A Review on Biodiesel Synthesis using Iron Doped Catalyst

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Abstract. This paper summarized on the history of biodiesel synthesis, biodiesel synthesis using iron doped catalyst. Biodiesel are gaining enormous attention from researchers and manufacturers considering its advantages of non-toxic, biodegradable, renewable, and environment-friendly in order to improve the air quality over the atmosphere followed by reducing the global warming problems effectively. Regarding the conventional biodiesel production method, manufacturers generally utilize vegetable oil and alcohols to pass through the transesterification process with the presence of homogeneous base catalyst. The utilization of this types of catalyst lead to another environmental issues that most of the researches are concerning about since the homogeneous catalysts are not reusable and causing separation problems between oil products and the catalyst itself. Therefore, it is highly necessary for the researches and manufacturers to further explore and investigate some catalyst types that are truly feasible for high-scale or industrial usage. Heterogeneous catalysts are known to consists of an identical phase with the reacting medium where the liquid phase contains the feedstock and reaction medium whereas the catalyst retain within the solid phase, hence resolving the separation problems that the homogeneous catalyst would lead to. Recently, researches have introduced the novel method of magnetic properties impregnation of catalytic active component onto the carbonaceous compound. This proposed action tends to provide the advantages of high surface area, separation ease, and preventing the leaching of catalytic active components from the catalyst. Both the potential iron doped carbon catalyst have been extensively researched and studied within this report. Besides, the catalyst properties have discussed further for analyzing the effects of the biodiesel yield that introduced by the chemical and physical properties of various types of catalysts.

1. Introduction

Biodiesel, is also known as fatty acid methyl ester (FAME) is being acceptable by the populations due to its reusability, biodegradability, eco-friendly properties, hence reducing the probability of global warming while having the similar features with the comparison of petrodiesel or fossil fuels [1].
Biodiesel is commonly established via transesterification process between the triglycerides (mainly fats or oils) and alcohols (mainly methanol or ethanol) with the presence of catalysts. Technically, biodiesel is yet to be considered as the complete alternative energy source for the conventional petrodiesel throughout the global due to its high production cost which take into account of the raw materials cost and labour cost [2]. In addition, insufficient stock of the raw materials and ineffective catalytic system are also the considerable challenges faced while manufacturing the biodiesel to replace the conventional fossil fuels as this issue might cause difficulties for meeting the population’s demand across the global and/or other environment policy related problems could introduce at the same time as well [3]. Despite all of that, biodiesel is still not fully commercialized and practicable globally due to the low biodiesel demand but an enormous capital production cost, hence resulting the manufacturer to sell the biodiesel in a higher price. Regarding the biodiesel production, there are generally 2 kinds of catalyst which are acid catalyst and base catalyst. According to the researches, the biodiesel production via vegetable oil mainly utilized the homogeneous base catalyst with the consideration of reduced mass transfer resistance effect, hence faster reaction efficiency compared to the heterogeneous catalysts [4]. However, the homogeneous base catalyst like NaOH introduces the drawback of soap foaming and emulsions within the solutions due to presence of high free fatty acid (FFA) content > 1% inside the feedstock whereas the homogeneous acid catalyst is able to encounter this issue [5]. The liquid form conventional catalyst that commonly used for the biodiesel production is not reusable and causing corrosion towards the reactor and storage tank. Besides that, it requires several pre-treatments before the catalyst get discharged, otherwise it might bring along the negative effects towards the aquatic lives. Therefore, heterogeneous catalyst is preferable to be utilized for catalysing the biodiesel production since the solid catalyst is reusable, hence reducing the cost of purchasing the new catalyst. In order to improve the separation efficiency and recoverability for the catalyst during the final stages of transesterification process, the heterogeneous catalyst which complied with magnetic properties are proposed by impregnating it with ferrite ion. Therefore, the costly mechanical separation methods such like filtration and centrifugation are not necessary as the magnetic decantation method has provided effective and desirable separation performance for the catalyst from the biodiesel [6].

