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A Concise Review on Zeolite-Supported Catalysts for the Transesterification of Algal Lipids into Biodiesel

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ABSTRACT

The fossil fuel stocks around the world were still declining, consequently, there has been a trend towards biofuels as an alternative energy source. Therefore, zeolite-based catalysts when used for efficient transesterification of algal lipids into biodiesel were conceder a critical area of research aimed at optimizing the conversion of algal lipids-a rich source of renewable energy-into biodiesel, a sustainable alternative to fossil fuels. Transesterification of vegetable oils and animal fats using homogeneous bases and acids to produce biodiesel is no longer regarded sustainable due to food compared to fuel competition, as well as environmental and economic challenges with feed stocks and catalyst systems. This review provided a comprehensive analysis of the potential of inedible oil like algae oil to produce biodiesel utilizing heterogeneous zeolite-based catalysts, utilizing heterogeneous zeolite-based catalysts. Zeolites are among the most diverse and significant types of heterogeneous catalysts and are suited for both laboratory and industrial applications. This review investigates the catalytic efficacy, recent advances, and future potential of zeolite-based catalysts in biodiesel production from algal lipids**.** Their unique properties, coupled with ongoing research to overcome existing challenges, underscore their potential role in fostering sustainable energy solutions and enhancing the efficiency of biodiesel synthesis.

1. Introduction

Every year, human demands for fossil fuels rise. Biodiesel is considered a key alternative fuel to help address this global issue. Vegetable oil derived from feed stocks high in saturated fatty acids is used to make biodiesel. It is typically made from waste, non-edible plant oil, animal fat, and pure vegetable oil. A promising alternative feedstock is microalgae, such as *Chlorella vulgaris*, due to their rapid growth rates and high lipid content. However, while considering a few factors, including light intensity, medium nutrition, pH, and salinity, this microalga is recognized for having a high lipid content. Lipids are typically extracted using methods like the Bligh-Dyer process and subsequently react with methanol during transesterification, the lipid content will be removed. However, the use of homogeneous catalysts presents challenges, primarily separation difficulties. The primary issue is catalyst separation, which necessitates extensive washing of the biodiesel, leading to product loss and potential quality degradation. Zeolite is one of the promising catalysts that can be used as a heterogeneous catalyst to catalyze the transesterifications process. Since zeolite is simpler to remove from biodiesel, no washing procedure will be required [1]. Both homogeneous and heterogeneous catalysts function equally well. With comparable chemical and physical characteristics to diesel, biodiesel is a potentially low-carbon, renewable, and biodegradable fuel substitute. With all these environmental advantages,

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biodiesel could not be often used as a full fuel replacement for traditional diesel. principal cause [1]. Its non-toxicity, sulfur-free nature, and biodegradability. Its aromatics give it an advantage over traditional gasoline and diesel [2]. The current review provides a dedicated and critical synthesis focused specifically on the intersection of zeolite catalyst design (e.g., hierarchy, acidity tuning) and the unique challenges of algal lipid conversion (e.g., handling FFAs, bulky molecules). Our novel contribution is the structured analysis of how zeolite properties must be tailored for algal feedstocks, which is not covered in such depth elsewhere

2. Zeolite-based Catalysts

Zeolites are crystalline microporous aluminosilicates, comprised primarily of silicon (Si), aluminum (Al), and oxygen (O), and were discovered in 1756 by the Axel Cronsted a swedish mineralogist [3].

The frameworks consist of $[SiO_4]^{4-}$ and $[A1O_4]^{5-}$ tetrahedra that corner-share to create various open configurations. The tetrahedra form cages with specific pore gaps with diameters range from about 0.3 to 1 nm, depending on the structural type. The lattice's negative charge is balanced by the positive charge of metal cations, either univalent or bivalent which are found within the material's pores. Metal cations can be substituted with acidic protons through ion exchange to ammonium and then calcination [4].

Zeolites' remarkable properties make them widely utilized in technical fields such as ion exchangers, adsorbents and most importantly catalysts, due to their chemical composition, ion exchange, and pore structure [5].

Zeolite's stability increases with the raise of Si/Al ratio in the structure, as zeolites with $Si/Al \geqslant 3.80$ are highly stable and maintain their structure even at high temperatures [6].

Zeolites have acid-base characteristics and are determined by the ion-exchanged cations and the Si/Al ratio of the primary structure. To adjust the basicity of zeolite, two methods are commonly used: ion-exchange with alkali metal ions and impregnation of basic components on the inner surface of the pores. Research suggests that the former produces weaker fundamental sites, whereas the latter produces stronger ones [7].

