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Hydrodynamic Cavitation Reactor for Efficient Biodiesel Production. A Review

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Abstracts: Biodiesel emerges as a viable option to replace fossil fuels, but the traditional process for the production of biodiesel requires a large energy expenditure, since transesterification has a slow conversion due to the immiscibility of alcohol and oil. On the other hand, with the hydrodynamic cavitation method, a shorter conversion time can be achieved with a high yield; however, there are few studies related to this method. Therefore, the objective of this article is to analyze information from different scientific publications to compare and visualize the parameters used to obtain biodiesel by means of a hydrodynamic cavitation reactor. For this reason, a bibliometric analysis and a systematic review based on the PRISMA method were carried out. In this sense, the relevant articles were selected from the Web of Science, Scopus and Google Scholar databases published between January 2018 and July 2023.Finally, the values of biodiesel yield efficiency were obtained by analyzing the different operating parameters and the different feedstock sources for its elaboration in the hydrodynamic cavitation reactors and comparing their results with international standards. American Society for Testing and Materials (ASTM) D6751 y European Committee for Standardization(EN)14214. It is concluded that hydrodynamic cavitation produces biodiesel that meets international standards and that the highest yields in biodiesel production in most studies have temperature ranges between 50 to 65°C, alcohol: oil molar ratio of 6:1, and methanol is the most used in tranasesterification.

Keywords: Hydrodynamic Cavitation, Transesterification, Biodiesel Production Efficiency.

1. INTRODUCTION

Biodiesel is currently considered an alternative with great potential to replace traditional fuels [1]. biodegradable, sustainable, clean-burning and non-toxic fuels [2]. Produces lower exhaust gas emissions, has better cetane number and flash point, higher lubricity and negligible sulfur content [3]. It is one of the most preferred biofuels used in the transportation industry due to its non-toxicity and biodegradability. Global biodiesel production expected to reach more than 23 billion liters by 2025 [4].The identification and implementation of sustainable biodiesel production alternatives must be based on rigorous assessments that integrate socioeconomic and environmental objectives at local, regional and global scales [5].Consequently, many investigations have evaluated the potential of alternative processes to those carried out in continuous stirred tank reactors, as disadvantages such as low reaction rate, long reaction time, high volume, weight and space requirements for equipment, sensitivity to the quality of reaction materials, energy demand and lack of cost-effectiveness are often encountered [6]. Therefore, the study of new and alternative technologies with the aim of intensifying the biodiesel fuel production process is very important in terms of production efficiency, process time, energy consumption and quality of the biodiesel produced [7]. In recent years, several studies have been carried out analyzing the production of biodiesel by means of hydrodynamic cavitation, such as the one conducted by Debabrata [8] in which a comprehensive review of the latest innovations in hydrodynamic cavitation technologies for continuous biodiesel production was conducted in which it was suggested that the technology could be implemented alone or in conjunction with other process intensification steps to improve biodiesel production. Other research has reported through systematic reviews that HC has proven to be a suitable option to replace some of the steps in the conventional biodiesel production process, with several improvements, such as fewer waste streams, less energy losses and higher energy efficiency [9] [10]. While there are a large number of review and research studies related to biodiesel production, to the authors' knowledge, there are no comprehensive review articles that focus only on HC-assisted biodiesel production. Therefore, as an objective of the following article a description is provided showing the operating parameters of the hydrodynamic cavitation reactors among them are the number and diameter of holes in the plate, feed pressure, reaction time, operating temperature, methanol/oil molar ratio, and the percentage of catalyst for the production of biodiesel. In summary, the present study is valuable in contributing to the literature on the ongoing research on biodiesel production. In addition, the information provided here could be useful to policy makers, industries and researchers in the field of chemical reactors.

2. METHOD

2.1. Inclusion And Exclusion Criteria For Scientific Investigations

Initially, researches that did not contain the keywords in the title, abstract and keywords were excluded. Duplicate investigations were eliminated according to the title. Subsequently, all researches were downloaded for review according to the inclusion criteria. Finally, all selected investigations were evaluated by reading according to the inclusion and exclusion criteria described below:

1. Studies demonstrating the efficacy of using hydrodynamic cavitation for biodiesel production were included.
2. Studies were included that worked with first through fourth generation biofuels.
3. Studies that worked with methods unrelated to the cavitation method (water, plants, etc.) were excluded.
4. Studies that were not in English were excluded.
5. Studies with insufficient data were excluded.