This research paper aims to inspire and motivate more researches to develop in-depth investigation and exploration regarding the biodiesel synthesis using iron doped carbon catalyst that have modified with magnetic properties. Besides that, this study brings out the idea of synthesizing the high-yield green fuel (biodiesel) via transesterification instead of the non-renewable fossil fuel through conventional method. Hence, this paper is capable to prove the sustainability and eco-friendliness of the biodiesel production via the iron doped carbon catalyst.

2. Latest Technologies for Biodiesel Production

2.1. Microwave Assisted Process

The biodiesel production via microwave assisted process basically describing the transesterification process that is proceeding under the microwave irradiation condition, hence shorten the reaction time and improving the production yield. The utilization of microwave for the biodiesel production based on the concept of emerging the electromagnetic radiations with the frequency ranges from 300 MHz to 30 GHz for affecting the molecular movement such as ion migration or dipole rotations but remained the structure of the molecule [7]. Followed by that, the microwaves effects slightly triggered the variance of the involved polar molecules and ions hence resulting molecular friction, and finally initiating the chemical reactions between the raw materials (oil, methanol, and base catalyst that contains both polar and ionic components). Since the energy provided by the microwave interacts with the molecules with a rapid rate, the transesterification process is able to accelerate within a short reaction time. Therefore, the biodiesel production via microwave assisted process produced high purity product, relatively low amount of by-product and a shorter separation time could be obtained [8]. However, the scale-up process for the laboratory-scale microwave assisted process is still containing much uncertainties and remain a challenge for the researches to improve it in order to upgrade this technique to become feasibly applicable for industrial biodiesel production.
2.2. Supercritical Process

Supercritical fluid, also known as the fluid consists of a temperature and pressure above its critical point, which means the liquid and gas phases do not exist at the same time, hence it is able to diffuse through any solids like a gas or dissolve any materials like a liquid. Researches have wisely utilized this unique property of the supercritical liquid and apply it as a part of the biodiesel production process. During the biodiesel production via supercritical process, researches have generally treated the water, carbon dioxide, and alcohol as the supercritical fluids [9]. As the liquid methanol is known to be a polar solvent and has a pair of hydrogen bonding in order to form the methanol clusters between the OH oxygen and OH hydrogen from another two methanol molecules. However, a supercritical methanol has a hydrophobic nature with a lower dielectric constant in order to allow the non-polar triglycerides can well-isolated with the supercritical methanol to form a single-phase oil-methanol mixture (methyl ester).

With this reason, the conversion rate for the oil into methyl ester was found to largely increase compared to the one that produced from triglycerides and liquid phase methanol via the conventional method, transesterification process [8].

On the other hand, there were several factors affecting the performance of the transesterification process via the supercritical process such like temperature effect, pressure effect, and the effect alcohol-oil molar ratio. Firstly, temperature is the prior factor among all factors that affects the transesterification process under the supercritical condition. According to the study of Kusdiana & Saka [10], the conversion rate for the triglycerides to methyl ester was 70 wt % which is relatively low when the supercritical fluid temperature of 200-230°C was applied as the process conditions whereas 95 wt % of triglycerides to methyl ester conversion rate was obtained at 350°C for only 4 minutes of the reaction time [11]. Additionally, the increment of temperature effects leads to the rising of pressure effects which could increase the triglycerides’ solubility, hence close contact between the alcohol and triglyceride has established. Finally, a high alcohol-oil molar ratio could result a favourable and desire transesterification process due to the increment of contacted area between the oil and alcohol under supercritical conditions. In overall, biodiesel production via supercritical process has the advantage of high product recovery rate, but also with the drawbacks of high energy consumption and excess alcohol usage in the supercritical conditions [8].