In general, zeolites are classified into two categories: synthetic and natural. When volcanic rocks and ash layers crystallize in response to groundwater or an alkaline/saline lake, natural zeolites are created, however, a variety of materials, including clays and industrial waste, are used to create synthetic zeolites [8, 9].

Currently, 180 synthetic zeolites have been identified. Prior synthetic zeolite includes A, Y, X, L, ZSM-5, and Omega. The International Zeolite Association (IZA) Structure Commission publishes, and often updates, the Atlas of Zeolite Structure Types, which assigns a three letter ID to each known framework topology, regardless of composition [4].

Synthetic zeolite is preferred in commercial uses over natural zeolite because of its uniform particle size and purity of crystal structure. X, A, ZSM-5, Y, and beta are synthetic zeolites, that have the most commercial applications [10].

Zeolite is synthesized by hydrothermal crystallization of aluminosilicate gels, which are generated by combining an aluminate and silica solution with alkaline hydroxide compounds or organic bases. Crystallization happens in an isolated hydrothermal environment with higher temperatures, autogenous pressure, and duration ranging from several hours to a few days. Factors that influence the type of zeolite are composition of the reaction mixture, nature of reactants and their pretreatments, temperature, reaction time, and pH [4].

Zeolite has a structure of tetrahedra with center T atoms where (T can be, Al, Ga, Si, Ge, B, P...) with oxygen atoms at the structure's vertices. Tetrahedral structure joined by vertex atoms of oxygen forms a three-dimensional system of channels and voids. Approximately two million structures of zeolite might be predicted according to various T-O-T angles, building units, and distances. However, zeolite crystallization is a relatively difficult process. Figure 1 illustrates the development of zeolite structure, whereas the IZA's Structure

Commission has only authorized approximately 250 known zeolite framework variants.

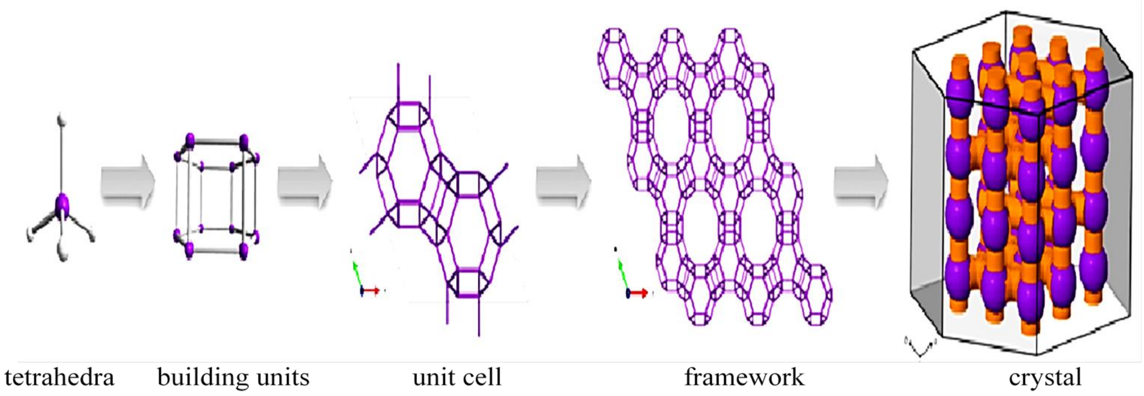

Figure 1. A schematic illustration of zeolite structure development [11].

Zeolite behaves similarly to acids in solution, having strong Brønsted acid sites like sulfuric acid. A Brønsted acid's strength is measured by the deprotonation energy (DPE) required to separate the proton from the conjugate anion through an indefinite length. The DPE values of zeolites could be determined using chemical computation methodologies. However, results change depending on the model due to zeolites structure, specifically the geometric limits placed on T-O-T angle connections. Whilst increasing the bond angles results in increased acidity of the acid site, due to lower energy that is needed to the deprotonation of bridging OH groups, the Strength of acid site variety with T-O-T bond angle. Figure 2 illustrates the strength of acid site variety with T-O-T bond angle.