2.2 Information Sources And Search Strategy

The systematic review of the present research was developed based on the PRISMA methodology and the data found were processed in a meta-analysis [11]. The Boolean string that was used as the search query was “TITLE-ABS-KEY Biofuel AND (TITLE-ABS-KEY Hydrodynamic Cavitation) OR TITLE-ABS-KEY (Hydrocavitation) OR TITLE-ABS-KEY (Biodiesel) OR TITLE-ABS-KEY (Cavitation Reactors)". In addition, it was verified that all included studies were no more than 5 years old as of 2023. The search recovered 638, 249 and 94 items from Web of Science, Scopus y Google Scholar respectively. Initially, 416 articles were found that were duplicated or in languages other than English and were excluded. Subsequently, 291 articles were excluded for having inappropriate or irrelevant content due to lack of information on biodiesel production, then a total of 193 articles were excluded for outdated information or repetitive results, and finally 6 articles obtained from the reference search were included to complement relevant information, leaving a total of 87 review articles and research papers retrieved.

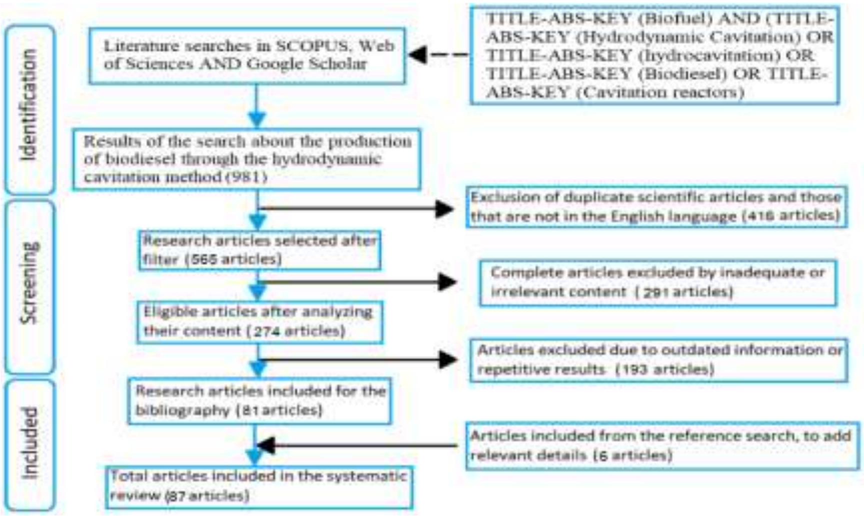


Figure 1: PRISMA Flow chart

3. RESULTS AND DISCUSSIONS

3.1. Comparison Of Hydrodynamic Cavitation Reactor with Conventional Reactor

It is essential to compare the performance of various methods available for biodiesel production, the comparison is made in terms of energy consumption, cavitational performance, and physicochemical properties of the biodiesel [12].In this case, the comparison of the hydrodynamic cavitation method with mechanical agitation for biodiesel production is carried out as shown in Table 1. It can be found that hydrodynamic cavitation resulted in 97.5 % conversion, while the stirring method resulted in 26 %, which was a much lower conversion during a similar reaction time of 20 min. This could be attributed to the high intensity of micro-level turbulence generated by oscillating cavities with high interfacial area. An HC reactor is very effective in eliminating mass transfer resistance during the reaction and, therefore, higher conversion. It can be found that HC for biodiesel production resulted in 20 min reaction time, which is about four times more compared to mechanical agitation. Higher yield efficiency and shorter reaction time to approach over 97.5% can be achieved with HC compared to mechanical agitation. However, there is no doubt that hydrodynamic cavitation was efficient in terms of time efficiency and performance [13].

Table 1: Comparison of hydrodynamic cavitation reactor and conventional reactor in biodiesel production.