2.3. Ultrasonic Irradiation Process

The ultrasonic irradiation supplied a large negative pressure gradient to the liquid followed by causing the liquid to break down into cavitation bubbles. These small cavities grow rapidly under high ultrasonic intensities and collapse immediately after seconds, hence rising the mass transfer condition by interrupting the interfacial boundary layers within the mixture of involved oil and alcohols [12]. Followed by that, the emulsification between the immiscible mixture (oil and alcohol) is able to improve effectively due to the mixture boundary layer enlargement which caused by the ultrasonic cavitation.

For transesterification process, ultrasonic mixing provides a better mixing with the improved mass transfer rates compared to the one that using conventional batch reactor for mixing since a well-mixing is the key for a high production of biodiesel. In overall, ultrasonic biodiesel production could be beneficial for small-scale production in terms of short reaction time and low energy consumption, but it would be a huge challenge to utilize this method if large scale industrial production is required due to the necessity of enormous increment of ultrasound probes and energy supplier.

2.4. Membrane Biodiesel Production

The membrane system that designed for the biodiesel production generally possessed with the potential characteristics of high selectivity, high surface area per unit volume, and the ability for controlling the level and concentration of the involved components during the mixing between the two phases. In the biodiesel production process via membrane system, the membrane reactor system is the first phase of the two phases to trans-esterify the triglycerides and alcohols to form biodiesel. Followed by that, the second phase is the separative membrane system which responsible for isolating the impurities such like catalysts, soap, organic or inorganic solvents, and absorbents from the crude biodiesel. Furthermore, the organic membrane is commonly suitable for the process which excluded high acidic and basic conditions whereas inorganic membranes such as metallic and ceramic are preferable while dealing with harsh conditions.
conditions such as high temperature, high pressure, and high vibration [13]. However, there are several prospects and challenges that might encounter during the biodiesel production through membrane system which has shown as Table 1. below, therefore, this technique can only be utilized feasibly after the listed challenges have been overcome.

### Table 1. Prospects and challenges for biodiesel production via membrane system [14], [15].

| Prospects | Challenges |
|-----------|------------|
| 1. Can be operated continuously | 1. High expectation for membrane systems |
| 2. Can combine both transesterification reaction and separation simultaneously | 2. Membrane systems are limited by pore size and shape of materials to be filtered |
| 3. Can provide both technical and economic advantages over alkaline catalyst when process low quality feed | 3. Soap formation when homogeneous alkaline catalyst is used |
| 4. Easy product removal during transesterification | 4. Leaching of solid alkaline catalyst |
| 5. Can reduce foaming of by-products, glycerol | 5. Yield are lower compared to those obtained heterogeneous catalyst in batch reactors |
| 6. Improving the efficiency of hot water washing step | |

#### 2.5. In-situ Transesterification

In-situ transesterification, also known as the reactive extraction which processed based on the concept of simplifying the biodiesel production process by allowing both the oil extraction and transesterification process to perform within a single step at the same time. In in-situ transesterification process, the lipids in the oil-bearing seeds directly contacts with the selected chemical solvent with the presence of a catalyst. The differences between the conventional method and in-situ transesterification for biodiesel production has shown as Figure 1. below. According to the research in recent years, the feedstock commonly consists of Jatropha oil, soybeans oil, and sunflower seed oil followed by mixing with the alcohol directly for the triglycerides transesterification process instead of the extracted oil mixed with the alcohols and catalysts, hence skipping the oil extraction process and resulting the reduction in operating cost [16]. Additionally, the use of co-solvent in in-situ transesterification process could stimulate the methanolsysis process, hence allowing the maximum amount of alcohol to consume during the transesterification process followed by obtaining a considerably high yield of biodiesel. According to researches, an approximately yield of 95% Chlorella pyrenoidosa biodiesel was obtained with the utilization of hexane as the co-solvent with the molar ratio of 76:1 (hexane to lipid) at a reaction temperature of 95°C and catalyst loading of 0.5 M H₂SO₄ [17]. In conclusion, the Figure 2. has shown all the schematic diagrams of the latest technology in biodiesel production whereas Table 2. has summarized all the latest technologies in biodiesel production that have been carried out in experimental basis.

