

Article

Sustainable Production of Biodiesel from Novel and Non-Edible *Ailanthus altissima* (Mill.) Seed Oil from Green and Recyclable Potassium Hydroxide Activated *Ailanthus* Cake and Cadmium Sulfide Catalyst

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Abstract: Heterogeneous catalyst prepared from *Ailanthus altissima* oil cake along with cadmium sulphide catalyst proved to be an efficient, cost-effective and sustainable source of biodiesel synthesis from *Ailanthus altissima* (Mill.) seed oil. *Ailanthus altissima* (Mill.) is a non-edible wild plant having significant oil content of 40%, being an ideal low cost and sustainable source of biodiesel production. After extraction of oil from the seeds, the remaining *Ailanthus* cake was treated through different techniques to be used as a novel heterogeneous catalyst. Free fatty acid content of the seeds was measured as 0.7%, which is very reasonable for effective trans-esterification process. The potassium hydroxide (KOH)-activated *Ailanthus* cake (KAC), calcined *Ailanthus* cake (CAC) and cadmium sulphide nanoparticles (CdS) were characterised with different techniques such as SEM at different magnifications, XRD and EDX. These catalysts were effectively utilised for biodiesel production owing to promising reusability, cost-effective and eco-friendly behaviour. For trans-esterification of *Ailanthus altissima* oil (AAO), the operating conditions on which maximum biodiesel yield obtained were 3:1 methanol to oil molar ratio, 0.5 wt.% catalyst concentration, 90 min reaction time, 60 °C and 600 rpm. The fuel properties of biodiesel obtained from *Ailanthus altissima* (Mill.) were also determined and analysed in detail. These properties, such as viscosity, density, pour point and cloud point, fall within the limits set by international standards of biodiesel.

Keywords: *Ailanthus altissima* seeds; biodiesel; calcined *Ailanthus* cake; CdS; non-edible oils

1. Introduction

Globally, the use of conventional energy resources has various irreversible damaging effects directly on the human health and the environment on the basis of their rapid depletion. Meanwhile, the use of biodiesel as a substitute for traditional fossil-based diesel has numerous benefits, including reducing dependence on declining fossil fuel resources, aiding in the reduction in global warming rate by using renewable environment friendly resources for the transport sector, and minimising the emissions of hazardous particles [1]. The estimated increase in demand of energy by the year 2030 is ~53% [2]. In the recent era, three main worldwide problematic affairs are global warming, air pollution and reliance

on the fossil fuel [3]. To address these issues, bio-scientists have now transformed the trend of fossil fuel dependency to biofuels. Biofuel has been directed as mainstream fuel that has a feasible effect on lowering pollution, providing job opportunities and expanding the fuel market [4].

The use of food sources as biofuel resource is the reason for food price increases, which are not economical because food is a necessity [5,6]. The focus is now towards the use of cost-effective biofuel resources such as algae oil, waste cooking oil and jatropha oil. Biofuels from non-edible sources are more useful when commercialised as it is more cost effective and results in less CO₂ emission from road transport [5].

Ailanthus altissima (Mill.) Swingle, commonly known as Tree of Heaven, belongs to the genus *Ailanthus* of family *Simaroubaceae*, a small tropical family native to China and East Asia. This plant has been used widely in traditional Chinese medicines and is proved to have antidiarrheal, antipyretic, antiparasitic, antibacterial, antiviral, antioxidant and other pharmacological effects [7]. *Ailanthus* oil contains stearic acid, palmitic acid, oleic acid and linoleic acid, which are converted to methyl esters via trans-esterification reaction to produce biodiesel. Biodiesel formation required a chemical process called as trans-esterification of the seed oil. In this process, glyceride of the oil reacts with the alcohol (methanol or ethanol) in the [8] presence of a catalyst to form a long chain of fatty acid methyl esters (FAMEs). In the trans-esterification process, both homogeneous and heterogeneous catalysts have been used [9,10]. The homogeneous catalysts, which may be simple acids and alkalis, were widely used for biodiesel production on commercial scale as these were easily available and cost effective, but the main problem was the production of byproducts in the process, i.e., soap and glycerin. Washing and drying the biodiesel to remove the catalysts used and the glycerol produced increased the product cost and time and also wastage of water, so this problem had to be solved to increase the yield. Thus, contrary to this, the heterogeneous catalysts have the properties to overcome the drawbacks of the homogeneous catalysts, so gradually they overcome the commercial industry of biodiesel owing to their higher efficiency rate, negligible soap formation and reduced glycerol formation, and the maximum conversion rate and reusability of the catalyst. Among the heterogeneous catalysts, the higher catalytic activity reported is that of alkalis as compared to those that are acidic [11,12].