Raw Materials	Applied reactor	Time (min)	Temperature (°C)	Maximum yield (%)	Ref.
Soybean oil	conventional	45	65	96.65	[14]
	HC	10-30	45	>95	[15], [16]
Castor oil	conventional	200	60.3	81.26	[17]
	HC	50.83	60.3	92,27	[17]
Palm oil	conventional	45	65	95,78	[14]
	HC	20	55	93,84	[18], [19]
Grave oil	conventional	60	65	91	[20]
	HC	30	40-55	80	[15] [21]
Used cooking oil	conventional	90	60	97	[22]
	HC	15	60	98	[22]

Table 1 shows the parameters of time, temperature and maximum yield in the production of biodiesel by hydrodynamic cavitation and mechanical agitation from different oils. Reduced times were obtained by the hydrodynamic cavitation method and with a trend of higher yields.

3.2. The Hydrodynamic Cavitation Reactor

Hydrodynamic cavitation reactors use the energy of the fluid flow to create a cavitation phenomenon in a controlled environment [1], [3]. Use the large amount of energy generated by the implosion of cavitation bubbles in a microenvironment with extreme local conditions, to accelerate the course of chemical reactions [23], leading to a very high increase in pressure, temperature and these promote direct reaction for the conversion of esters [1], [3]. In cavitation, to achieve pressure reduction in a flow system, cavitation devices such as Venturi tubes and orifice plates are used to increase the velocity of the fluid [24], [4]. These effects are described by Bernoulli equation (1)

$$p_1 + \frac{1}{2}\rho v_1^2 = p_2 + \frac{1}{2}\rho v_2^2 \qquad (1)$$

where p is the pressure, ρ is the density of the liquid and v is the liquid velocity. A cavitation bubble is generated when the pressure decreases to a value low enough to generate the growth of an existing gas pocket in the liquid [11]. The following equation is used to determine the cavitation number(2)

$$\sigma = \frac{P_1 - P_2}{\frac{1}{2}\rho v^2} \qquad (2)$$

where σ = cavitation number (dimensionless), P1 = reference pressure (Pa), P2 = fluid vapor pressure (Pa), ρ = fluid density (kg/m3), v = fluid velocity (m/s)

Figure 2 shows the schematic of a cavitation reactor to carry out the transesterification reaction. The assembly consists of a storage tank, a positive displacement pump, a pressure gauge and flow control valves that are connected at the desired locations in the main, bypass and pump inlet line. The suction side of the pump is connected to the bottom of a storage tank. The pump discharge is branched to the main line and the bypass line [15].

