et al. [237] had an annual production capacity of 40,000 t/yr. The first plant used a plug flow reactor to produce biodiesel from soybean oil using the supercritical method (also called SC-PFR). The second and third plants used packed bed reactors catalyzed by CuO (also called Cu-based PBR) and Pd/Al_2O_3(also called Pd-based PBR) to produce biodiesel from soybean oil, respectively. Total capital expenditures for SC PFR, Cu-based PBR, and Pd-based PBR from soybean oil were calculated to be $29.4 million, $21 million, and $15,800,000, respectively [237]. Although the annual production capacity of the biodiesel plant intensified by ultrasonic cavitation was 50,000 t/yr, the total capital investment was only $4,027,000 [221], which is 7.35 times less than the SC PFR plant, 5.25 times less than the Cu-based PBR plant, and 3.95 times less than the Pd-based PBR plant.

8.1.1.2. Production costs. Both stirred tank reactor and ultrasonic cavitation were expected to have production costs of $56,673,000 and $53,710,000, respectively. This meant that the ultrasonic cavitation product was 5.2 % less than that of the stirred tank reactor. Vegetable oil was the primary cost factor in the manufacturing of biodiesel. The oil cost was 4 % lower than the stirred tank reactor due to ultrasonic cavitation's better conversion efficiency. The cost of chemicals alone in the stirred tank reactor was greater than the cost of ultrasonic cavitation by 2.2 %. Other product expenses, such as the cost of utilities, labor, and chemicals, were lower in the stirred tank reactor than in ultrasonic cavitation by 7.7 %. Utility costs were another noteworthy difference, with the ultrasonic cavitation process using 23 % less energy than the stirred tank reactor. This was brought on by the condenser, boiler, and electricity using more steam and cooling water. Additionally, stirred tank reactors used nearly three times as much energy as ultrasonic cavitation [221]. This was caused by the strong creation and collapse of smaller holes, which resulted in micromixing and a slower transesterification reaction time [238]. Additionally, stirred tank reactors used in the methanol separation and biodiesel purification used 26.5 % and 1.3 % more energy than ultrasonic cavitation. This is because less methanol was transported because of its increased efficiency, and the cost of waste disposal was around 20 % less than with a stirred tank reactor. The cost of producing biodiesel using ultrasonic cavitation was $1024/t less than the recent US pricing of $1090/t, which seems more reasonable given the current state of the economy [221].

8.1.1.3. Profitability. Profitability gauges how economically and practically feasible the biodiesel-producing process is. The net present value, payback period, and return on investment can all be used to determine profitability [239]. According to Tasic et al. [241] and Lee et al. [240], the homogeneously and heterogeneously catalyzed stirred tank reactor had a negative net present value [240,241]. However, because of decreased capital and product costs, which allowed for better sales margins at the selling price of $1090/t, the net present value of sunflower oil transesterification intensified by ultrasonic cavitation was positive. According to Tasic et al. [240] and Lee et al. [241], the payback period for homogeneously catalyzed transesterification using a stirred tank was 7.9 and 9.2 years, respectively [240,241]. At the end of the first operating year, the ultrasonic cavitation intensified reaction's payback period was 7.2 years. At the end of the first year, the internal rate of return was 18.28 %. Due to its greater internal rate of return and net present value, ultrasonic cavitation intensification is therefore more profitable than a stirred tank reactor. However, the problems with the commercial scale-up implementation have not yet been resolved. This could be resolved by combining many reactors, increasing the yield of biodiesel [162].

8.1.2. Economic analysis of hydrodynamic cavitation process

In a separate study, Ali Gholami et al. [183] conducted an economic analysis of both of the biodiesel plants, both of which had an annual capacity of 33,000 t/yr and had been in operation for 7920 h per year. To produce biodiesel from sunflower oil, one of the plants utilized hydrodynamic cavitation, and the other one employed a mechanically stirred tank reactor [183].

8.1.2.1. Total capital investment. The hydrodynamic cavitation intensified biodiesel plant's total capital investment was roughly 33.3 % of that of the mechanically stirred tank reactor biodiesel plant. Because there were fewer and smaller pieces of equipment used in the process, the hydrodynamic cavitation intensification biodiesel plant required less capital investment. Hydrodynamic cavitation can reduce the cost of the upstream and downstream streams of the mechanically stirred reactor plant by 27 % and 47 %, respectively. In the mechanically stirred tank reactor, the cost of the distillation column purchased accounts for 31 %. This was due to the need for greater capacity columns to handle large amounts of biodiesel. The size of the column that was necessary was lowered, nevertheless, due to the reactor's improved performance in the hydrodynamic cavitation system. A water washing column downstream for both mechanically stirred reactors and hydrodynamic cavitation was the second most expensive piece of equipment, costing 22 % and 41 %, respectively. The mechanically stirred tank reactor system and the hydrodynamic cavitation system both accounted for 18 % and 30 % of the third-highest purchased columns, respectively, which was the methanol separation column. Due to the hydrodynamic system's better conversion efficiency, a distillation column with a smaller diameter was suitable, resulting in a 14 % decrease in the mechanically stirred reactor's column cost. In the end, the mechanically stirred reactor cost was 18 % covered by the cost of the bought equipment for the hydrodynamic cavitation reactor. The shorter residence period in the hydrodynamic cavitation reactor was the cause of this difference's magnitude. Overall, the findings showed that the hydrodynamic cavitation biodiesel factory required around

65 % less capital than the mechanical stirring tank plant [183].

Yamuna Thoppil et al. [242] stated that the total capital investment and fixed cost for a biodiesel plant that produced biodiesel from soybean oil using the conventional method were $122,828,695 and $55,620,541 respectively. However, it was discovered that the hydrodynamic cavitation intensification biodiesel manufacturing method required $4,027,000 in total capital expenditure and $2, 743,000 in fixed capital investment, respectively [242]. This demonstrated a notable difference between using hydrodynamic cavitation to reduce total capital investment and fixed capital investment.

8.1.2.2. Total product cost. According to the study, Ali Gholami et al. [183] using a mechanical stirred tank reactor system instead of a hydrodynamic cavitation system allowed for a 10 % reduction in overall product cost. The raw material, sunflower oil, which accounted for more than 66 % of the overall cost of production, was the cause of the higher product cost. However, due to the reactor's improved conversion efficiency, just a modest amount of sunflower oil was needed for the hydrodynamic cavitation system plant. As a result, the price of sunflower oil in the hydrodynamic cavitation plate was 5 % less than that of the manually stirred tank reactor. The contribution of chemicals, utilities, and labor to both biodiesel plants resulted in the second-highest product cost. In comparison to stirred tank reactor-based biodiesel plants, their total cost was 17 % cheaper than the hydrodynamic cavitation-based plant. 6.5 % of the total production costs at both sites were attributable to the cost of chemicals alone. The hydrodynamic cavitation plant's utility costs were a considerable 15 % less than those of the manually stirred tank-based biodiesel facility. This was explained by the increased amount of steam used in the downstream process at the distillation column of the mechanically stirred tank reactor plant. The reactor in the hydrodynamic cavitation system used 6.37 kW while the reactor in the mechanically stirred tank reactor used 19.1 kW. This was owing to the efficient and vigorous microscopic mixing of methanol and oil in the hydrodynamic cavitation system brought about by the continual creation and collapse of bubbles. Per ton of biodiesel produced by using hydrodynamic cavitation, the total product cost was $975 [183].

The cost of producing biodiesel using fresh palm oil and a mechanically stirred tank reactor system was $1087/t, according to Sakdasri et al. [243]. They set the market price for palm oil at $580/t, which was 19 % less than the price of sunflower oil [243]. On the other side, Marchetti et al. [244] used a stirred tank reaction system and set a lower bound selling cost of $1058/t [244]. Additionally, Lee et al. [245] estimated that microalgae could be produced at a minimum cost of $3500/t [245]. The final product cost of closed-loop hydrodynamic cavitation was $986/t, suggesting that the system for intensifying hydrodynamic cavitation in the production of biodiesel might be competitive in terms of total production costs [183]. According to Yamuna Thoppil et al. [242] the plant that produced 2600 t/yr of biodiesel from coffee oil derived from used coffee grounds using a mechanically stirred tank reactor required a total production cost of cost $6,952,567 [242]. Although the facility had a 33,000 t/y annual output capacity, its total production cost was only $605,000 thanks to the hydrodynamic cavitation intensified reactor's effective functioning [183]. The more effective reactor might use fewer raw materials and labor costs to operate.