![Figure 1. Differences between conventional method and in-situ method for biodiesel production](image-url)
Figure 2. Latest technology in biodiesel production, (a) Microwave assisted, (b) Supercritical, (c) Ultrasonic irradiation, (d) Membrane
| Method                          | Advantages                                      | Limitations                                      | Feedstock          | Optimal operating conditions       | Yield | Ref. |
|--------------------------------|------------------------------------------------|-------------------------------------------------|--------------------|-------------------------------------|-------|------|
| Supercritical Process          | Short reaction time                             | High equipment capital cost                      | Soybean oil       | Temperature: 280°C                  | 98%   | [18] |
|                                | High purity product                             | High energy usage                                |                    | Pressure: 12.8 MPa                 |       |      |
|                                | Well-mixing reaction                            | Excess alcohol usage                             |                    | M/O ratio: 24:1                    |       |      |
|                                | Catalyst is not required                        |                                                 |                    | Reactor type: Batch-type vessel    |       |      |
|                                | Allow large-scale continuous production         |                                                 |                    |                                     |       |      |
| Microwave Assisted Process     | High conversion rate                            | Difficult to scale-up from laboratory scale to   | Safflower seed oil| Temperature: 333 K                  | 98.4% | [19] |
|                                | Short reaction time                             | industrial scale                                 |                    | Catalyst loading: 1 wt%             |       |      |
|                                | Less energy consumption                         | Solid feedstock is not preferable                |                    | Reaction time: 6 mins               |       |      |
|                                |                                                 |                                                 |                    | M/O ratio: 10:1                     |       |      |
| Ultrasound Assisted Process    | Well-mixing between oil and alcohol             | Large catalyst usage                             | Canola oil         | Temperature: 55°C                   | 95%   | [20] |
|                                | Less energy usage                               | Not fully-commercialized due to its infeasibility|                    | Reactor conditions: 450 W           |       |      |
|                                | Short reaction time                             |                                                 |                    | M/O ratio: 6:1                      |       |      |
|                                |                                                 |                                                 |                    | Catalyst loading: 1 wt%             |       |      |
| In-situ Transesterification Process | Less alcohol required                        | Difficult to scale-up from laboratory scale to   | Linseed oil       | Temperature: 40°C                   | 94%   | [21] |
|                                | Most of the oil types are applicable            | industrial scale                                 |                    | Pressure: 60 MPa                    |       |      |
|                                | Eliminate the selection of costly oil feedstocks| Not fully-commercialized industrially due to its|                    | M/O ratio: 10:1                     |       |      |
|                                |                                                 | profitability                                    |                    | Reaction time: 90 mins              |       |      |
|                                |                                                 |                                                 |                    | Catalyst loading: 6.8 wt%           |       |      |
| Microwave Assisted Process     | High selectivity                                | Not easy to scale into industrial scale          | Soybean oil       | Temperature: 65°C                   | 94.5% | [22] |
|                                | Efficient separation                            | High membrane cost                               |                    | Catalyst loading: 40.5 wt%          |       |      |
|                                | Environmental-friendly                          | Fouling issues                                   |                    | Reaction time: 150 mins             |       |      |
|                                |                                                 |                                                 |                    | M/O ratio: 6:1                      |       |      |
3.0 Catalyst Heterogeneous Catalyst

3.1. Heterogeneous Catalysts Iron Doped Carbon Catalyst

Catalyst plays an extremely significant role within the modern era of scientific and technologies as it is able to improve the reaction rate, reduce the chemical process temperature, and provide specific selectivity during the asymmetric synthesis. Both the homogeneous and heterogeneous catalysts have their benefits. For example, heterogeneous catalysts are readily to be separated from the product mixture solution but the reaction rate is limited due to the catalyst’s insufficient surface area, whereas the homogeneous catalyst provides a fast reaction rate and high product conversion, however, separation problem between the catalyst and the product will occur since the catalyst is miscible within the reaction medium, hence causing a series of pollution problems after it being discharged into the environment [23]. Therefore, the iron doped carbon catalyst has highly sought the attentions from the researches due to its high reusability and self-isolation ability. Based on the information above, iron doped nanoparticles are potentially utilized for attaching with the catalyst support material which is usually a solid with high surface area in order to maximize the magnetic decantation strength for the catalyst to isolate from the mixture solution [24].