Many studies have been carried out on the production of biodiesel using *Ailanthus altissima* (Mill) seed oil. The present study comprises the synthesis of heterogeneous catalyst from the oil cake residue of the same plant to use in the trans-esterification reaction for biodiesel production. *Ailanthus* cake, either calcined or KOH activated, has not been used for biodiesel production in any prior work. The catalytic efficiency of calcination and KOH activation has been evaluated by analysing their effects through characterisation using scanning electron microscopy (SEM), energy dispersive X-ray diffraction (EDX) and powder X-ray diffraction (XRD). For biodiesel analysis, different qualitative and quantitative analyses have been discussed, such as gas chromatography–mass spectrometry (GCMS) and Fourier transfer infrared spectroscopy (FTIR).

2. Experimental

2.1. Materials

Analytical grade reagents such as isopropanol, n-hexane, potassium hydroxide, methanol, sodium hydroxide, chloroform, ethanol, sodium sulphide and cadmium sulphate were used and purchased from Sigma Aldrich and Merck Co., Germany. *Ailanthus* flowers and pods were examined in detail and photographed, as shown in (Figure 1). *Ailanthus* seeds were first collected from Terich, Chitral, Pakistan; the seeds were washed with warm water and dried overnight in an oven at 50 °C. Seed oil percentage was determined using a Soxhlet apparatus (Behr Labor-Technik). After the determination of oil content, bulk oil was extracted mechanically via an electric oil expeller (KEK P0015, 10127).