8.1.2.3. Profitability. To assess the profitability of these two varieties of plants, the net present value was chosen as a metric. Mechanically stirred tank reactor-based plants had a negative net present value. It was not a lucrative plant as a result. Additionally, some researchers conducted economic analyses of biodiesel synthesis from canola oil catalyzed by the basic homogeneous catalyst and biodiesel production from sunflower oil catalyzed by the basic homogeneous and heterogeneous catalyst, reported a similar situation [237,240,241]. However, because hydrodynamic cavitation was more effective, the net present value was positive and had a return on investment of 25.6 %. Additionally, Lee et al. [237] revealed that the payback period of a hydrodynamic cavitation-based biodiesel facility was 3.9 and 5.2 years shorter. According to Dongwoo Lee et al. [237], the payback period for the supercritical technique of producing biodiesel from soybean oil was approximately 10 years, which was longer than 3 years when the hydrodynamic cavitation process intensifies the biodiesel production process [237].

8.2. Economic analysis of microwave reactor

8.2.1. Energy input-output analysis and economic evaluation

The scaling up to the industrial level of biodiesel production has some significant disadvantages. Research, additional knowledge of input-output energy, and economic analysis are important in achieving this. One technique for analyzing issues of sustainability is energy analysis [246].

8.2.1.1. Energy input-output analysis. Neda Yari et al. [128] assessed the input-output energy of the production of biodiesel from fish oil using potassium methoxide as the catalyst. Methanol, glycerol, biodiesel catalysts, mono and diglycerides, electrical energy, fish oil, methanol, potassium methoxide, and labor were considered the output energies in their study [128]. Energy productivity, which measures the weight of biodiesel to energy input, energy ratio, specific energy, and net energy which measures the difference between input and output energy was the energy input and output indicators used [246,247]. For the synthesis of microwave-irradiated biodiesel from fish oil, the total input and output were 48.8 and 50.8 MJ per litter of biodiesel, respectively. 85.9 % fish oil, 12.2 % methanol, 0.4 % catalyst, 1.3 % electrical energy, 0.18 % machine energy, and 0.07 % labor force made up the input energies. Therefore, the higher value of the input energies was given by the fish oil. Additionally, 0.017 kg of biodiesel were produced for every MJ of energy, with a kilogram of biodiesel requiring 59.81 MJ of specific energy. The net energy produced by the transesterification reaction was 2.02 MJ/litter, and the energy ratio was 1.04. The energy ratio of 1.041 meant that for every single MJ of energy consumed, 0.018 kg of biodiesel was produced, yielding an output energy of 1.041 MJ. The reaction generated 2.03 MJ of net energy

per litter of biodiesel [128]. The fact that the net energy was positive shows that energy was used throughout the process of making biodiesel [246,248]. Production of microwave-intensified biodiesel from fish oil used 85.7 % renewable energy and 14.3 % non-renewable energy, respectively [128].

The share of renewable and non-renewable energies used in the conventional biodiesel production process, however, was 77 % and 23 %, respectively [248]. This showed that the intensification of biodiesel production using microwave radiation generated more renewable energy than the traditional approach. From an energy perspective, it is desirable to use the microwave irradiation technique of biodiesel synthesis because non-renewable energy sources are not replenishable naturally [246]. According to the paper, 1.05 kg of fish oil, 0.263 kg of methanol, 0.009 kg of catalyst, 0.002 kWh of electrical energy, and 0.1 h of machine energy were all utilized to make 1L of biodiesel from fish oil that had been microwave-intensified [128]. However, Leila Naderloo et al. [246] reported that 0.033 h of labor force, 1.184 kg of used cooking oil, 0.169 kg of methanol, 0.012 kg of catalyst, 0.002 kW h of electrical energy, and 0.1 h of mechanical energy were required to produce one litter of biodiesel intensified by ultrasonic device [246]. This demonstrated that producing 1L of biodiesel required the same amount of mechanical and electrical energy as producing the same amount of oil and catalyst.

8.2.1.2. Economic evaluation. The economic worth of the process could be assessed using input-output analysis. The primary unit of cost assessment can be the volume of biodiesel produced. Product costs come in two flavors: fixed costs and variable costs. The price of chemicals, oil, labor, and electrical energy were the variable product costs of biodiesel produced from fish oil and amplified by microwave irradiation, according to Neda Yari et al. [128]. The only output taken into account in their computation was biodiesel. The biodiesel yield was 99 %. By calculating the gross margin, the total cost of production, fixed costs, variable costs, and productivity, an economic analysis was carried out. The mass of biodiesel to the overall cost of the product is the ratio of economic productivity. The variable production cost, fixed production cost, and total production cost per liter of biodiesel for the microwave-assisted manufacture of biodiesel from fish oil were determined to be 0.6502$, 0.0039$, and 0.6541$, respectively. Additionally, the productivity was 1.6637 kg/$, meaning that 1.7 kg of biodiesel from fish oil were produced for every dollar invested with the use of microwave irradiation. The variable production cost, fixed production cost, and total production cost per liter of biodiesel generated using the conventional technique were determined to be 1.197 $, 0.004 $, and 1.201 $, respectively. Additionally, the productivity was 0.946 kg/$. Therefore, by using microwave irradiation to produce biodiesel, the cost per liter of biodiesel may be decreased by 45.6 %, 25 %, and 45.5 %, respectively, compared to the conventional method of production. By using microwave intensification, productivity can be increased by 38.5 % compared to the productivity of the conventional approach, or by 0.4637 kg/$ [128].

9. Conclusions

Green technology innovation can assist in striking a balance between improved environmental management and sustainable economic development. Biomass is a more environmentally friendly and sustainable energy source than fossil fuels. Since biomass is renewable and carbon neutral, it has attracted a lot of interest in its synthesis and production as biofuels. Recent research on the intensification of biodiesel production using cavitation and microwave reactors indicates that these technologies have the potential to increase the yield, energy efficiency, and financial sustainability of biodiesel production. This paper amply illustrated the effects of process variables for microwave and cavitation-aided biodiesel transesterification process. It has been described in various practical studies that have been carried out under optimal circumstances how microwave and cavitation-aided amplification are better than the conventional in terms of biodiesel yield. The authors conclude that while cavitation and microwave reactors may involve higher initial investment costs, their improved energy efficiency, and higher biodiesel yield can lead to cost savings in the long run. Furthermore, activation energy analysis plays a crucial role in understanding the biodiesel intensification process using cavitation and microwave reactors. Moreover, the study assesses these technologies' energy efficiency and contrasts it with conventional biodiesel production methods. Promising advantages such as improved product yields, shorter reaction times, lower energy consumption, and enhanced economic viability are provided by cavitation and microwave reactors. These advantages are attained through improving reaction kinetics and lowering the requirement for catalysts, doing away with the need for a lot of chemicals, and saving energy. The assessment also emphasizes how important it is to carry out a comprehensive review of the financial viability of employing these technologies. The review concludes that cavitation and microwave process intensification of biodiesel provides opportunities for future perspectives as well as suggestions concerning the selection criteria of raw materials, catalysts, and processing methods to make the production of biodiesel more affordable, quick, environmentally friendly, clean, and sustainable.

10. Future outlook

In addition to developing technologies for cavitation and microwave reactors in the production of biodiesel, further in-depth study is still needed to optimize the current technology to scale it up for use in commercial applications. Moving ahead, the biofuel sector should also take into account specific environmental sustainability methods like life cycle assessment and energy and exergy studies of production processes to assess their financial worth and environmental impact. Researchers can determine the most sustainable and energy-efficient methods by investigating more on those reactor designs, process variables, and feedstock sources to apply the technologies in large-scale biodiesel production. Further research and development in this area could facilitate the widespread adoption of these technologies in the biodiesel industry. From an economic standpoint, the biodiesel production industry may experience reductions in costs when cavitation and microwave reactors are employed more frequently.

Data availability statement

No data was used for the research described in the article.