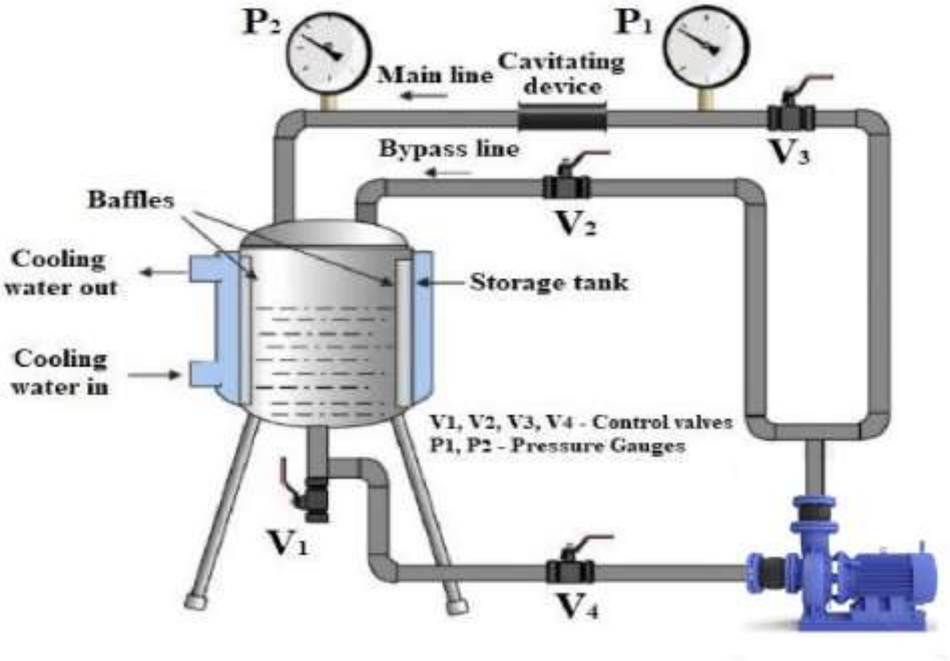


Figure 2: Schematic Of A Hydrodynamic Cavitation Reactor

These reactors intensify the mass transfer rate and heat transfer of chemical processes by causing local disturbances and microcirculation within the reactor [25]. Hydrodynamic cavitation reactors provide narrower and more stable thin emulsions compared to conventional reactors, which in turn increases the reaction rate, achieving higher conversion rates in a shorter time and reduce solvent requirements [2], [1]. However, these reactors are not compatible with heterogeneous catalysts [26]. Figure 2 shows an evaluation of strengths, weaknesses, opportunities and threats, known as the SWOT matrix for biodiesel production. Two main types of HCRs are reported in the literature and in the current market: stationary and rotary HCRs, which are reviewed in the following sections.

3.3. Stationary Hydrodynamic Cavitation Reactors

Stationary HCRs employ venturis, orifice, wedge and vortex diode as the constrictive part to increase the linear velocity of the working fluid, leading to a low pressure region where cavitation events are induced [27]. Due to their simple geometry and ease of fabrication and operation, stationary HCRs have been extensively studied and widely used on a laboratory scale to investigate the effectiveness and mechanism of hydrodynamic cavitation technology [28]. The stationary or non-rotational HCR is cost-effective to be considered as an industrial reactor. Consequently, venturi, orifice types are typically used to investigate the ability of hydrodynamic cavitation in the inactivation of microorganisms and water treatment [29]. Stationary HCRs present two predominant mechanisms in partial cavitation, reentrant jet mechanism, induced by an adverse pressure gradient at high cavitation numbers and shock wave mechanism, induced by cloud collapse at low cavitation numbers [30].

3.3.1. Orifice Plate Cavitation Reactor

An orifice plate is the most commonly used flow restriction and pressure reduction device, and includes a well that is designed to generate a specific pressurized flow [31]. Due to the sudden change in pipe diameter, the intensity of bubble collapse that occurs in a borehole is significant. Bubble generation occurs at the edge of the orifice, releasing a large amount of energy into the surrounding liquids in mechanical, thermal and chemical forms [22]. The magnitude of the pressure drop strongly influences the turbulence intensity downstream of the constriction, and the pressure drop depends mainly on the geometry of the constriction and the fluid flow conditions [32]. Figure 3 shows four orifice plates with different numbers of holes.