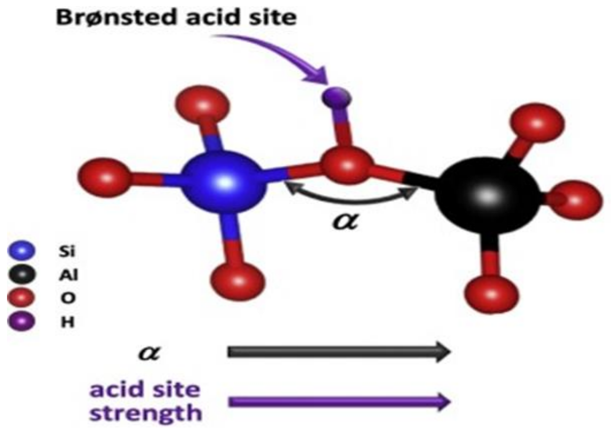

Figure 2. Strength of acid site variety with T-O-T bond angle [11].

Recent technologies have improved the synthesis of catalysts, including zeolites using organic structure directing agents (SDA) for example, small peptides, fatty acids, and amino acids, may act as SDAs. Using the interaction of silica with organic SDA, researchers created innovative porous, high-silica zeolite compounds that mimic natural zeolites while also introducing unique structures [12].

Zeolites, which are made up of connected silicate tetrahedra, may now build considerably larger cages and tunnels capable of absorbing and catalyzing organic particles, transforming them into value-added compounds Figure 3 A, Mesoporous silica phases form a materials family which can be synthesized using common organic surfactants as SDA. Figure 3 A – D shows Different Catalyst Structures of zeolite.

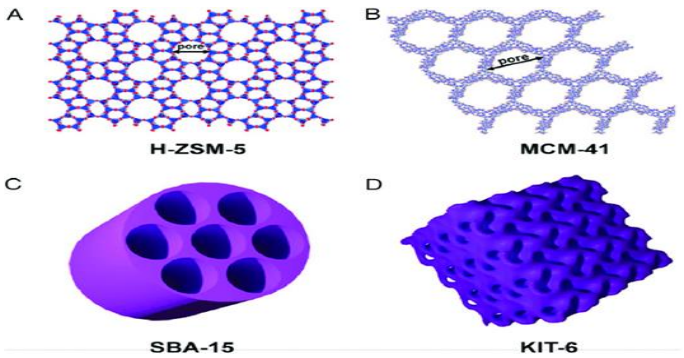

Figure 3. Different Catalyst Structure. (A) H-ZSM-5 zeolite crystal structure. (B) MCM-41 mesoporous crystal [13] structure. (C) Schematic of SBA-15 mesoporous silica. (D) Schematic of cubic mesoporous KIT-6 silica.

Zeolites as potential catalysts has attracted a lot of attention in the production of biodiesel due to shape selectivity in obtaining hydrocarbons within the range of characteristics seen in fossil fuels [14, 15].

Currently, heterogeneous catalysts are used in around 70% commercial chemical processes. The use of acidic zeolites instead of harmful catalysts such as H_2SO_4, HF, and $AlCl_3$ have transformed the petrochemical industry. Metal-containing zeolites can be used as catalysts for hydroisomerization, hydrocracking, and reforming processes, enabling large-scale production of high-quality fuels and bulk chemicals. Zeolites represent a true revolution in catalysis due to their combination of acid functions, homogeneous micropores that provide shape selectivity, and ease of regeneration [16].

3. Biodiesel synthesis

Biodiesel is a mixture of long-chain fatty acids of monoalkyl esters generated from vegetable oils, animal fats, or waste oil by esterification and/or transesterification with alcohols, typically methanol and ethanol as shown in Figure 4. An additional amount of methanol is employed to direct the reaction towards the desired side of the equation. An additional amount of methanol is recovered and recycled [17].

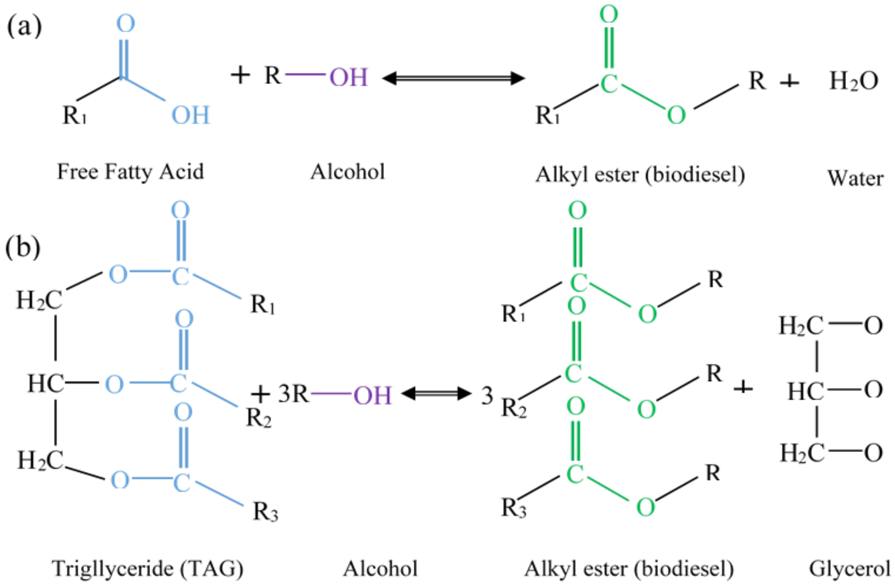

Figure 4. A schematic diagram of the production of biodiesel using: (a) Esterification and (b) Transesterification reaction [17].