CRediT authorship contribution statement

Yonas Desta Bizualem: Writing – review & editing, Writing – original draft, Visualization, Resources, Investigation, Conceptualization. **Amare Gashu Nurie:** Writing – original draft, Visualization, Supervision, Resources, Investigation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] L.F. Chuah, et al., Marine environment and maritime safety assessment using Port State Control database, Chemosphere 304 (2022) 135245.
[2] S. Rahim, et al., Do natural resources abundance and human capital development promote economic growth? A study on the resource curse hypothesis in the Next Eleven countries, Resources, Environment and Sustainability 4 (2021) 100018.
[3] W. Chen, Y. Lei, The impacts of renewable energy and technological innovation on environment-energy-growth nexus: new evidence from a panel quantile regression, Renew. Energy 123 (2018) 1–14.
[4] Z. Chen, et al., Can green credit policy promote low-carbon technology innovation? J. Clean. Prod. 359 (2022) 132061.
[5] S. Griffiths, et al., Decarbonizing the oil refining industry: a systematic review of sociotechnical systems, technological innovations, and policy options, Energy Res. Social Sci. 89 (2022) 102542.
[6] S. Afshan, I. Ozturk, T. Yaqoob, Facilitating renewable energy transition, ecological innovations and stringent environmental policies to improve ecological sustainability: evidence from MM-QR method, Renew. Energy 196 (2022) 151–160.
[7] Z. Yang, et al., Alleviating the misallocation of R&D inputs in China's manufacturing sector: from the perspectives of factor-biased technological innovation and substitution elasticity, Technol. Forecast. Soc. Change 151 (2020) 119878.
[8] Z. Yang, et al., Wage distortion and green technological progress: a directed technological progress perspective, Ecol. Econ. 181 (2021) 106912.
[9] L. Xu, et al., Heterogeneous green innovations and carbon emission performance: evidence at China's city level, Energy Econ. 99 (2021) 105269.
[10] D. Popp, The Role of Technological Change in Green Growth, 2012.
[11] A.E. Caglar, M. Ulug, The role of government spending on energy efficiency R&D budgets in the green transformation process: insight from the top-five countries, Environ. Sci. Pollut. Control Ser. 29 (50) (2022) 76472–76484.
[12] M. Umar, et al., The imperativeness of environmental quality in the United States transportation sector amidst biomass-fossil energy consumption and growth, J. Clean. Prod. 285 (2021) 124863.
[13] M. Asadullah, et al., Optimization of palm kernel shell torrefaction to produce energy densified bio-coal, Energy Convers. Manag. 88 (2014) 1086–1093.
[14] H.C. Ong, et al., Catalytic thermochemical conversion of biomass for biofuel production: a comprehensive review, Renew. Sustain. Energy Rev. 113 (2019) 109266.
[15] A.T. Hoang, et al., Progress on the lignocellulosic biomass pyrolysis for biofuel production toward environmental sustainability, Fuel Process. Technol. 223 (2021) 106997.
[16] A. Saravanan, et al., Recent advances and sustainable development of biofuels production from lignocellulosic biomass, Bioresour. Technol. 344 (2022) 126203.
[17] A.H. Alami, et al., Investigating algae for CO2 capture and accumulation and simultaneous production of biomass for biodiesel production, Sci. Total Environ. 759 (2021) 143529.
[18] N.S. Ab Rasid, et al., Recent advances in green pre-treatment methods of lignocellulosic biomass for enhanced biofuel production, J. Clean. Prod. 321 (2021) 129038.
[19] M.E. Bildirici, Economic growth, and biomass energy, Biomass Bioenergy 50 (2013) 19–24.
[20] E. Commission, EU Agricultural Outlook for Markets, Income, and Environment, European Commission, DG Agriculture and Rural Development Brussels, 2020, 2020–2030.
[21] B. Kupiec, Legal Status of a Renewables Self-Consumer under Polish Law in Light of Directive (EU) 2018/2001 of the European Parliament and the Council of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources, 2021.
[22] A. Van Grinsven, et al., Used Cooking Oil (UCO) as a Biofuel Feedstock in the EU, CE Delft, Delft, The Netherlands, 2020 200247.
[23] P. Ruiz, et al., ENSPRESO-an open, EU-28 wide, transparent, and coherent database of wind, solar and biomass energy potentials, Energy Strategy Rev. 26 (2019) 100379.
[24] M. Munir, et al., Sustainable production of bioenergy from novel non-edible seed oil (Prunus cerasoides) using bimetallic impregnated montmorillonite clay catalyst, Renew. Sustain. Energy Rev. 109 (2019) 321–332.
[25] S. Sahani, T. Roy, Y.C. Sharma, Clean and efficient production of biodiesel using barium cerate as a heterogeneous catalyst for the biodiesel production; kinetics and thermodynamic study, J. Clean. Prod. 237 (2019) 117699.
[26] B.R. Vahid, M. Haghighi, Biodiesel production from sunflower oil over MgO/MgAl2O4 nanocatalyst: effect of fuel type on catalyst nanostructure and performance, Energy Convers. Manag. 134 (2017) 290–300.
[27] S.-Y. Chen, et al., Carbonaceous Ti-incorporated SBA-15 with enhanced activity and durability for high-quality biodiesel production: synthesis and utilization of the P123 template as carbon source, Appl. Catal. B Environ. 181 (2016) 800–809.
[28] T. Kober, et al., Global energy perspectives to 2060–WEC's world energy scenarios 2019, Energy Strategy Rev. 31 (2020) 100523.
[29] R. Foroutan, et al., Transesterification of waste edible oils to biodiesel using calcium oxide@ magnesium oxide nanocatalyst, Waste Manag. 105 (2020) 373–383.
[30] M. Olkiewicz, et al., Biodiesel production from sewage sludge lipids catalyzed by Brønsted acidic ionic liquids, Appl. Catal. B Environ. 181 (2016) 738–746.
[31] J. Van Gerpen, Biodiesel processing and production, Fuel Process. Technol. 86 (10) (2005) 1097–1107.
[32] B. Freedman, E. Pryde, T. Mounts, Variables affecting the yields of fatty esters from transesterified vegetable oils, J. Am. Oil Chem. Soc. 61 (10) (1984) 1638–1643.
[33] H.C. Ong, et al., Engine performance and emissions using Jatropha curcas, Ceiba pentandra, and Calophyllum inophyllum biodiesel in a CI diesel engine, Energy 69 (2014) 427–445.
[34] L.F. Chuah, et al., Kinetic studies on waste cooking oil into biodiesel via hydrodynamic cavitation, J. Clean. Prod. 146 (2017) 47–56.
[35] B.H. Samani, et al., The rotor-stator type hydrodynamic cavitation reactor approach for enhanced biodiesel fuel production, Fuel 283 (2021) 118821.
[36] A.V. Mohod, et al., Intensification of biodiesel production using hydrodynamic cavitation based on high-speed homogenizer, Chem. Eng. J. 316 (2017) 751–757.