The attached nanoparticles onto the solid catalyst does not only provide the advantages of increased catalyst surface area which could lead to high reaction rate, but also forms a stable suspension within the reaction medium when the nanoparticles are well dispersed into the catalyst, so that allowing the elevation of reaction rate [25]. The mechanism of iron doped catalyst is shown as Figure 3. below. These nanoparticles generally constituted of a series of metals such like iron, cobalt, or nickel, and alloys like iron oxides or ferrites which consist of high-strength magnetic moments when the external magnetic field has applied [26]. For example, the iron doped nanoparticles might disperse throughout the mixture solution with the absence of applied magnetic field, however, the iron doped nanoparticles will be deposited selectively towards a specific direction with the presence of applied external magnetic field. This kind of operations enable the iron doped nanoparticles catalyst to be recovered and reused again and again after every cycles of the clean and convenient magnetic decantation process. According to the study of Guo et al. 2006 [27], the recovery rate of an iron doped catalyst is about 2 times faster compared to the non-iron doped catalyst [24].

![Figure 3. General mechanism of iron doped catalyst (26).](image-url)

According to the study of Kang Liu and Rui Wang, 2017 [28], their conducted experiment was successfully synthesized a novel bifunctional bamboo charcoal-based iron doped solid base catalyst (K/BC-Fe$_2$O$_3$) via the in-situ impregnation-calcination method. The schematic diagram of the formation mechanism within the alkaline active sites on the iron doped catalyst (K/BC-Fe$_2$O) surface has shown as Figure 4. as below. At the beginning of the activation process, the gasification reaction undergone continuously within the active sites around the vicinity of the potassium salts compound followed by
forming the process intermediates, finally the K₂O species formed. Thus, the transesterification process has occurred with high efficiency within the active sites of the K₂O species [29].

Figure 4. Formation mechanism of the alkaline active sites onto the iron doped catalyst surface [29].

The maximum production yield was achieved 98% conversion rate with the optimal operating conditions: 2.5 wt% of catalyst amount, a methanol to oil molar ratio of 8:1, 1-hour reaction time, and a temperature of 60°C. Nevertheless, the conducted regeneration experiments in this research highlighted the high catalytic activity of the iron doped catalyst that could still maintained after the 4 times catalyst reused. Therefore, this research has presented a truly potential novel bifunctional heterogeneous iron doped catalyst in the biodiesel production field [29].

According to the study of Yi-Tong Wong et al, 2019 [30], the sulfonated iron doped solid acid catalyst, ZrFe-SA-SO₃H and ZrFe-CMC-SO₃H were synthesized via the 4-step process. Firstly, the Fe³⁺ ion undergoes the chelation process to produce the –(COO)₃Fe structure, followed by reducing the –(COO)₃Fe structure into Fe₂O₄ via the subsequent calcination process at a temperature of 400°C since the stable iron doped core of the Fe₂O₄ does not allow the reduction reaction to occur below 400°C. Then, the chelation and embedding process with Zr⁴⁺ tend to construct a dense carbon shell with the –(COO)₃Zr structure which act as the protection for the magnetic core from the sulfuric acid dissolution process during the sulfonation reaction. Finally, the external part of the carbon shell was partially carbonized during the sulfonation, hence creating a strong Bronsted acid sites for the carbon skeleton structure in order to proceed the biodiesel production process via the esterification of oleic acid [30]. The preparation process for this catalyst has shown as Figure 5. schematically as below.