Triglycerides (TAGs) are generated from a variety of feed stocks, including plant oils, animal fats, or other lipids [18].

However, depending on the source of feed stocks, different fatty acids, and their percentage compositions can be found.

Physical-chemical characteristics of the feedstock oil are determined by the profile of higher fatty acids linked in triacylglycerols, like mono- and diacylglycerols, free fatty acids (FFAs) [16].

Since FFAs react with base catalysts to produce carboxylic acid salts (soap) and water, they are undesired components in feedstock oil thus reducing biodiesel yields, and makes products more viscous, forms emulsions, and makes it harder to separate glycerol from biodiesel [10].

Typically, esterification and transesterification processes are carried out in the existence of homogeneous acid catalysts, for instance H_2SO_4, HCl, p-toluene sulfonic acid, H_3PO_4, BF_3, $AlCl_3$, $ZnCl_2$, and HF, additionally base catalysts, for instance NaOH and KOH or methoxide [19].

Nevertheless, due to their corrosivity homogeneous catalytic methods are not suitable for practical implementation, toxicity, non-recyclability, and non-reusability. Additional disadvantages of these types of system comprise environmental contamination and difficulties in products purification and isolation. Thus, developing efficient and recoverable heterogeneous catalytic systems is a significant issue in this field [5, 20].

In this case, zeolite-based catalysts are viewed as the most recognizable heterogeneous catalytic. Zeolite-based catalysts are widely used in biodiesel synthesis due to their capacity to execute transesterification and esterification reactions. Table 1 summarizes major research papers on biodiesel synthesis in the presence of zeolite-based catalysts.

Table 1: Studies report on production of biodiesel using zeolite-based catalysts [5].

Origin of oil	**Molar ratio of Si:Al**	**Molar ratio of alcohol:oil**	**Time h / Temp ^{0}C**	**Catalyst g.**	**Yield (%)**
Frying oil waste	10/H-MOR	MeOH/30:01	03/60	01	80.90
Frying oil waste	25/H-ZSM-5	MeOH/30:01	03/60	01	80.60
Frying oil waste	13/H-beta	MeOH/30:01	03/60	01	< 70
Frying oil waste	3/H-FAU	MeOH/30:01	03/60	01	< 75
$C_{18}H_{34}O_2$ acid	25/H-ZSM-5	MeOH/15:01	01/60	0.50	~ 80
$C_{18}H_{34}O_2$ acid	13/H-beta	MeOH/15:01	01/60	0.50	70
$C_{18}H_{34}O_2$ acid	10/TPA_3 /H-beta	MeOH/20:01	06/60	0.10	84
$C_{18}H_{34}O_2$ acid	10/H-MOR	MeOH/15:01	01/60	0.50	80
$C_{18}H_{34}O_2$ acid	3/H-FAU	MeOH/15:01	01/60	0.50	75
Cooking oil waste	10/TPA_3 /H-beta	MeOH/08:01w/w	20/60	06 wt. %	83.9
Jatropha oil	10/TPA_3 /H-beta	MeOH/08:01w/w	20/60	06 wt. %	92.6
$C_{18}H_{34}O_2$ acid	10/30%SiW12 /Hbeta	MeOH/20:01	10/60	0.10	86
Soybean oil	10/30%SiW12 /Hbeta	MeOH/04:01w/w	08/65	0.20	95
Soybean oil	10/30%SiW11 /Hbeta	MeOH/04:01w/w	08/65	0.20	96
$C_{18}H_{34}O_2$ acid	10/30%SiW11 /Hbeta	MeOH/20:01	10/60	0.10	82

Biodiesel can be made from more than 300 different edible and non-edible vegetable oils [10]. There are four types of biofuels that can be categorized based on feedstock: first, second, third, and fourth generation as shown in Figure 5.