[37] M. Farvardin, et al., Enhancement of biodiesel production from waste cooking oil: ultrasonic-hydrodynamic combined cavitation system. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 2019, pp. 1–15.
[38] T. Mahlia, et al., Patent landscape review on biodiesel production: technology updates, Renew. Sustain. Energy Rev. 118 (2020) 109526.
[39] B.S. Caldas, et al., Supercritical ethanolysis for biodiesel production from edible oil waste using ionic liquid [HMim][HSO4] as catalyst, Appl. Catal. B Environ. 181 (2016) 289–297.
[40] J. Gardy, et al., Biodiesel production from used cooking oil using a novel surface functionalized TiO2 nano-catalyst, Appl. Catal. B Environ. 207 (2017) 297–310.
[41] A. Demirbas, Progress and recent trends in biodiesel fuels, Energy Convers. Manag. 50 (1) (2009) 14–34.
[42] V. Singh, et al., Biodiesel production using a novel heterogeneous catalyst, magnesium zirconate (Mg2Zr5O12): process optimization through response surface methodology (RSM), Energy Convers. Manag. 174 (2018) 198–207.
[43] M.K. Lam, K.T. Lee, A.R. Mohamed, Life cycle assessment for the production of biodiesel: a case study in Malaysia for palm oil versus jatropha oil, Biofuels, Bioproducts, and Biorefining: Innovation for a sustainable economy 3 (6) (2009) 601–612.
[44] S. Dwivedy, K. Rayaguru, G. Sahoo, Effect of drying methods on quality characteristics of medicinal Indian borage (Coleus aromaticus) leaves, J. Food Process. Technol. 3 (11) (2012) 1–6.
[45] S. Hoseini, et al., Biodiesels from three feedstock: the effect of graphene oxide (GO) nanoparticles diesel engine parameters fuelled with biodiesel, Renew. Energy 145 (2020) 190–201.
[46] S. Hoseini, et al., Characterization of biodiesel production (ultrasonic-assisted) from evening-primroses (Oenothera lamarckiana) as novel feedstock and its effect on CI engine parameters, Renew. Energy 130 (2019) 50–60.
[47] G.P. Pousa, A.L. Santos, P.A. Suarez, History and policy of biodiesel in Brazil, Energy Pol. 35 (11) (2007) 5393–5398.
[48] U. Rajak, T.N. Verma, Effect of emission from ethylic biodiesel of edible and non-edible vegetable oil, animal fats, waste oil and alcohol in CI engine, Energy Convers. Manag. 166 (2018) 704–718.
[49] H.C. Ong, et al., Biodiesel production from Calophyllum inophyllum-Ceiba pentandra oil mixture: optimization and characterization, J. Clean. Prod. 219 (2019) 183–198.
[50] A.S. Silitonga, et al., Biodiesel synthesis from Ceiba pentandra oil by microwave irradiation-assisted transesterification: ELM modeling and optimization, Renew. Energy 146 (2020) 1278–1291.
[51] S. Hoseini, et al., Performance and emission characteristics of a CI engine using graphene oxide (GO) nano-particle additives in biodiesel-diesel blends, Renew. Energy 145 (2020) 458–465.
[52] B. Hosseinzadeh Samani, et al., Evaluation of an enhanced ultrasonic-assisted biodiesel synthesized using safflower oil in a diesel power generator, Biofuels 11 (4) (2020) 523–532.
[53] I.B. Banković-Ilić, O.S. Stamenković, V.B. Veljković, Biodiesel production from non-edible plant oils, Renew. Sustain. Energy Rev. 16 (6) (2012) 3621–3647.
[54] J. Jitjamnong, Effect of barium loading on CaO derived from waste egg shell heterogeneous catalyst for canola oil biodiesel, in: MATEC Web of Conferences, EDP Sciences, 2018.
[55] F. Jamil, et al., Biodiesel production by valorizing waste Phoenix dactylifera L. Kernel oil in the presence of synthesized heterogeneous metallic oxide catalyst (Mn@ MgO-ZrO2), Energy Convers. Manag. 155 (2018) 128–137.
[56] S.P. Souza, J.E. Seabra, L.A.H. Nogueira, Feedstocks for biodiesel production: Brazilian and global perspectives, Biofuels 9 (4) (2018) 455–478.
[57] S.K. Bhatia, et al., Conversion of waste cooking oil into biodiesel using heterogeneous catalyst derived from cork biochar, Bioresour. Technol. 302 (2020) 122872.
[58] B.A. Guneser, E. Yilmaz, S. Ok, Cold pressed versus refined winterized corn oils: quality, composition and aroma, Grasas Aceites 68 (2) (2017) e194-e194.
[59] I. Ambat, V. Srivastava, M. Sillanpää, Recent advancement in biodiesel production methodologies using various feedstock: a review, Renew. Sustain. Energy Rev. 90 (2018) 356–369.
[60] R.B. Latha, D. Nasirullah, Physico-chemical changes in rice bran oil during heating at frying temperature, J. Food Sci. Technol. 51 (2014) 335–340.
[61] M.O. Lari, A.Z. Sahin, Effect of retrofitting a silver/water nanofluid-based photovoltaic/thermal (PV/T) system with a PCM-thermal battery for residential applications, Renew. Energy 122 (2018) 98–107.
[62] S.K. Nayak, P.C. Mishra, Investigation on jojoba biodiesel and producer gas in dual-fuel mode, Energy Sources, Part A Recovery, Util. Environ. Eff. 38 (15) (2016) 2265–2271.
[63] A. Sarve, M.N. Varma, S.S. Sonawane, Optimization and kinetic studies on biodiesel production from Kusum (schleichera triguga) oil using response surface methodology, J. Oleo Sci. 64 (9) (2015) 987–997.
[64] C. Solaimuthu, D. Senthilkumar, K. Ramasamy, An Experimental Investigation of Performance, Combustion and Emission Characteristics of Mahua (Madhuca Indica) Oil Methyl Ester on Four-Stroke Direct Injection Diesel Engine, 2013.
[65] S. Sahay, U. Yadav, S. Srinivasamurthy, Potential of Moringa oleifera as a functional food ingredient: a review, Magnesium 8 (9.06) (2017) 4–90.
[66] S.V. Mazanov, et al., Continuous production of biodiesel from rapeseed oil by ultrasonic assist transesterification in supercritical ethanol, J. Supercrit. Fluids 118 (2016) 107–118.
[67] I. Nurfitri, et al., Potential of feedstock and catalysts from waste in biodiesel preparation: a review, Energy Convers. Manag. 74 (2013) 395–402.
[68] J.M. Dias, C.A. Ferraz, M.F. Almeida, Using mixtures of waste frying oil and pork lard to produce biodiesel, World Academy of Science, Engineering and Technology 44 (2008) 258–262.
[69] M. Canakci, A.N. Özsezen, Evaluating waste cooking oils as alternative diesel fuel, Gazi University Journal of Science 18 (1) (2005) 81–91.
[70] R. Ramaraj, R. Kawaree, Y. Unpaprom, Direct transesterification of microalga Botryococcus braunii biomass for biodiesel production, Emergent Life Sciences Research 2 (2016) 1–7.
[71] K. Zhang, et al., Lipid production and composition of fatty acids in Chlorella vulgaris cultured using different methods: photoautotrophic, heterotrophic, and pure and mixed conditions, Ann. Microbiol. 64 (3) (2014) 1239–1246.
[72] C. Ratledge, et al., Downstream processing, extraction, and purification of single cell oils, in: Single Cell Oils, Elsevier, 2010, pp. 179–197.
[73] J. Zhang, et al., Process characteristics for microwave-assisted hydrothermal carbonization of cellulose, Bioresour. Technol. 259 (2018) 91–98.
[74] J. Fan, et al., Direct microwave-assisted hydrothermal depolymerization of cellulose, J. Am. Chem. Soc. 135 (32) (2013) 11728–11731.
[75] A. de la Hoz, A. Diaz-Ortiz, A. Moreno, Microwaves in organic synthesis. Thermal and non-thermal microwave effects, Chem. Soc. Rev. 34 (2) (2005) 164–178.
[76] J. Tanner, C. Romero-Sierra, S. Davie, Non-thermal effects of microwave radiation on birds, Nature 216 (5120) (1967), 1139-1139.
[77] A.W. Go, et al., Biodiesel production under subcritical solvent condition using subcritical water treated whole Jatropha curcas seed kernels and possible use of hydrolysates to grow Yarrowia lipolytica, Fuel 120 (2014) 46–52.
[78] V. Kesari, B. Basu, High Power Microwave Tubes: Basics and Trends, Morgan & Claypool Publishers San Rafael, CA, USA, 2018.
[79] G.B. Dudley, R. Richert, A. Stiegman, On the existence of and mechanism for microwave-specific reaction rate enhancement, Chem. Sci. 6 (4) (2015) 2144–2152.
[80] S. Chandrasekaran, S. Ramanathan, T. Basak, Microwave material processing—a review, AIChE J. 58 (2) (2012) 330–363.
[81] A. Tangy, et al., Continuous flow through a microwave oven for the large-scale production of biodiesel from waste cooking oil, Bioresour. Technol. 224 (2017) 333–341.
[82] Y. Fernández, et al., Comparative study of conventional and microwave-assisted pyrolysis, steam and dry reforming of glycerol for syngas production, using a carbonaceous catalyst, J. Anal. Appl. Pyrol. 88 (2) (2010) 155–159.
[83] S.S. Lam, A.D. Russell, H.A. Chase, Microwave pyrolysis, a novel process for recycling waste automotive engine oil, Energy 35 (7) (2010) 2985–2991.
[84] R. Omar, J.P. Robinson, Conventional and microwave-assisted pyrolysis of rapeseed oil for biofuel production, J. Anal. Appl. Pyrol. 105 (2014) 131–142.
[85] Q. Guo, et al., Microwave processing techniques and their recent applications in the food industry, Trends Food Sci. Technol. 67 (2017) 236–247.