Figure 3: Shows four orifice plates with different number of holes

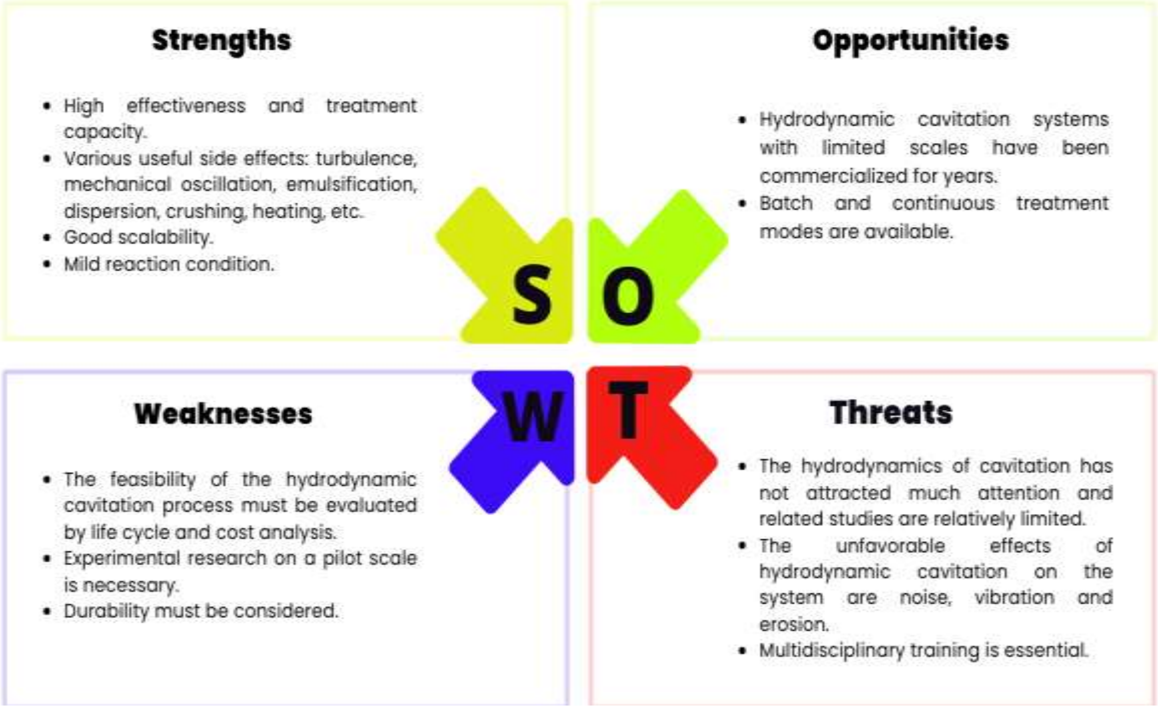
3.3.2. Venturi Cavitation Reactor

Venturi tubes have been used as a way to produce microbubbles in cavitation processes [33]. A venturi tube generally consists of three sections: the converging inlet, the throat and the diverging cone [34]. Unlike orifice plates, the fluid inside a venturi contracts and expands smoothly; therefore, the pressure and velocity of the fluid vary constantly [35]. This gradual change in fluid conditions avoids a drastic change in orifice pressure, which is beneficial for the generation of microbubbles and their stability, cavitation is determined by the flow resistance, which is significantly dependent on the geometrical design of the Venturi [8]. Due to their lower energy consumption and higher bubble generation capacity, venturis outperform orifice plates in industrial applications [36].

3.4. Rotational Cavitation Reactors

They consist of rotating parts that generate cavitation. Rotating HCRs use circular discs or cylinders with numerous dimples or spaces to create cavitation including blind holes, teeth, etc. These are located on the rotor [5], [37], [38]. Irregular surfaces (due to dimples or hollows) within the rotating part create variations in the working cross-sectional area, i.e. cavitation bubbles are periodically induced and crushed by the motion of the rotor, which forces the liquid fluid to expand or contract as it flows through the área , This results in repetitive pressure differentials [28], [30]. To evenly distribute the liquid stream, the inlet port is located in the center and the outlet port is placed at the top of the shaft for sealing and cooling purposes. The cavitation generated by this process is due to the opposite movement of two shear layers; therefore, this type of cavitation is called shear cavitation [39].

Reactor performance is based on the rotor and stator structure (diameter, rotor/stator distance, thickness, etc.) and the geometry (shape, diameter, edge, pitch angle, etc.) and arrangement of the cavitation generation unit. Distance is an important factor affecting reactor performance, interaction type, and small distances can significantly improve cavitation generation efficiency. This is because for these reactors a small distance results in a greater compression effect between the two vortices formed inside the cavitation generating units located in the stator and rotor, forming stronger and wider SC and VC Regions [40].



Strengths

- High effectiveness and treatment capacity.
- Various useful side effects: turbulence, mechanical oscillation, emulsification, dispersion, crushing, heating, etc.
- Good scalability.
- Mild reaction condition.

Opportunities

- Hydrodynamic cavitation systems with limited scales have been commercialized for years.
- Batch and continuous treatment modes are available.

Weaknesses

- The feasibility of the hydrodynamic cavitation process must be evaluated by life cycle and cost analysis.
- Experimental research on a pilot scale is necessary.
- Durability must be considered.