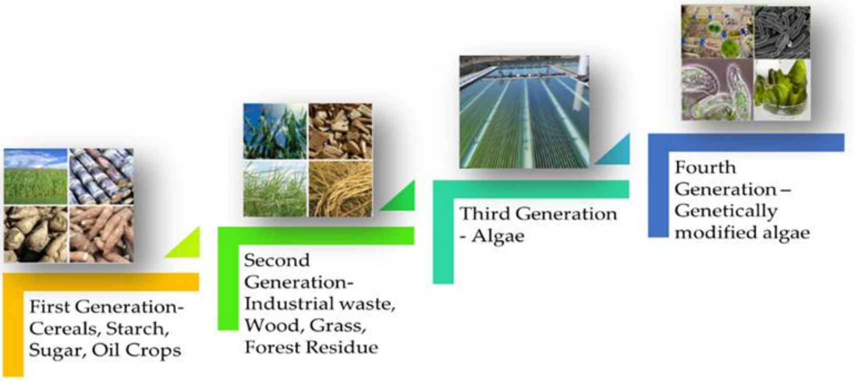

Figure 5. Biofuel feedstock generation [21, 22].

4. Algae Oils

Algae are simple aquatic microscopic organisms, classified into two populations: filamentous and phytoplankton. Proteins, carbohydrates, lipids, and nucleic acids are all found in various amounts in algae. While the quantities vary depending on the species of algae, some can contain up to 40% fatty acids [23]. The chemical compositions of several microalgae are shown in Table 2.

Table 2: Algal chemical composition as a percentage of dry matter [10].

Species of algae	Carbohydrate	Protein	Nucleic acid	Lipid
Scenedesmus obliquus	10 - 17	50 - 56	3 - 6	12 - 14
Scenedesmus quadricauda		47		1.9
Chlorella vulgaris	12 - 17	51 - 58	4 - 5	14 - 22
Prymnesium parvum	25 - 33	28 - 45	1 - 2	22 - 38
Chlorella pyrenoidosa	26	57		2
Scenedesmus dimorphus	21 - 52	8 - 18		16 - 40
Dunaliella salina	32	57		6
Chlamydomonas rheinhardii	17	48		21
Spirogyra sp.	33 - 64	6 - 20		11 - 21
Dunaliella bioculata	4	49		8
Euglena gracilis	14 - 18	39 - 61		14 - 20
Tetraselmis maculata	15	52		3
Porphyridium cruentum	40 - 57	28 - 39		9 - 14

One study of algae Lyngbya found the following profile: fatty acids both monounsaturated and saturated, which were detected in the following percentages: 15 palmitic (16:0), 7.4 linoleic (18:2), 11 stearic (18:0), 8.4 iso-(17:0), and 36 oleic (18:1), [24]. This alga's high proportion of monounsaturated and saturated fatty acids optimizes fuel quality by reducing polymerization during combustion, unlike polyunsaturated fatty acid that can pose a stability concern as high amounts of poly-unsaturated fatty acids tend to reduce the stability of biodiesel. Algal oil stands out for its high yield, making it ideal for biodiesel production [10].

Algae oil yields are estimated to be approximately 200 times higher per acre than the best-performing plant or vegetable oils [25]. Microalgae have the most rapidly growing rate, they can go through the entire growth cycle every few days, for example Diatom algae has the possibility to yield 46 tons of oil per hectare annually. Different types of algae produce varied quantities of oil. Specific algae may harvest up to fifty percent oil by mass [26].

Although using algae to produce biodiesel has not yet been commercialized, exploratory studies have been conducted to determine the estimated previous numbers. Table 3 shows the oil contents of different microalgae.

Table 3: The oil percentage of certain microalgae [10].

Microalgae	Wt.% of dry basis
chlorella sp.	28 - 32
botryococcus braunii	25 - 75
cylindrotheca sp.	16 - 37
dunaliella primolecta	23
crypthecodinium cohnii	20
monallanthus salina	>20
nannochloris sp.	20 - 35
isochrysis sp.	25 - 33
neochloris oleoabundans	35 - 54
phaeodactylum tricornutum	20 - 30
tetraselmis sueica	15 - 23
nannochloropsis sp.	31 - 68
schizochytrium sp.	50 - 77

nitzschia sp.	45 - 47

Since algae commonly yield a lot of polyunsaturated fatty acids, for example, Chlorella prototheorids has an average of (62.8%) of polyunsaturated fatty acids, which are greater than those of Cladophora fracta (50.9%), [25]. This would present undesired qualities of biodiesel, Nonetheless, polyunsaturates have lesser melting points than monounsaturates or saturates, therefore algal biodiesel should have considerably better cold weather qualities than many other bio-oils. Table 4 shows the Compositions of fatty acid in algal oils on a dry matter basis (wt. %).