Figure 5. A 4-step process for synthesizing the sulfonated iron doped solid acid catalyst [30].
This sulfonated iron doped acid catalyst is able to supply both high surface-acidity density and considerable magnetization. The synthesized catalyst was tested to provide 92.5-99.5% of biodiesel yield for the first catalytic cycle at temperature of 90°C with 4-hours of reaction time. However, the biodiesel yield has shown to be decreased 9% after five cycles of catalytic activity were proceeded by using the ZrFe-SA-SO₃H catalyst. Therefore, this catalyst indicated a relatively low recoverability compared to other industrialized catalyst but still feasible and practicable for industrial usage considering the acceptable yield amount of the biodiesel production [30].

According to the study of Indu Ambat (2019) [31], the potassium impregnated nano-magnetic ceria catalyst was synthesized from the rapeseed oil for the biodiesel production, water treatment, and biocatalysis. This catalyst is basically prepared based on the concept of impregnating the cerium oxide, CeO₂ iron doped nanoparticles into the potassium ions [32]. Moreover, a 25 wt% of potassium impregnated Fe₃O₄-CeO₂ nano-magnetic catalyst performed the best yield of biodiesel production. In addition, a 96.13% yield of biodiesel production could be obtained with the utilization of the following reaction parameters: a 4.5 wt% amount catalyst added, temperature of 65°C, 1:7 molar ratio of methanol to oil, and 120 minutes of reaction time [33]. The resulted biodiesel properties were determined using EN 14214 method, hence all these results are potentially indicated that the Fe₃O₄-CeO₂ nano-magnetic catalyst is a feasible catalyst for the desired quality biodiesel production by using the rapeseed oil as the oil feedstock [34].

Pingbo Zhang (2014) [35] had reported the novel iron doped solid base catalyst CaO/CoFe₂O₄ for the biodiesel production. The iron doped catalyst in this study was synthesized by first preparing a CoFe₂O₄ iron doped cores from the reaction between CoSO₄∙7H₂O and FeCl₃∙6H₂O. The CoFe₂O₄ iron doped core was then mix with the anhydrous CaCl₂ with a Ca²⁺ to CoFe₂O₄ molar ratio of 5:1. After the NaOH solution was added into the mixture, the mixture solution was stirred for 30 minutes at room temperature and aged for 18 hours at 65°C. Finally, the iron doped solid base catalyst, CaO/CoFe₂O₄ was obtained after the magnetic precursor was dewatered at 80°C for 12 hours and undergone the calcination process at 800°C for 3 hours [36]. The results from the characterization demonstrated that the stronger magnetic strength which provided from the CaO/CoFe₂O₄ catalyst compared to the CaO/ZnFe₂O₄ and CaO/MnFe₂O₄ catalysts due to its higher wettability and basicity as better wettability has the advantage to the enhanced contact between the catalyst and reactants, as well as better water resistance in order to protect the active sites of the catalyst support, CaO [35].

Another novel catalyst is the heteropolyacid-supported cotton-regenerated magnetic cellulose microsphere (MCM) catalyst which presented by Han et al, 2016 [36]. The catalyst was synthesized by first regenerating the cellulose microsphere (CM) by using the cotton. Then, the cellulose microsphere(s) were modified by mixing the triethylenetetramine (TETA) with the presence of NaCO₃ at 50°C for 8 hours followed by the co-precipitation process using the mixture solution of Fe (II) and Fe (III) salts in order to obtain the magnetic cellulose microsphere (MCM). Next, the mixture of heteropolyacid (HPW) and MCM was the heated in an oil-bath at a temperature of 60°C for an 8-hours continuous stirring, finally, the MCM was filtered and dried in order to obtain the MCM-HPW catalyst [38].