Threats

- The hydrodynamics of cavitation has not attracted much attention and related studies are relatively limited.
- The unfavorable effects of hydrodynamic cavitation on the system are noise, vibration and erosion.
- Multidisciplinary training is essential.

Figure 4: SWOT matrix for the production of biodiesel using a hydrodynamic cavitation reactor.

3.5. Effect Of Key Operating Conditions On Transesterification.

Transesterification is the reaction of a triglyceride with methanol, the main one being a successive three-stage reversible reaction. Initially, methanol reacts with the triglyceride producing a diglyceride, then the diglyceride reacts with methanol producing a monoglyceride, and finally the monoglyceride reacts with methanol producing glycerol, the reactions are shown in Figure 5. One mole of biodiesel is produced at each stage [2].

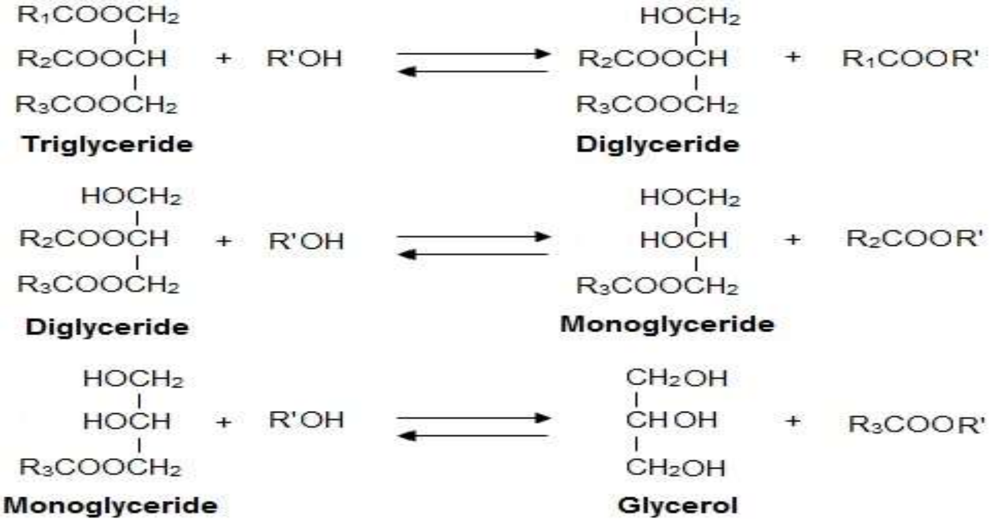


Figure 5: Transesterification reactions in the production of biodiesel

Therefore, the general reaction can be summarized as follows

$$\text{Triglyceride} + 3\ \text{R}'\text{OH} \quad \leftrightarrow \quad \text{Glycerol} + 3\ \text{FAME}$$

In previous studies, several operating conditions were considered as determinants in the production of biodiesel assisted by hydrodynamic cavitation [30]. These conditions include cavitation intensity, temperature, alcohol:oil molar ratio, type and amount of catalyst, reaction time, etc. Table 2 compiles the main operating conditions in the transesterification reaction by hydrodynamic cavitation found in the literature, to obtain maximum yield in biodiesel production.

Table 2: Review of different studies on biodiesel production by HC

Raw Materials	Device type	Bore diameter (mm)	Number of holes	Feed pressure (MPa)	Alcohol:oil molar ratio	Catalyst (%)	Maximum yield (%)	Ref.
Soybean oil	Orifice plate	2	16	-	4:4(v/w)	NaOH (1%)	98	[15], [41]
Sunflower oil	Venturi	-	-	1.01	3:1	NaOH (1%)	94-99	[30], [42]
Tomb Oil	Orifice plate	2	3	0.5	6:1	NaOH (1.2%)	71,8	[43]
		3	7	-	4.5:1	NaOH (1%)	80	[15], [21]
Used cooking oil	Orifice plate	0.3	100	7 bar	6.8:1	NaOH (1%)	99	[15]

It can be seen from Table 1 that biodiesel production is mostly carried out by basic catalysis, mainly using NaOH as catalyst, with concentrations between 1 and 1.2%. In addition, methanol is the most commonly used alcohol in transesterification, with molar ratios between 3:1 and 7:1.