[86] R. Vadivambal, D. Jayas, Non-uniform temperature distribution during microwave heating of food materials—a review, Food Bioprocess Technol. 3 (2) (2010) 161–171.
[87] S. Singh, et al., Microwave processing of materials and applications in manufacturing industries: a review, Mater. Manuf. Process. 30 (1) (2015) 1–29.
[88] W. Abdelmoez, E. Ashour, S.M. Naguib, A review on green trend for oil extraction using subcritical water technology and biodiesel production, J. Oleo Sci. 64 (5) (2015) 467–478.
[89] M. Dębowski, et al., Evaluation of anaerobic digestion of dairy wastewater in an innovative multi-section horizontal flow reactor, Energies 13 (9) (2020) 2392.
[90] M. Zieliński, M. Dębowski, P. Rusanowska, Influence of microwave heating on biogas production from Sida hermaphrodita silage, Bioresour. Technol. 245 (2017) 1290–1293.
[91] M. Zieliński, et al., Comparison of microwave thermohydrolysis and liquid hot water pretreatment of energy crop Sida hermaphrodita for enhanced methane production, Biomass Bioenergy 128 (2019) 105324.
[92] S.N. Nayak, C.P. Bhasin, M.G. Nayak, A review on microwave-assisted transesterification processes using various catalytic and non-catalytic systems, Renew. Energy 143 (2019) 1366–1387.
[93] S.X. Tan, et al., State of the art review on development of ultrasound-assisted catalytic transesterification process for biodiesel production, Fuel 235 (2019) 886–907.
[94] M.Z. Arniza, et al., Synthesis of transesterified palm olein-based polyol and rigid polyurethanes from this polyol, J. Am. Oil Chem. Soc. 92 (2) (2015) 243–255.
[95] C.O. Kappe, Microwave dielectric heating in synthetic organic chemistry, Chem. Soc. Rev. 37 (6) (2008) 1127–1139.
[96] E. Martinez-Guerra, et al., Microwave and ultrasound enhanced extractive-transesterification of algal lipids, Appl. Energy 129 (2014) 354–363.
[97] P.D. Patil, et al., Optimization of microwave-assisted transesterification of dry algal biomass using response surface methodology, Bioresour. Technol. 102 (2) (2011) 1399–1405.
[98] D.C. Campos, et al., Investigation of dielectric properties of the reaction mixture during the acid-catalyzed transesterification of Brazil nut oil for biodiesel production, Fuel 117 (2014) 957–965.
[99] J. Bart, E. Gucciardi, S. Cavallaro, Lubricant Use and Disposal, Biolubricants: science and technology, 2013, pp. 755–823.
[100] L. Guan, et al., Application of dielectric spectroscopy for engine lubricating oil degradation monitoring, Sensor Actuator Phys. 168 (1) (2011) 22–29.
[101] P. Lidström, et al., Microwave assisted organic synthesisÐa review, Tetrahedron 57 (2001) 9225–9283.
[102] N.A. Mohamad Aziz, et al., Prospects and challenges of microwave-combined technology for biodiesel and biolubricant production through a transesterification: a review, Molecules 26 (4) (2021) 788.
[103] A.K. Man, R. Shahidan, Microwave-assisted chemical reactions, J. Macromol. Sci., Pure Appl. Chem. 44 (6) (2007) 651–657.
[104] D. Bogdal, Microwave-assisted Organic Synthesis: One Hundred Reaction Procedures, Elsevier, 2005.
[105] B.G. Terigar, et al., Transesterification of soybean and rice bran oil with ethanol in a continuous-flow microwave-assisted system: yields, quality, and reaction kinetics, Energy Fuel. 24 (12) (2010) 6609–6615.
[106] B.L. Hayes, Recent advances in microwave-assisted synthesis, Aldrichim Acta 37 (2) (2004) 66–77.
[107] J. Alcañiz-Monge, et al., Zirconia-supported tungstophosphoric heteropolyacid as heterogeneous acid catalyst for biodiesel production, Appl. Catal. B Environ. 224 (2018) 194–203.
[108] S. Balasubramanian, et al., Oil extraction from Scenedesmus obliquus using a continuous microwave system–design, optimization, and quality characterization, Bioresour. Technol. 102 (3) (2011) 3396–3403.
[109] R. Halim, M.K. Danquah, P.A. Webley, Extraction of oil from microalgae for biodiesel production: a review, Biotechnol. Adv. 30 (3) (2012) 709–732.
[110] S.S. Lam, H.A. Chase, A review on waste to energy processes using microwave pyrolysis, Energies 5 (10) (2012) 4209–4232.
[111] V.G. Gude, et al., *Microwave enhanced Methods for Biodiesel Production and Other Environmental Applications.* Green Chemistry for Environmental Remediation, Wiley Interscience, New York, 2011, pp. 209–249.
[112] S.N. Nayak, M.G. Nayak, C.P. Bhasin, Parametric, kinetic, and thermodynamic studies of microwave-assisted esterification of Kusum oil, Fuel Communications 8 (2021) 100018.
[113] S. Oza, et al., An ultrasound-assisted process for the optimization of biodiesel production from waste cottonseed cooking oil using response surface methodology, Water-Energy Nexus 4 (2021) 187–198.
[114] H. Yuan, B. Yang, G. Zhu, Synthesis of biodiesel using microwave absorption catalysts, Energy Fuel. 23 (1) (2009) 548–552.
[115] A. Kanitkar, et al., A critical comparison of methyl and ethyl esters production from soybean and rice bran oil in the presence of microwaves, Bioresour. Technol. 102 (17) (2011) 7896–7902.
[116] F. Motasemi, F. Ani, A review on microwave-assisted production of biodiesel, Renew. Sustain. Energy Rev. 16 (7) (2012) 4719–4733.
[117] L. Scares, A. Franca, L. Oliveira, Feasibility of biodiesel production in a continuous flow microwave reactor with static mixing, in: 2017 8th International Conference on Mechanical and Aerospace Engineering (ICMAE), IEEE, 2017.
[118] D. Panadare, V. Rathod, Microwave-assisted enzymatic synthesis of biodiesel with waste cooking oil and dimethyl carbonate, J. Mol. Catal. B Enzym. 133 (2016) S518–S524.
[119] J. Giuntoli, Advanced Biofuel Policies in Select EU Member States: 2018 Update, International Council on Clean Transportation, 2018.
[120] K. Thirugnanasambandham, V. Sivakumar, Investigation on biodiesel production from cotton seed oil using microwave irradiated transesterification process, Environ. Prog. Sustain. Energy 34 (4) (2015) 1229–1235.
[121] P. Chipurici, et al., Ultrasonic, hydrodynamic and microwave biodiesel synthesis–A comparative study for continuous process, Ultrason. Sonochem. 57 (2019) 38–47.
[122] F. Bucciol, et al., Enabling technologies and sustainable catalysis in biodiesel preparation, Catalysts 10 (9) (2020) 988.
[123] B.T. Ergan, G. Yılmazer, M. Bayramoğlu, Fast, high quality and low-cost biodiesel production using dolomite catalyst in an enhanced microwave system with simultaneous cooling, Cleaner Chemical Engineering 3 (2022) 100051.
[124] T.M. Barnard, et al., Continuous-flow preparation of biodiesel using microwave heating, Energy Fuel. 21 (3) (2007) 1777–1781.
[125] I. Choedkiatsakul, et al., Biodiesel production in a novel continuous flow microwave reactor, Renew. Energy 83 (2015) 25–29.
[126] S.M. Safieddin Ardebili, X. Ge, G. Cravotto, Flow-mode biodiesel production from palm oil using a pressurized microwave reactor, Green Process. Synth. 8 (1) (2019) 8–14.
[127] I. Choedkiatsakul, et al., Integrated flow reactor that combines high-shear mixing and microwave irradiation for biodiesel production, Biomass Bioenergy 77 (2015) 186–191.
[128] N. Yari, et al., Energy indicators for microwave-assisted biodiesel production from waste fish oil, Energy Sources, Part A Recovery, Util. Environ. Eff. 44 (1) (2022) 2208–2219.
[129] K. Esengun, O. Gündüz, G. Erdal, Input–output energy analysis in dry apricot production of Turkey, Energy Convers. Manag. 48 (2) (2007) 592–598.
[130] T.M. Mata, et al., Properties and sustainability of biodiesel from animal fats and fish oil, Chemical Engineering Transactions 38 (2014) 175–180.
[131] N. Dangol, D.S. Shrestha, J.A. Duffield, Life-cycle energy, GHG and cost comparison of camelina-based biodiesel and biojet fuel, Biofuels 11 (4) (2020) 399–407.
[132] T.L.T. Nguyen, S.H. Gheewala, S. Garivait, Full chain energy analysis of fuel ethanol from cassava in Thailand, Environ. Sci. Technol. 41 (11) (2007) 4135–4142.
[133] S.M. Alimagham, et al., Energy flow analysis and estimation of greenhouse gases (GHG) emissions in different scenarios of soybean production (Case study: gorgan region, Iran), J. Clean. Prod. 149 (2017) 621–628.
[134] J. Singh, On-farm Energy Use Pattern in Different Cropping Systems in Haryana, India. Master of Science, International Institute of Management, University of Flensburg, Germany, 2002.
[135] I.K. Hong, J.W. Park, S.B. Lee, Optimization of fish-oil-based biodiesel synthesis, J. Ind. Eng. Chem. 19 (3) (2013) 764–768.
[136] A. Mohammadi, et al., Energy inputs–yield relationship and cost analysis of kiwifruit production in Iran, Renew. Energy 35 (5) (2010) 1071–1075.