Table 4: Compositions of fatty acid in algal oils on a dry matter basis (wt. %) [25].

Fatty acids	Chlorella protothecoides	Cladophora fracta
saturates	10.80 ± 0.60	12.50 ± 0.70
monounsaturates	24.10 ± 1.20	33.70 ± 1.60
polyunsaturates	62.80 ± 2.50	50.90 ± 1.90
free	2.60 ± 0.20	3.60 ± 0.30

5. Transesterification of Algae Oil by Zeolite

Numerous research has explored the activities of heterogeneous materials to mitigate the problems associated with the employment of homogenous bases and liquid acids as a catalyst's alcoholysis [27]. Table 5 lists a variety of solid bases and acids used as catalysts to produce biodiesel. Solid acids were primarily composed of heteropoly acids, zeolite materials, and pure or modified oxides of transition metals such as molybdenum and zirconium, alumina, and silica

Table 5: A review of heterogeneous catalysts used in transesterification [27].

Acids	Bases
zeolitic compounds like, HeY, H-MOR, ZSM-5, ETS-10, H-Beta, and ETS-4.	oxides of alkaline-earth metals: MgO, CaO, BaO, SrO.
sulfated zirconia (SO_4-2-ZrO_2) supported with Al_2O_3 or SiO_2.	carbonates of alkaline-earth metals: $MgCO_3$, $CaCO_3$, $BaCO_3$, $SrCO_3$.
sulfated zirconia combined with other transitional metal oxides like: SO_4-2-ZrO_2/MO_3. SO_4-2-ZrO_2/WO_3.	carbonates of alkaline-earth metals: K_2CO_3
free sulfated SnO_2 or supported usually over Al_2O_3 or SiO_2	transitional metal oxides, free and mixed like: CaLaO3, CuO, ZnO, $CaZrO_3$, $CaCeO_3$, $CaTiO_3$, $CaMnO_3$ etc.
Acetates of Zn or Cu supported over SiO_2	basic zeolites.
heteropoly acids and their derivatives like: $H_4SiW_{12}O_{40}$, $H_3PW_{12}O_{40}$.	Cs-exchanged sepiolite.
Acids	**Bases**
supported organosulphonic acids, mostly mesoporous SiO_2 and occasionally Al_2O_3.	hydrotalcites (Mg-Al).
nafion	Zn aluminate ($ZnAl_2O_4$, ZA).

The transesterification of algal oil that is rich with free fatty acids and triglyceride into biodiesel utilizing heterogeneous catalyst, can potentially be very efficient technology due to sustainability in the environment, catalyst reusability, expense reduction, and the high purity of glycerol and biodiesel [10].

Heterogeneous catalysts can be separated and purified more easily than the reaction mixture due to their distinct phase. Furthermore, they have no difficulty with equipment corrosion and are easier to recycle [28].

In a heterogeneous base reaction, the catalyst's Brønsted or Lewis basic sites react with a monohydric alcohol, often ethanol or methanol. In the resulting processes as shown in Figure 6, the produced alkoxide mixture reacts with the oil's triglyceride ester to release biodiesel and glycerol [29].