3.5.1. Cavitation Intensity

The intensity of cavitation, generated by hydrodynamic cavitation reactors, is a key factor determining the efficiency of the process, although cavitation intensity does not have a precise physical definition, it is generally used to characterize the severity of the cavitation phenomenon. Several indicators, such as chemical effects (radical formation), acoustic and optical radiation (noise and sonoluminescence), mechanical effects (vibrations and pressure fluctuations), and others (pH, temperature, etc.) can indirectly indicate the intensity of cavitation [44]. Generally speaking, the cavitation intensity increases with increasing input energy in hydrodynamic cavitation reactors, and reaches a critical value when cavitation of the constriction device is achieved, whose geometrical parameters are important to control the cavitation intensity, e.g., in an orifice plate, the same depends on the number and size of holes [33], [45]. In addition, cavitation is related to the cavitation number (Cv), consequently, when the value of Cv is greater than 1 cavitation is not optimal, and the intensity of cavitation increases as the value of Cv decreases to less than 1 [15], [46].

3.5.2. Temperature

Reaction temperature is an important parameter to increase both the rate of the chemical reaction and the yield of biodiesel, an increase in temperature up to the boiling point of the alcohol favors a higher conversion of triglycerides into biodiesel [20]. In addition, raising the reaction temperature has an impact on the physical characteristics of the reactant mixture, particularly the viscosity, which can alter the hydrodynamic behavior [47]. In the investigation of Patil y Baral [12] , analyzed the effect of temperature in the range of 50-70% and it was observed that raising the reaction temperature from 50 to 60°C increased the conversion from 58 to 71.8%. Furthermore, a further increase in temperature above 65°C leads to a reduction in conversion, a similar trend has also been reported in the study of Thakkar et al [17], I also note that increasing the temperature above 65°C causes a slight reduction in conversion due to partial vaporization of the methanol.

3.5.3. Alcohol: Oil- Molar Ratio

The molar ratio is one of the fundamental variables influencing the reaction process. From a stoichiometric point of view, the alcohol:oil molar ratio should be 3:1 [13]. However, in a real reaction system a higher molar ratio is preferable to increase the miscibility of methanol and triglyceride molecules, as well as to increase the possibility of their contact, can obtain a higher yield and conversion to the final product due to the reversible nature of the reaction in transesterification[48]. In addition, high amounts of alcohol are required to dissociate the bond between the triglyceride and the fatty acid to increase productivity and complete the reaction in a shorter time [2]. It could be found that, in the study of Samuel, et al [3] varying the molar ratio of alcohol:oil between 3.5 and 7, keeping constant the amount of catalyst (4% by weight) and a reaction time (40 min) and it was shown that the yield increased slightly as the molar ratio of alcohol to oil increased. However, the maximum yield was achieved with a ratio of 6:1, when this ratio was exceeded the yield started to decrease, thus establishing, as the optimum yield point to the one obtained, this was also demonstrated in the research of Khan, et al. [13] that varying the molar ratio from 3:1 to 7:1 led to an increase in conversion, from 44-45% to 97.5%. However, exceeding that 7:1 limit, excess methanol reduced the conversion from 97.5% (with 1:6) to 94.0% (with 1:7) and this could be related to the dilution of the oil due to methanol.

3.5.4. Catalyst Type And Quantity

There are several types of catalysts, among the most common are those using homogeneous catalysts, both acid and alkaline, heterogeneous acid and alkaline catalysts and enzymatic catalysts using lipases [49]. Acid catalyzed processes are used when the oil has a high concentration of free fatty acids (FFA), requiring longer reaction times and higher molar proportions of alcohol [20]. On the other hand, alkaline catalyzed processes are significantly affected by the way in which the reagents are mixed [50]. The amount of catalyst in the transesterification reaction is an essential factor that significantly influences the maximum biodiesel yield [13]. The process is usually started with a lower catalyst concentration, and then progressively increased depending on the reaction conditions and the amount of products obtained, since it is observed that the content of fatty acid methyl esters increases to some extent with increasing catalyst dosage [2]. Additional increases in the amount of catalyst do not significantly influence the yield of biodiesel production [51]. Chuah et al. [52] investigated the impact of KOH concentration on the transesterification of used cooking oil by varying the amount of catalyst between 0.5 and 1.25% by weight, with the increase of catalyst concentration from 0.5 to 1% by weight, the conversion increased from 63% to 98.1% in a reaction time of 15 minutes. However, by further increasing the catalyst concentration from 1 to 1.25% by weight, the conversion experienced a slight reduction from 98.1 to 91%, similar results have been reported in the study of Thakkar et al. [17] where it was observed that the yield was increased up to a catalyst amount of 1% by weight. However, beyond that point, performance declined considerably.