[137] A.C.M. Loy, et al., Development of high microwave-absorptive bifunctional graphene oxide-based catalyst for biodiesel production, Energy Convers. Manag. 180 (2019) 1013–1025.
[138] Moina Athar, Sadaf Zaidi, S.Z. Hassan, Intensification and optimization of biodiesel production using microwave-assisted acid-organo catalyzed transesterification process, Sci. Rep. 10 (2020) 21239.
[139] N. Azcan, O. Yilmaz, Microwave assisted transesterification of waste frying oil and concentrate methyl ester content of biodiesel by molecular distillation, Fuel 104 (2013) 614–619.
[140] M.H. Gina, et al., Effect of microwave-assisted system on transesterification of castor oil with ethanol, Univ. Sci. 19 (3) (2014) 193–200.
[141] R. Kumar, G.R. Kumar, N. Chandrashekar, Microwave-assisted alkali-catalyzed transesterification of Pongamia pinnata seed oil for biodiesel production, Bioresour. Technol. 102 (11) (2011) 6617–6620.
[142] S. Zhang, et al., Rapid microwave-assisted transesterification of yellow horn oil to biodiesel using a heteropolyacid solid catalyst, Bioresour. Technol. 101 (3) (2010) 931–936.
[143] M.-C. Hsiao, C.-C. Lin, Y.-H. Chang, Microwave irradiation-assisted transesterification of soybean oil to biodiesel catalyzed by nanopowder calcium oxide, Fuel 90 (5) (2011) 1963–1967.
[144] G.D. Yadav, M.P. Hude, A.D. Talpade, Microwave-assisted process intensification of lipase-catalyzed transesterification of 1, 2 propanediol with dimethyl carbonate for the green synthesis of propylene carbonate: novelties of kinetics and mechanism of consecutive reactions, Chem. Eng. J. 281 (2015) 199–208.
[145] A. Guldhe, et al., Synthesis of biodiesel from Scenedesmus sp. by microwave and ultrasound-assisted in situ transesterification using tungstated zirconia as a solid acid catalyst, Chem. Eng. Res. Des. 92 (8) (2014) 1503–1511.
[146] N. Tippayawong, P. Sittisun, Continuous-flow transesterification of crude jatropha oil with microwave irradiation, Sci. Iran. 19 (5) (2012) 1324–1328.
[147] C. Mazzocchia, et al., Fatty acid methyl esters synthesis from triglycerides over heterogeneous catalysts in the presence of microwaves, Compt. Rendus Chem. 7 (6–7) (2004) 601–605.
[148] Y. Umar, et al., Valorisation of high acid value waste cooking oil into biodiesel via supercritical methanolysis, ChemEngDayUK 2019 (2019).
[149] M.Y. Ong, et al., Optimization and kinetic study of non-catalytic transesterification of palm oil under subcritical condition using microwave technology, Energy Convers. Manag. 196 (2019) 1126–1137.
[150] S. Saka, Y. Isayama, A new process for catalyst-free production of biodiesel using supercritical methyl acetate, Fuel 88 (7) (2009) 1307–1313.
[151] S. Saka, et al., New process for catalyst-free biodiesel production using subcritical acetic acid and supercritical methanol, Fuel 89 (7) (2010) 1442–1446.
[152] O. Aboelazayem, M. Gadalla, B. Saha, Valorisation of high acid value waste cooking oil into biodiesel using supercritical methanolysis: experimental assessment and statistical optimization on typical Egyptian feedstock, Energy 162 (2018) 408–420.
[153] Z. Ilham, S. Saka, Optimization of supercritical dimethyl carbonate method for biodiesel production, Fuel 97 (2012) 670–677.
[154] O. Farobie, Y. Matsumura, State of the art of biodiesel production under supercritical conditions, Prog. Energy Combust. Sci. 63 (2017) 173–203.
[155] K.T. Tan, K.T. Lee, A.R. Mohamed, Optimization of supercritical dimethyl carbonate (SCDMC) technology for the production of biodiesel and value-added glycerol carbonate, Fuel 89 (12) (2010) 3833–3839.
[156] A. Sharma, P. Kodgire, S.S. Kachhwaha, Biodiesel production from waste cotton-seed cooking oil using microwave-assisted transesterification: optimization and kinetic modeling, Renew. Sustain. Energy Rev. 116 (2019) 109394.
[157] P.D. Patil, et al., In situ ethyl ester production from wet algal biomass under microwave-mediated supercritical ethanol conditions, Bioresour. Technol. 139 (2013) 308–315.
[158] V.M. Rathnam, G. Madras, Conversion of Shizochitrium limacinum microalgae to biodiesel by non-catalytic transesterification using various supercritical fluids, Bioresour. Technol. 288 (2019) 121538.
[159] C.-Y. Wei, T.-C. Huang, H.-H. Chen, Biodiesel production using supercritical methanol with carbon dioxide and acetic acid, J. Chem. 2013 (2013).
[160] L.F. Chuah, et al., A review of cleaner intensification technologies in biodiesel production, J. Clean. Prod. 146 (2017) 181–193.
[161] L.F. Chuah, et al., Influence of green catalyst on transesterification process using ultrasonic-assisted, J. Clean. Prod. 136 (2016) 14–22.
[162] M. Tabatabaei, et al., Reactor technologies for biodiesel production and processing: a review, Prog. Energy Combust. Sci. 74 (2019) 239–303.
[163] S. Erenturk, Ö. Korkut, Effectiveness of activated mistalea (Viscum album L.) as a heterogeneous catalyst for biodiesel partial hydrogenation, Renew. Energy 117 (2018) 374–379.
[164] L. Du, et al., Transesterification of castor oil to biodiesel using NaY zeolite-supported La2O3 catalysts, Energy Convers. Manag. 173 (2018) 728–734.
[165] A. Bayat, M. Baghdadi, G.N. Bidhendi, Tailored magnetic nano-alumina as an efficient catalyst for transesterification of waste cooking oil: optimization of biodiesel production using response surface methodology, Energy Convers. Manag. 177 (2018) 395–405.
[166] M. Takase, et al., High-performance heterogeneous catalyst for biodiesel production from non-edible oil, Renewable Energy Focus 25 (2018) 24–30.
[167] N.P. Suvik Oza, Pravin Kodgire, Surendra Singh Kachhwaha *An ultrasound-assisted process for the optimization of biodiesel production from waste cottonseed cooking oil using response surface methodology*, Water-Energy Nexus 4 (2021) 187–198.
[168] M.A. Sundaramahalingam, et al., An intensified approach for transesterification of biodiesel from Annona squamosa seed oil using ultrasound-assisted homogeneous catalysis reaction and its process optimization, Fuel 291 (2021) 120195.
[169] R.S. Vinoth Thangarasu, A. Ramanathan, Modeling of process intensification of biodiesel production from Aegle Marmelos Correa seed oil using microreactor assisted with ultrasonic mixing, Ultrason. Sonochem. 60 (2020) 104764.
[170] G.L. Maddikeri, P.R. Gogate, A.B. Pandit, Intensified synthesis of biodiesel using hydrodynamic cavitation reactors based on the interesterification of waste cooking oil, Fuel 137 (2014) 285–292.
[171] A. Pal, et al., Biodiesel production through hydrodynamic cavitation and performance testing, Renew. Energy 35 (3) (2010) 619–624.
[172] N.S. Kolhe, A.R. Gupta, V.K. Rathod, Production and purification of biodiesel produced from used frying oil using hydrodynamic cavitation, Resource-Efficient Technologies 3 (2) (2017) 198–203.
[173] A.H. Demirbas, I. Demirbas, Importance of rural bioenergy for developing countries, Energy Convers. Manag. 48 (8) (2007) 2386–2398.
[174] L. Chuah, et al., Waste cooking oil biodiesel via hydrodynamic cavitation on a diesel engine performance and greenhouse gas footprint reduction, Chemical Engineering Transactions 50 (2016) 301–306.
[175] W.N.W. Ab Rashid, et al., Synthesis of biodiesel from palm oil in capillary millichannel reactor: effect of temperature, methanol to oil molar ratio, and KOH concentration on FAME yield, Procedia Chem. 9 (2014) 165–171.
[176] M. Barekati-Goudarzi, et al., Continuous microwave-assisted in-situ transesterification of lipids in seeds of invasive Chinese tallow trees (Triadica sebifera L.): kinetic and thermodynamic studies, Biomass Bioenergy 107 (2017) 353–360.
[177] N. Kaur, A. Ali, Biodiesel production via ethanolysis of jatropha oil using molybdenum impregnated calcium oxide as solid catalyst, RSC Adv. 5 (18) (2015) 13285–13295.
[178] Z. Wu, et al., Modeling of an industrial scale hydrodynamic cavitation multiphase reactor for Prileschajew epoxidation, AIChE J. 66 (5) (2020) e16914.
[179] D. Yuvarajan, et al., Experimental investigation on the influence of titanium dioxide nanofluid on emission pattern of biodiesel in a diesel engine, Atmos. Pollut. Res. 9 (1) (2018) 47–52.
[180] L.V. Malade, U.B. Deshannavar, Decolorisation of reactive red 120 by hydrodynamic cavitation, in: Materials Today: Proceedings, vol. 5, 2018, pp. 18400–18409, 9.
[181] H. Gupta, et al., Biodiesel production from waste cooking oil using sequential process intensification technique (ultrasound and microwave), in: IOP Conference Series: Materials Science and Engineering, IOP Publishing, 2021.
[182] A.D. Patil, S.S. Baral, Process intensification of thumba methyl ester (Biodiesel) production using hydrodynamic cavitation, Chem. Eng. Res. Des. 171 (2021) 277–292.
[183] A. Gholami, F. Pourfayaz, A. Saifoddin, Techno-economic assessment and sensitivity analysis of biodiesel production intensified through hydrodynamic cavitation, Energy Sci. Eng. 9 (11) (2021) 1997–2018.