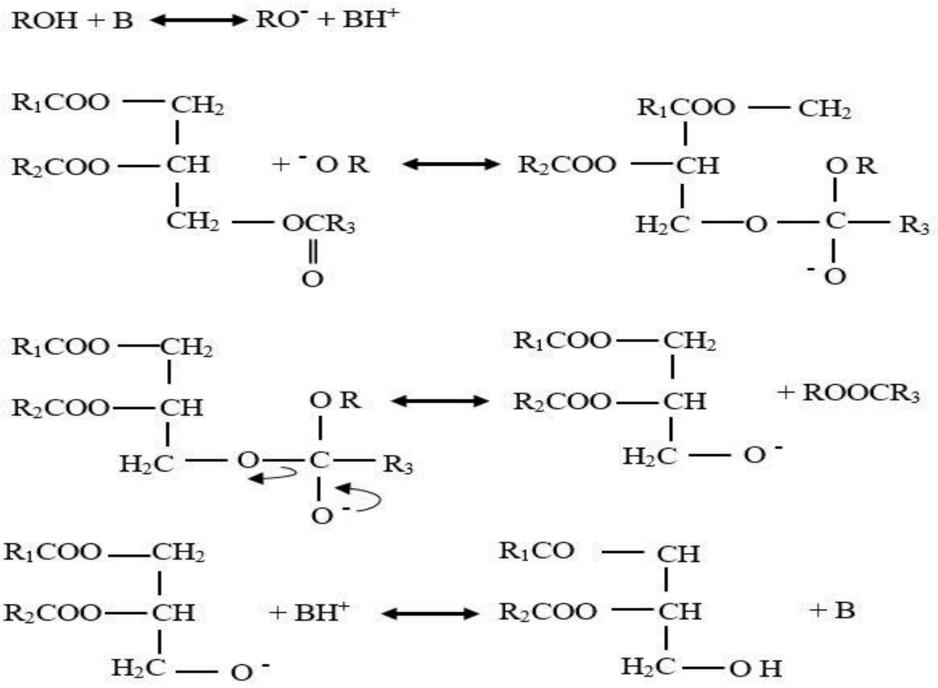

Figure 6. Base catalyzed transesterification mechanism [29].

In acid catalysis, acidity must be Brønsted kind, making of water and glycerol throughout the process of transesterification have previously been informed to effectively deactivate Lewis's acid sites. Originally, a carbonyl group is protonated to increase its electrophilicity, making it more available for attacking by nucleophilic Figure 7 shows the acid catalyzed transesterification mechanism [29].

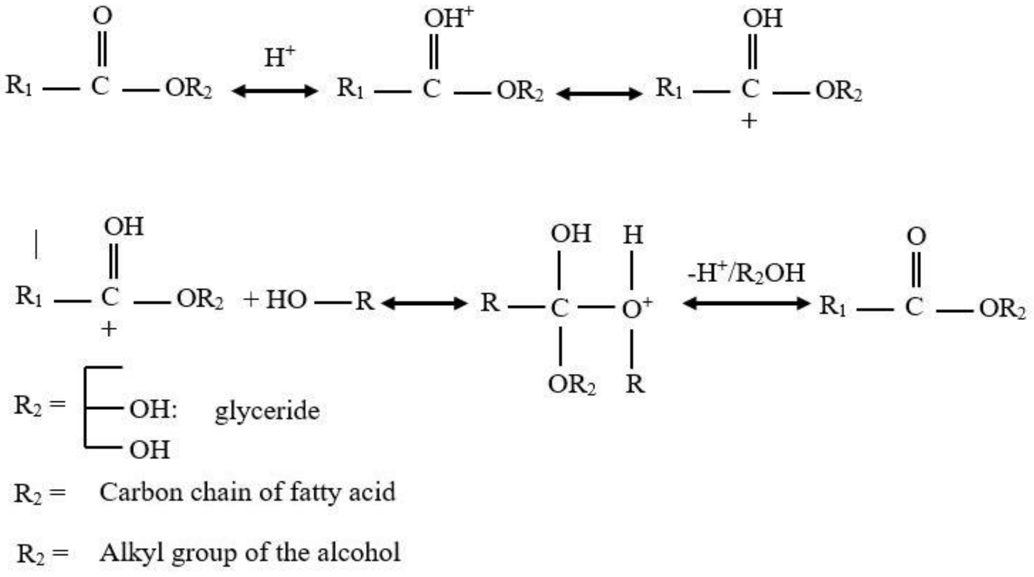

Figure 7. Acid catalyzed transesterification mechanism [29].

Heterogeneous basic zeolites are commonly utilized in lipid algal transesterification due to their abundance, low expense, low corrosion effect, and high basicity. As opposed to Brønsted or Lewis basicity factors, the density besides

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strength of basic sites significantly impact the rate of the reaction [30].

However, high porosity, the existence of stronger Brønsted acidity, a suitable hydrophilic/hydrophobic equilibrium on the surface, in heterogeneous acidic zeolites are regarded as essential features for enhanced catalytic activity. Acid zeolites have shown promise in producing biodiesel from high FFA-containing microalgae biomasses [31].

Zeolites being microporous alumina-silicate crystals with molecular sieve, varying acidity, and shape selectivity, their microporous characteristic limits the entry of bulky molecules. Several studies have been conducted to synthesize zeolites without limitations. Synthesizing hierarchical zeolites with bimodal micro- and mesoporosity results in increased surface area and similar acidity qualities to ordinary zeolites [32].

Studies were conducted to generate biodiesel through transesterification of microalgal oil and to compare the activity of two distinct catalysts, ZSM-5 and Beta, with varying crystalline and porosities structures [33].