3.5.5. Reaction Time

The most determinant factor in the reaction yield is the reaction time, it has been observed that, at the beginning, the increase in time led to an increase in the yield of biodiesel produced, but with the passage of time, it was reduced. Due to the reversible nature of the reaction and its propensity to generate methanol, a longer reaction time resulted in a decrease in yield [50], This is because, if the reagents are mixed for longer periods than necessary, typical of traditional methods, a catalyst-depleting soap may be generated, particularly if the oil contains a significant amount of free fatty acids, which decreases the efficiency in the production of fatty acid methyl esters (FAME) [18]. Therefore, it is important to determine the optimal reaction time. In the study conducted by Samuel, et al. [3] the reaction time was modified between 35 and 60 minutes, it was evidenced that, by increasing the reaction time from 30 to 35 minutes, the performance experienced a slight increase, going from 92.1% to 92.4% However, the peak yield for esters, which was 92.5%, was achieved at 40 min, a similar trend as that obtained by Bargole et al. [15] with a maximum yield of 99% biodiesel within 5 min of reaction time.

3.6. Characterization Of the Properties Of Biodiesel Synthesized By Cavitation-Based Hydrodynamic Processes.

The characteristics of the biodiesel obtained from the hydrodynamic cavitation process are analyzed to compare whether these parameters are within the specifications of international standards American Society for Testing and Materials (ASTM) D6751 [53] y European Committee for Standardization (EN) 14214 [54], as this ensures adequate quality control of the product and is presented in Table 3.

Table 3: Comparison of key properties of biodiesel obtained by HC and corresponding specifications.

Property	Used cooking oil [15]	Grave oil [12]	Used cooking oil [22]	Safflower oil [1]	ASTM D6751	At 14214
Density at 15°C (kg/m^3)	860	853	880	870	860-900	850-900
Viscosity (mm^2/s)	3.9	3.54	4.62	4.52	1.9-6	3.5-5
Flash point (°C)	166	155	135	157	130 min	120 min
Acid number (mg KOH/g)	0.3	0.134	0.3	0.37	0.5 max	0.5 max

The results revealed that the density, viscosity, flash point and acid number of the biodiesel obtained from different oils by hydrodynamic cavitation acid number in the biodiesel obtained from different oils by hydrodynamic cavitation met international met international standards D6751 and at 14214, therefore, biodiesel can be used as an alternative fuel.

CONCLUSIONS

The present review demonstrates that, when comparing biodiesel production by hydrodynamic cavitation versus conventional mechanical agitation, hydrodynamic cavitation is the most effective process in terms of time, cost, energy consumption and quality of the biodiesel produced. Therefore, it is presented as an innovative, more optimized and sustainable alternative in biodiesel production.

The highest yields in biodiesel production in most studies are reported in the following conditions: in temperature ranges between 50 to 65°C, alcohol:oil molar ratio of 6:1, considering that methanol is the most used alcohol in tranasesterification. In addition, a catalyst concentration of 1% by weight of the oil, generally using NaOH as a basic catalyst; however, it is advisable to experiment with concentrations of 0.5 to 1.2% by weight.

In addition, the properties of the biodiesel obtained by hydrodynamic cavitation met the specifications of international standards ASTM D6751 and EN 14214, therefore, the biodiesel obtained by the cavitation process can be used as an alternative fu

Nomenclature

HC: Hydrodynamic cavitation
HCR: Hydrodynamic Cavitation Reactor
FAME: Fatty acid methyl esters

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