This catalyst was specifically utilized for the transesterification of the highly acidic Pistacia chinensis seed oil in order to produce biodiesel as the end-product. This study indicated that 93.1% of biodiesel yield has been converted from the FAME under the following optimal conditions: 15 wt% catalyst amounts, methanol to oil ratio of 10:1, temperature of 60°C and 80-minutes reaction time [39]. Nevertheless, the synthesized catalyst was observed to be separated efficiently from the mixture with the magnetic field application, as well as potentially reused for at least 4 cycles of catalytic activity and maintain the catalytic stability at the same time. Thus, the MCM-HPW catalyst fulfilled the requirements of a “green” biodiesel due to its reusability and environmental-friendly characteristics [38].

Fan Zhang et al, 2017 [40] study has reported another two type of novel catalysts which were the iron doped carbonaceous solid acid (C-SO₃H@Fe/JHC) and base (Na₂SiO₃@Ni/JRC) catalysts. These
catalysts were synthesized by loading active groups into the carbonaceous catalyst support which derived from the Jatropha-hull hydrolysate and hydrolysis residue which were responsible for the esterification and transesterification process of Jatropha oil respectively to synthesize the biodiesel [41]. The Jatropha-hull carbon coated-iron doped catalyst was sulfonated by concentrated sulfuric acid to form the final catalyst product, iron doped carbonaceous solid acid catalyst C-SO$_3$H@Fe/JHC [42]. On the other hand, the iron doped solid base catalyst was synthesized by first incubating both the Jatropha hydrolysis residue and nickel nitrate mixture within the oil-bath to obtain Ni/JRC followed by calcinating the product under an extremely high temperature to give the Ni/JRC supporter [41]. Then, the Na$_2$SiO$_3$·9H$_2$O was set to load with the Ni/JRC supporter followed by the calcination process at 400°C for 2 hours, lastly the final product, iron doped carbonaceous solid base catalyst, Na$_2$SiO$_3$@Ni/JRC was obtained. The preparation route for these two catalysts was presented as Figure 6. below [40].

![Figure 6. Preparation route of the iron doped carbonaceous solid acid and base catalyst [40].](image)