[184] I.A. Khan, et al., Efficient production of biodiesel from Cannabis sativa oil using intensified transesterification (hydrodynamic cavitation) method, Energy Sources, Part A Recovery, Util. Environ. Eff. 42 (20) (2020) 2461–2470.
[185] D. Ghayal, A.B. Pandit, V.K. Rathod, Optimization of biodiesel production in a hydrodynamic cavitation reactor using used frying oil, Ultrason. Sonochem. 20 (1) (2013) 322–328.
[186] I. Choedkiatsakul, et al., Biodiesel production from palm oil using combined mechanical stirred and ultrasonic reactor, Ultrason. Sonochem. 21 (4) (2014) 1585–1591.
[187] S. Mahshid, M. Askari, M.S. Ghamsari, Synthesis of TiO2 nanoparticles by hydrolysis and peptization of titanium isopropoxide solution, J. Mater. Process. Technol. 189 (1–3) (2007) 296–300.
[188] S. Bargole, S. George, V.K. Saharan, Improved rate of transesterification reaction in biodiesel synthesis using hydrodynamic cavitating devices of high throat perimeter to flow area ratios, Chemical Engineering and Processing-Process Intensification 139 (2019) 1–13.
[189] Bahram Hosseinzdeh Samani, et al., The rotor-stator type hydrodynamic cavitation reactor approach for enhanced biodiesel fuel production, Fuel 283 (2021) 118821.
[190] G.-W. Yu, et al., Transesterification of soybean oil by using the synergistic microwave-ultrasonic irradiation, Ultrason. Sonochem. 39 (2017) 281–290.
[191] W.W.S. Ho, H.K. Ng, S. Gan, Advances in ultrasound-assisted transesterification for biodiesel production, Appl. Therm. Eng. 100 (2016) 553–563.
[192] J. David, N. Cheeke, Fundamentals and Applications of Ultrasonic Waves, 2017.
[193] P.A. Oliveira, et al., Ultrasound Methods for Biodiesel Production and Analysis, Biofuels-State of Development, 2018, pp. 121–148.
[194] K. Yasui, Fundamentals of acoustic cavitation and sonochemistry, in: Pankaj, M. Ashokkumar (Eds.), Theoretical and Experimental Sonochemistry Involving Inorganic Systems, 2011.
[195] S.M.S. Ardebili, et al., Optimization of biodiesel synthesis under simultaneous ultrasound-microwave irradiation using response surface methodology (RSM), Green Process. Synth. 4 (4) (2015) 259–267.
[196] V.L. Gole, P.R. Gogate, Intensification of synthesis of biodiesel from non-edible oil using a sequential combination of microwave and ultrasound, Fuel Process. Technol. 106 (2013) 62–69.
[197] B.L. Hayes, Microwave Synthesis: Chemistry at the Speed of Light, CEM Pub, 2002.
[198] H.M. Tellez, et al., Comparative kinetic study and microwaves non-thermal effects on the formation of poly (amic acid) 4, 4′-(hexafluoroisopropylidene) diphthalic anhydride (6FDA) and 4, 4′-(hexafluoroisopropylidene) bis (p-phenylene oxy) dianiline (BAPHF). Reaction activated by microwave, ultrasound, and conventional heating, Int. J. Mol. Sci. 12 (10) (2011) 6703–6721.
[199] M.J. Haas, et al., A process model to estimate biodiesel production costs, Bioresour. Technol. 97 (4) (2006) 671–678.
[200] E. Martinez-Guerra, V. Gude, Chemical engineering and processing: process intensification alcohol effect on microwave-ultrasound enhanced transesterification reaction, Chem. Eng. Process. Process Intensif 101 (2016) 1–7.
[201] F.U. Din, et al., Effective use of nanocarriers as drug delivery systems for the treatment of selected tumors, Int. J. Nanomed. (2017) 7291–7309.
[202] N. Narkhede, A. Patel, Biodiesel production by esterification of oleic acid and transesterification of soybean oil using a new solid acid catalyst comprising 12-tungstosilicic acid and zeolite Hβ, Ind. Eng. Chem. Res. 52 (38) (2013) 13637–13644.
[203] K.N.P. Rani, et al., Kinetic studies on the esterification of free fatty acids in jatropha oil, Eur. J. Lipid Sci. Technol. 115 (6) (2013) 691–697.
[204] P. Mazo, et al., Kinetics of the transesterification of castor oil with maleic anhydride using conventional and microwave heating, J. Am. Oil Chem. Soc. 89 (2012) 1355–1361.
[205] A. Demirbas, Biodiesel production from vegetable oils via catalytic and non-catalytic supercritical methanol transesterification methods, Prog. Energy Combust. Sci. 31 (5–6) (2005) 466–487.
[206] L. Jermolovicius, B. Schneiderman, J. Senise, Alteration of esterification kinetics under microwave irradiation, in: Advances in Microwave and Radio Frequency Processing: Report from the 8th International Conference on Microwave and High-Frequency Heating Held in Bayreuth, Germany, September 3–7, Springer, 2001, 2006.
[207] L. Pelle, et al., Microwave assisted organic synthesis-a review, Tetrahedron 57 (2001) 9225–9283.
[208] L. Perreux, A. Loupy, A tentative rationalization of microwave effects in organic synthesis according to the reaction medium, and mechanistic considerations, Tetrahedron 57 (45) (2001) 9199–9223.
[209] D. Boldor, et al., Microwave assisted extraction of biodiesel feedstock from the seeds of invasive Chinese tallow tree, Environ. Sci. Technol. 44 (10) (2010) 4019–4025.
[210] B. Terigar, et al., Continuous microwave-assisted isoflavone extraction system: design and performance evaluation, Bioresour. Technol. 101 (7) (2010) 2466–2471.
[211] A.N. Sarve, M.N. Varma, S.S. Sonawane, Ultrasound-assisted two-stage biodiesel synthesis from non-edible Schleichera triguga oil using heterogeneous catalyst: kinetics and thermodynamic analysis, Ultrason. Sonochem. 29 (2016) 288–298.
[212] I.M. Lokman, U. Rashid, Y.H. Taufiq-Yap, Microwave-assisted methyl ester production from palm fatty acid distillate over a heterogeneous carbon-based solid acid catalyst, Chem. Eng. Technol. 38 (10) (2015) 1837–1844.
[213] K. Ramachandran, et al., Recent developments for biodiesel production by ultrasonic assist transesterification using different heterogeneous catalyst: a review, Renew. Sustain. Energy Rev. 22 (2013) 410–418.
[214] M. Choudhury, P. Borthakur, T. Bora, Synthesis and Characterization of Silicious Mordenite, 1998.
[215] Y. Liu, et al., Kinetic studies on biodiesel production using a trace acid catalyst, Catal. Today 264 (2016) 55–62.
[216] T. Lieu, S. Yusup, M. Moniruzzaman, Kinetic study on microwave-assisted esterification of free fatty acids derived from Ceiba pentandra Seed Oil, Bioresour. Technol. 211 (2016) 248–256.
[217] M. Chai, et al., Esterification pretreatment of free fatty acid in biodiesel production, from laboratory to industry, Fuel Process. Technol. 125 (2014) 106–113.
[218] M. Feyzi, et al., Preparation, characterization, kinetic and thermodynamic studies of MgO-La2O3 nanocatalysts for biodiesel production from sunflower oil, Chem. Phys. Lett. 677 (2017) 19–29.
[219] J. Li, et al., Biodiesel production from Camptotheca acuminata seed oil catalyzed by novel Brönsted–Lewis acidic ionic liquid, Appl. Energy 115 (2014) 438–444.
[220] V.G. Deshmane, Y.G. Adewuyi, Synthesis and kinetics of biodiesel formation via calcium methoxide base-catalyzed transesterification reaction in the absence and presence of ultrasound, Fuel 107 (2013) 474–482.
[221] A. Gholami, F. Pourfayaz, A. Maleki, Techno-economic assessment of biodiesel production from canola oil through ultrasonic cavitation, Energy Rep. 7 (2021) 266–277.
[222] C. Stavarache, et al., Ultrasonically driven continuous process for vegetable oil transesterification, Ultrason. Sonochem. 14 (4) (2007) 413–417.
[223] P. Cintas, et al., A new pilot flow reactor for high-intensity ultrasound irradiation. Application to the synthesis of biodiesel, Ultrason. Sonochem. 17 (6) (2010) 985–989.
[224] K. Okitsu, et al., A two-step continuous ultrasound assisted production of biodiesel fuel from waste cooking oils: a practical and economical approach to produce high quality biodiesel fuel, Bioresour. Technol. 101 (14) (2010) 5394–5401.
[225] P.R. Gogate, Cavitational reactors for process intensification of chemical processing applications: a critical review, Chem. Eng. Process: Process Intensif. 47 (4) (2008) 515–527.
[226] A. Delavari, F. Halek, M. Amini, Continuous biodiesel production in a helicoidal reactor using ultrasound-assisted transesterification reaction of waste cooking oil, Clean Technol. Environ. Policy 17 (2015) 273–279.
[227] M. Mostafaei, et al., Optimization of ultrasonic-assisted continuous production of biodiesel using response surface methodology, Ultrason. Sonochem. 27 (2015) 54–61.
[228] N.E. Leadbeater, L.M. Stencel, Fast, easy preparation of biodiesel using microwave heating, Energy Fuel. 20 (5) (2006) 2281–2283.