The microporous nature of zeolite prevents the entrance of bulky-lipid molecules. Organ silanes were used to functionalize zeolitic seeds, resulting in hierarchical nano zeolites. After salinization, both zeolites' crystalline structure and Si:Al ratios (about 30) remained fixed. Ar-adsorption-desorption results show an increase in the exterior surface area of both zeolites, as well as the presence of secondary porosity in the about of micro-mesopores. This component may be critical in enhancing bulky lipid penetration and access to acid active sites. H-Beta had a larger surface area and pore volume than H-ZSM-5 after salinization. Another significant attribute of zeolites for the transesterification process is acidity. NH_3-TPD analysis revealed that hierarchical H-ZSM-5 had fewer and weaker acid sites, but H-Beta zeolite remained mostly unaltered [34].

Hierarchical zeolites produced more biodiesel than ordinary zeolites due to the improved bimodal porosity of the acid site and the easy access for bulky reactants. H-Beta zeolites have superior performance in acid-catalyzed transesterification due to their unique textural characteristics, porosity, and acidity. Another study found that using strong acid zeolites (BEA, FAU-X, and USY) for transesterification of triglycerides resulted in low yield of biodiesel due to limited access to acidic active sites in microporous zeolites [35].

Variations of Si to Al ratio in zeolites can also improve their catalytic performance during transesterification reactions. Optimizing the Si to Al ratio is crucial for maintaining an optimal hydrophobic equilibrium, preventing zeolite deactivation by water and controlling acidity [36]. A magnetic catalyst constructed from $MgO/ZSM\text{-}5@Fe_3O_4$ was incorporated with 15% polyethylene glycol (PEG) to enhance the catalyst's basicity, surface area, and mesoporosity, was utilized for microwave supported transesterification of Spirulina platensis. The radiation of microwave stimulated microalgae to release oil, which was then combined with ethanol to create biodiesel with the help of a catalyst [37].

Meanwhile, mesostructured solid materials do not suffer from bulky component penetration. KIT-5 as a mesoporous organosilica material having a large surface area and an organized mesoporous cage-type structure, making it suitable for bulky FFA as a reactant. The catalyst's acidity must also be considered, as a result, KIT-5 was filled with phosphotungstic acid (PTA) at doses ranging from five to forty percent. KIT-5 filled with 35 percent PTA demonstrated superior efficiency in algal FFA direct esterification to biodiesel at low temperatures. This is due to the combination of mesoporosity, acid site quantity, and strength. After multiple cycles, the catalyst exhibited extremely high activity levels [38].

Utilizing algal feedstock may be particularly a challenge when compared to other feed stocks. due to its high concentration of FFAs, in addition to triglycerides. FFAs can be non-polar or polar, whereas triglycerides are a non-polar material. Algal lipids’ polarity can affect the functioning of solid acid catalysts in esterification and transesterification reactions. Various algal lipids, such as palmitic acid, glyceryl tripalmitate, glyceryl dipalmitate, dipalmitoyl phosphocholine, and sorbitan mono-palmitate were employed as prototypical components for solid with acid-catalyzed biodiesel (methyl palmitate) generation [39].

6. Conclusions

Transesterification involving heterogeneous catalysts derived from zeolites, oxides, and their derivatives will keep going to draw industrial interest. Solid acid and solid base catalysts are possibly less expensive and can be separated and reused for the next transesterification process. If properly designed, they exhibit very little sensitivity to free fatty acids in the feed, thus generating highly pure biodiesel with qualities that satisfy worldwide requirements. Future zeolite catalysts should be designed with tailored porosity and acid-base properties, although further research is needed to determine the actual reaction processes and strategies for improving the conversion of triglyceride esters using several of these catalysts.

The use of algae to produce biodiesel and other industrial raw materials is undoubtedly a multipurpose alternative. However, some concerns must be addressed before the full benefits can be realized. It is necessary to determine the optimum economical methods for algae cultivation and oil extraction. More research should be done on inexpensive algae species that have a high oil content and thrive quickly in particular environments. Additionally, the high-quality glycerol derived by heterogeneous transesterification of algal oil offers tremendous promise for decreasing industrial dependence on non-renewable petrochemicals as raw materials.

Further studies are needed to optimize catalyst synthesis, understand reaction mechanisms in confined pores, and scale up the process. Zeolites and oxides have demonstrated encouraging results in the formation of a wide range of gaseous and liquid products, including diols, olefins, formaldehyde, allyl alcohols, hydrogen and methane fuel, in addition to further liquid hydrocarbons such as light naphtha and diesel. Further significant an include glycerol carbonate and derived alcohols such as 1,3-ditert-butoxypropan-2-ol, which have great qualities as a combustion improver for diesel fuel. As a result, their attention can be focused on improving their performance.

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