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Modeling the energy ratio and productivity of biodiesel with different reactor dimensions and ultrasonic power using ANFIS

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ABSTRACT

To analyze issues relating to sustainability, the energy consumed for producing one kilogram of a product was utilized to compare systems. Moreover, the energy indices of biodiesel production using the ultrasound-assisted transesterification reactions might be affected by the reactor dimensions and the ultrasonic power. The present study aimed to model the energy productivity and ratio in producing biodiesel from the waste cooking oil through ANFIS model. The properties of the produced biodiesel demonstrated that it possessed a desirable quality. The total energy inputs and outputs measured 36.652 and 45.007 MJ L^{-1}, respectively. In addition, the mean scores of the energy ratio and productivity were 1.283 and 0.024 MJ/kg, respectively. The inputs of the ANFIS model comprised the diameter of the reactor and the height and the percentage of the ultrasonic power. The results indicated that there was an initial rise in the ratio of the energy with the increase of the height and the diameter of the reactor as well as the ultrasonic power, followed by a drop. Further, the results of employing the ANFIS model demonstrated that MSE and R^2 values measured $5.54e^{-6}$ and 0.87 for the energy ratio and $2.94e^{-7}$ and 0.80 for the energy productivity, respectively. However, the adjusted R^2 of the linear regression model without intercept measured 0.773 and 0.774 for the energy ratio and productivity, respectively. Accordingly, the ANFIS model could predict the energy ratio and productivity more precisely than the linear regression model.

1. Introduction

Given the benefits of biodiesel, including renewability, non-toxic feature, low air pollution and limited fossil resources, its production has taken center stage in recent decades, making it an inevitable alternative. Biodiesel is a renewable and biodegradable fuel that can be obtained from fresh or waste vegetable oil or animal fat. This fuel can be mixed with diesel and be utilized in gasoline engines. Biodiesel, as an alternative to fossil fuels, enjoys many advantages which make it usable without any need for major changes in the design of engines [1]. Biodiesel has much higher concentration of cetane, property of lubrication and cloud point. Blending five to seven percent of biodiesel slightly increases the engine power and reduces the concentration of CO2 and CO. Moreover, adding biodiesel results in significant improvements to lubrication properties [2].

The estimated waste vegetable oil collected from seven European countries measured 0.4 million tons, whereas the total amount that could be collected measured significantly higher, i.e., 0.7–1 million tons [3]. In the United States of America, the most common sources of oil for producing biodiesel are soybean and yellow oil (primarily, cooking oil recycled from restaurants). The Energy Information Administration estimated that the production of biodiesel with competitive applications from the yellow oil would be limited to 100 million gallons per year (6523 barrels per day) [4].

According to the Iranian statistics, the amount of waste cooking oil exceeds 428 t per year. The collection of waste cooking oil and its conversion into clean fuel play a major role in diminishing air pollution, contributing to the national economy. Thus, in addition to providing clean fuel as a result of biodiesel production, the oil losses are also prevented. In studies conducted by Chhetri Arjun et al. and Khalisanni et al. the waste cooking oil was utilized as an alternate feedstock and raw material for biodiesel production [5,6]. In their studies, the physical and fuel properties of the produced biodiesel were evaluated, too.

Given the recent scientific developments, ultrasonic irradiation is used in a wide range of applications, and through modifying the effective parameters in ultrasound, the processes would be improved, and various physical, chemical and biological effects would be achieved [7]. The groundwork for using ultrasonic power is growing more and more, and given its high efficiency, low maintenance costs, low need for

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instruments, reduced process time, useful function and environment friendliness, it is considered a green technology [8, 9].

The most basic effect of ultrasonic is cavitation, providing modern and effective results in the biological, chemical, and physical processes. The reactors that create cavitation with the help of ultrasound are known as sonochemical reactors [10,11].

The ultrasonic energy can be effectively utilized in optimizing the process of converting triglycerides into biodiesel. The following cases have been evaluated and compared with transesterification: the effects of low-frequency ultrasonic power (28 and 40 kHz) on the production of biodiesel from fatty acids with C8-C10 carbons [12], free fatty acids [13] and triglycerides [14–18] using methanol or ethanol in the presence of various catalysts such as sodium hydroxide [19,20], sulfuric acid [12] and potassium hydroxide [13,15]. The results of this study revealed that the reaction time was significantly reduced from two hours to half an hour through using ultrasound [12,14,17–19]. The results also demonstrated that using ultrasound diminished the required number of catalysts [13,15,16,18] and prevented the saponification of the reaction [16,17]. Furthermore, the molar ratio of methanol to fatty acids could be lessened threefold to achieve an efficiency higher than 95–97%, regardless of raw materials [18,12,13,15,17,20].

Biodiesel is mainly produced in batch reactors, in which the mixing process is performed by heating and mechanical stirring. Using ultrasound is an effective method for providing mixing and activation energy, and due to developing ultrasonic currents and high local temperatures, the mechanical stirring and heating are not necessary in the reaction [19]. Additionally, using ultrasonic irradiation causes emulsification and more effective transfer of the mass, resulting in a tenfold rise in the speed of formation of ester as opposed to the conventional stirring methods [12,13].