Both these acid and base catalysts were observed to be effectively recovered with the average recovery yield of 90.3 wt% and 86.7 wt% respectively after at least 5 cycles of catalytic activity were proceeded. Besides that, a highest 96.7 % of biodiesel yield production could be obtained via the two-step biodiesel production (first esterification using the C-SO$_3$H@Fe/JHC catalyst, then transesterification using the Na$_2$SiO$_3$@Ni/JRC catalyst) [40]. Table 3. has summarized the different types of iron doped catalyst for biodiesel production in recent years. In conclusion, the iron doped bamboo charcoal solid base catalyst possessed the highest biodiesel yield among the other iron doped catalysts that listed in the Table 3.
| Catalyst | Catalyst feedstock | Synthesis process | Catalyst characterization | Oil feedstock | Operating conditions | Catalyst reusability | Yield | Ref. |
|----------|-------------------|-------------------|--------------------------|---------------|----------------------|----------------------|-------|-----|
| Iron doped bamboo charcoal solid base catalyst (K/BC-Fe₂O₃) | Support: bamboo charcoal Magnetic: γ-Fe₂O₃ Chemicals: KNO₃ | 1. In-situ synthesis 2. Impregnation 3. Calcination | Magnetic saturation: 35.4 emu/g Basic density: N/A | Soybean oil | Reaction temperature: 60°C Catalyst loading: 2.5 wt% M/O ratio: 8:1 Reaction time: 60 mins | Cycles number: 4 | Biodiesel yield after the multiple cycles: 94% | 98% [29] |
| Sulfonated iron doped solid acid catalyst (ZrFe-SA-SO₃H), (ZrFe-CMC-SO₃H) | Support: carbon Magnetic: Fe₃O₄ Chemicals: Oleic acid | 1. Chelation 2. Calcination 3. Embedding 4. Sulfonation | Magnetization: 3.7-8.1 Am²/kg Acid density: 4.4-8.4 mmol/g | Jatropha curcas oil | Reaction temperature: 90°C Catalyst loading: 2.5 wt% Reaction time: 4 hrs | Cycles number: 5 | Biodiesel yield after the multiple cycles: 90.3% | 92.7-99.5% [30] |
| Nano-iron doped potassium impregnated ceria catalyst (Fe₃O₄-CeO₂) | Support: ceria Magnetic: FeCl₂·4H₂O, FeCl₃·6H₂O Chemicals: KOH | 1. Co-precipitation 2. Impregnation 3. Calcination | Magnetic saturation: 0.75 emu/g Basic density: 0.308 mg KOH/g | Rapeseed oil | Reaction temperature: 65°C Catalyst loading: 4.5 wt% Reaction time: 120 mins M/O ratio: 7:1 | Cycles number: 5 | Biodiesel yield after the multiple cycles: 80.94% | 96.13% [31] |
| Catalyst | Catalyst feedstock | Synthesis process | Catalyst characterization | Oil feedstock | Operating conditions | Catalyst reusability | Yield | Ref. |
|----------|-----------------|------------------|------------------------|---------------|---------------------|---------------------|-------|-----|
| Iron doped solid base catalyst (CaO/CoFe$_2$O$_4$) | Support: CaO Magnetic: CoFe$_2$O$_4$ Chemicals: NaOH | Magnetic cores: 1. Titration 2. Mixing 3. Drying Catalyst: 1. Impregnation 2. Calcination | Magnetic saturation: 45 emu/g Basic density: N/A | Soybean oil | Reaction temperature: 80°C Catalyst loading: 1.0 wt% M/O ratio: 5:1 Reaction time: 3 hrs | Cycles number: 5 Biodiesel yield after the multiple cycles: 80% | 87.4% | [35] |
| Magnetic cellulose microsphere supported heteropolyacid catalyst (MCM-HPW) | Support: cotton Magnetic: Fe$_3$O$_4$ Chemicals: heteropolyacid | 1. Regeneration 2. Co-precipitation 3. Immobilization | Magnetization: N/A Acid density: N/A | Pistachio chinensis seed oil | Reaction temperature: 60°C Catalyst loading: 15 wt% Reaction time: 80 mins M/O ratio: 10:1 | Cycles number: 4 Biodiesel yield after the multiple cycles: 80.7% | 93.1% | [37] |
Table 3. Different types of iron doped catalyst for biodiesel production (cont’d).

| Catalyst | Catalyst feedstock | Synthesis process | Catalyst characterization | Oil feedstock | Operating conditions | Catalyst reusability | Yield | Ref. |
|----------|--------------------|-------------------|--------------------------|---------------|----------------------|---------------------|-------|------|
| Iron doped carbonaceous solid acid and base catalyst (C-SO₃H@Fe/JHC), (Na₂SiO₃@Ni/JRC) | Support: Jatropha hull | Acid: 1. Hydrothermal 2. Pyrolysis 3. Sulfonation | Magnetic saturation: Acid: 11.2 emu/g Base: 15.0 emu/g | Jatropha curcas oil | Acid: Reaction temperature: 90°C Catalyst loading: 10 wt% Reaction time: 120 mins M/O ratio: 12:1 | Cycles number: 5 Biodiesel yield after the multiple cycles: Acid: 90.3% Base: 86.7% | 96.7% | [40] |

Jatropha curcas oil | Acid: Reaction temperature: 90°C Catalyst loading: 7 wt% Reaction time: 120 mins M/O ratio: 9:1 | Base: Reaction temperature: 65°C Catalyst loading: 7 wt% Reaction time: 120 mins M/O ratio: 9:1 | 96.7% | [40] |
4. Conclusions
In conclusion, the use of the iron doped nanoparticles bounded catalyst is to create such high recoverability of the catalyst and reuse it in order to save the capital cost of the biodiesel production process. Besides that, the iron doped catalyst usage allows the elimination of additional purification treatments that required for the products when the homogeneous catalysts are utilized for catalysing the process, hence making the iron doped catalyst to be more commercialized and recognized by the public due to its environmental-friendliness and economical benign.

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