[229] Y. Groisman, A. Gedanken, Continuous flow, circulating microwave system and its application in nanoparticle fabrication and biodiesel synthesis, J. Phys. Chem. C 112 (24) (2008) 8802–8808.
[230] N.E. Leadbeater, T.M. Barnard, L.M. Stencel, Batch and continuous-flow preparation of biodiesel derived from butanol and facilitated by microwave heating, Energy Fuel. 22 (3) (2008) 2005–2008.
[231] V. Lertsathapornsuk, et al., Microwave assisted in continuous biodiesel production from waste frying palm oil and its performance in a 100 kW diesel generator, Fuel Process. Technol. 89 (12) (2008) 1330–1336.
[232] J. Encinar, et al., Soybean oil transesterification by the use of a microwave flow system, Fuel 95 (2012) 386–393.
[233] V.G. Gude, et al., Microwave energy potential for biodiesel production, Sustainable Chemical Processes 1 (2013) 1–31.
[234] P.D. Patil, et al., Microwave-assisted catalytic transesterification of camelina sativa oil, Energy Fuel. 24 (2) (2010) 1298–1304.
[235] B. Salamatinia, et al., Intensification of biodiesel production from vegetable oils using ultrasonic-assisted process: optimization and kinetic, Chem. Eng. Process: Process Intensif. 73 (2013) 135–143.
[236] E. Martinez-Guerra, V.G. Gude, Synergistic effect of simultaneous microwave and ultrasound irradiations on transesterification of waste vegetable oil, Fuel 137 (2014) 100–108.
[237] D. Lee, et al., Design and economic analysis of biodiesel production process of simultaneous supercritical transesterification and partial hydrogenation using soybean oil with Pd/Al2O3 catalyst, Chem. Eng. Res. Des. 172 (2021) 264–279.
[238] A. Gholami, et al., Biodiesel production from Norouzak (Salvia leriifolia) oil using choline hydroxide catalyst in a microchannel reactor, Renew. Energy 136 (2019) 993–1001.
[239] D.A. Mellichamp, Profitability, risk, and investment in conceptual plant design: optimizing key financial parameters rigorously using NPV%, Comput. Chem. Eng. 128 (2019) 450–467.
[240] M.B. Tasić, O.S. Stamenković, V.B. Veljković, Cost analysis of simulated base-catalyzed biodiesel production processes, Energy Convers. Manag. 84 (2014) 405–413.
[241] S. Lee, D. Posarac, N. Ellis, Process simulation and economic analysis of biodiesel production processes using fresh and waste vegetable oil and supercritical methanol, Chem. Eng. Res. Des. 89 (12) (2011) 2626–2642.
[242] Y. Thoppil, S.H. Zein, Techno-economic analysis and feasibility of industrial-scale biodiesel production from spent coffee grounds, J. Clean. Prod. 307 (2021) 127113.
[243] W. Sakdasri, R. Sawangkeaw, S. Ngamprasertsith, Techno-economic analysis of biodiesel production from palm oil with supercritical methanol at a low molar ratio, Energy 152 (2018) 144–153.
[244] S.N. Gebremariam, J.M. Marchetti, Biodiesel production through sulfuric acid catalyzed transesterification of acidic oil: techno-economic feasibility of different process alternatives, Energy Convers. Manag. 174 (2018) 639–648.
[245] J.-C. Lee, et al., Techno-economic assessment of conventional and direct-transesterification processes for microalgal biomass to biodiesel conversion, Bioresour. Technol. 294 (2019) 122173.
[246] L. Naderloo, H. Javadikia, M. Mostafaei, Modeling the energy ratio and productivity of biodiesel with different reactor dimensions and ultrasonic power using ANFIS, Renew. Sustain. Energy Rev. 70 (2017) 56–64.
[247] A. Mohammadshirazi, et al., Energy and cost analyses of biodiesel production from waste cooking oil, Renew. Sustain. Energy Rev. 33 (2014) 44–49.
[248] A. Mohammadshirazi, et al., Energy and cost analyses of biodiesel production from waste cooking oil, Renew. Sustain. Energy Rev. 33 (2014) 44–49.