Another benefit of using ultrasound reactors is an approximate 50% reduction in the required amount of methanol. In most cases, the molar ratio of 5.4 methanol to 1 oil would be sufficient for reaction when the ultrasonic power is utilized [21]. Furthermore, the mass transfer is improved through the ultrasonic cavitation. Also, compared to the conventional stirring methods, there will be a 50% reduction in the consumption of catalysts which accounts for a large portion of the costs of biodiesel production [21].

Glycerin is one of the by-products of biodiesel production. Higher conversion efficiency and lower extra methanol lead to a much faster chemical conversion and faster separation of glycerin. Moreover, due to lower catalyst consumption and the high quality of produced biodiesel with the help of ultrasound, the produced glycerin will have lower catalysts and monoglycerides, resulting in reduced biodiesel refining costs [21].

The designs of ultrasonic reactors are affected by a lot of factors, including the ratio of ultrasonic vibrating probe diameter to the reactor diameter, the height of the reactor, the depth to which the probe penetrates into the liquid, and the characteristics of the chamber (material and shape of reactor) [22,23] in the ultrasound-assisted transesterification reaction. The use of ultrasonic power for mixing leads to the upwards trend of producing biodiesel with a higher quality because of the creation of the cavitation phenomenon and the formation of emulsion droplets between alcohol and oil phases [24]. Additionally, using ultrasound improves the transfer of the mass between oil and alcohol reactants, reduces the catalyst and methanol required for the oil molar ratio, and decreases both the free and total glycerol concentrations into the conventional mixing [25]. Methanol has higher reaction yields as opposed to other types of alcohol [26]. In a study performed by Nasir et al., the design, simulation of the biodiesel production process, integration of the reactor and separation systems, and sustainability of the biodiesel production were investigated [27]. To produce biodiesel from waste frying oils (WFO) under various conditions, Burcu Uzun et al. conducted a study and investigated the effects of different types and concentrations of catalysts, molar ratios of methanol to oil, reaction times, reaction temperatures and washing steps on biodiesel yields [1].

In a study conducted by Singh et al., the production of biodiesel from soybean oil using ultrasound was examined. The results demonstrated that an increase in the applied ultrasound energy initially increased the efficiency of the reaction until the maximum was reached. Then, any further increase in the ultrasound energy led to the downward trend of the reaction, resulting from degraded molecules of methyl ester, followed by oxidation and formation of aldehydes, ketones, and components with short chains. In this research, a 150-kJ ultrasonic energy was required for a maximum efficiency of 97%. It was also concluded that the energy applied to the reactor had to be between 125 and 215 kJ to increase the efficiency exceeding 97% [28].

Moreover, in a study performed by Lee et al., it was shown that a rise in the ultrasonic power somewhat increased the reaction efficiency, and any further increases resulted in a reduction in the reaction efficiency [29].

The frequency of ultrasonic waves affects the critical sizes of bubbles, and a rise in frequency leads to reductions in the volume and time of disintegration of cavitation bubbles [30]. The results of a study into the production of biodiesel from soybean using ultrasound revealed that frequency played a major role in the reactions of biodiesel production [31].

With an increase in frequency, cavitation is reduced in fluids. Therefore, to achieve equal cavitation requires a rise in the ultrasonic power. So, the use of low-frequency ultrasonic energy is preferred for biodiesel production [32]. In terms of acoustics, the frequency of ultrasonic waves is inversely correlated with power. In other words, high power is produced at low frequencies (20–100 kHz). Therefore, higher amplitudes (power) are required for creating similar cavitation effects which are produced at low frequencies. Therefore, higher power cannot be achieved at high frequencies, and given the aforementioned limitations, cavitation is not created at high frequencies [33].

In addition, the vibration amplitude has a strong influence on transesterification. Not to mention, the vibration amplitude is directly related to the input energy into the system, and how it affects the efficiency of the reaction is similar to that of ultrasound. In other words, the efficiency of the reaction is first increased with a rise in the vibration amplitude up to a certain quantity, and then it levels off or is increased.

In a study performed on the production of biodiesel from soybean oil using ultrasonic energy, it was shown that the highest efficiency of the reaction (over 99%) occurred in the first 5 min when the vibration amplitude was 100% and the maximum consumed energy was 133.17 kJ. The reaction efficiency in low vibration amplitudes continues to have an upward trend, whereas it is severely reduced in high vibration amplitudes [28].

In a study done on the production of biodiesel from palm oil, methanol and alkali metal oxide catalysts (e.g., CaO, BaO, SrO), with the help of ultrasound at a molar ratio of 9 to 1 and a 3% catalyst concentration, it was concluded that increasing the vibration amplitude led to the upward trend of the efficiency of the reactions. In addition, the same behavior was observed between the vibration amplitudes of 75% and 100% [34].

Increasing the ratio of the diameter of the rod to that of the reactor (though to a certain amount) and in other words, reducing the diameter of the reactor would result in a rise of the cavitation activity, with a variable optimum ratio according to the type of the chemical activity [35,36].

A study was performed by Klima et al. with the aim of optimizing a 20 kHz reactor based on the numerical simulation of the local distribution of the ultrasonic energy intensity and conducting qualitative comparisons with the experimental results. In this study, for a vibrating rod with a diameter measuring 13 mm surrounded by water; the maximum intensity of cavitation, diameter and height of the reactor were 25, 90 and 102 mm, respectively [37].