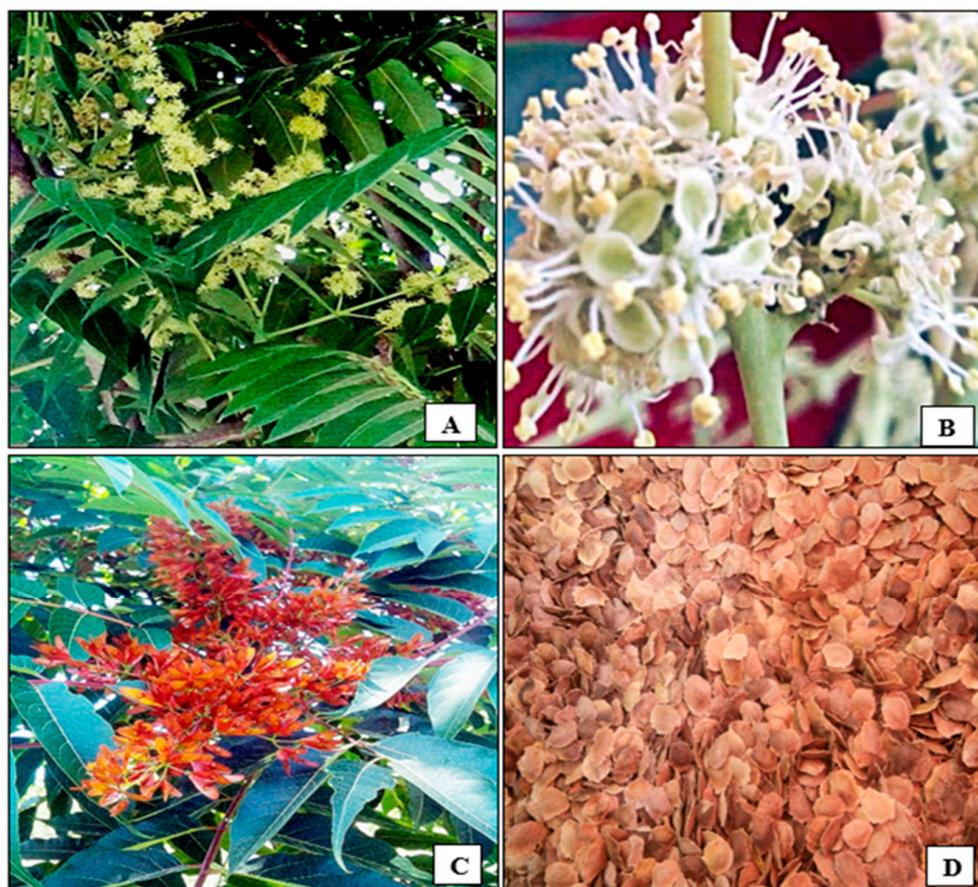


Figure 1. (A) Flowering branch of *Ailanthus altissima*, (B) flower, (C), pods, (D) seeds that have been peeled off.

2.2. Synthesis of Heterogeneous Catalyst

2.2.1. Calcined Ailanthus Cake (CAC)

The principal step in this process is the absolute purification of the cake from all types of impurities. To ensure this, the oil cake was washed (50 mL water) and soaked in water to remove impurities such as dust. The washed cake was then dried in the oven at a temperature of 65–70 °C. The cake was dried enough to be crushed and ground to very fine, minute powder. The ground powder was then placed in a muffle furnace for calcination. The temperature of the furnace was set at 450 °C and calcined for 3 h. The resultant material was then taken out and again crushed and kept for further processing [13].

2.2.2. KOH-Activated Ailanthus Cake (KAC)

The required amount of CAC was added to 1 M solution of KOH and then mixed well by magnetic stirrer on a hot plate. The temperature was set at 70–75 °C to mix it well at 600 rpm. The stirring continued until the liquid mixture converted into a visible paste. The paste formed was kept at room temperature for cooling. The paste was then moved to the muffle furnace for calcination at different temperatures (200–500 °C) and time (1–5 h); however, the best results were achieved by calcination of synthesised catalysts at 450 °C for 3 h. The product was then crushed and ground into fine powder [13].

2.2.3. Cadmium Sulphide Nanoparticles (CdS)

Cadmium sulphide nanoparticles were prepared via green synthesis using a method reported previously [14]; 0.1 M solution of sodium sulphide was freshly prepared in aqueous solution, then a tea decoction solution was prepared and gradually added to the solution and stirred vigorously. Then, another freshly prepared solution of cadmium

sulphate was added to the mixture. Then another solution of 1 M NaOH was added to stabilise its pH to 11; a brownish yellow colour was obtained. The resultant solution experienced continuous, vigorous stirring for 4 h to obtain precipitates at a temperature of 90 °C. The precipitates derived were then washed several times with methanol and the resultant solution was then centrifuged and dried. A final brown yellow solution was obtained and was then further processed for calcination in the muffle furnace for 4 h at a temperature of 450 °C [14].

2.3. Biodiesel Synthesis Procedure

The trans-esterification method is used to convert crude oil acquired from seeds to biodiesel. Twenty-five millilitres of *Ailanthus* oil portion was heated to 60 °C on the hot plate. Methoxide was formed by the addition of 0.50 g of catalysts to the 150 mL of methanol and was stirred by the magnetic stirrer over the hot plate for 1 h at 65 °C. The pre-heated oil was then cooled at room temperature and then added to the beaker. The mixture was then again heated at temperature of 65 °C for two hours [15]. After the completion of biodiesel reaction, a small amount of glycerol was separated from the product by a separating funnel. The upper lighter layer is that of FAMES and the lower dense layer is that of glycerol. The crude product was washed with water to neutralise the catalyst and the glycerin was removed. The product was then put in the rotary evaporator to remove extra alcohol/water content, which was lowered to 0.05% (v/v) to meet ASTM biodiesel specifications.

Different trans-esterification reactions were performed to determine the optimal biodiesel yield with different reaction parameters. Catalyst concentration is the key factor in determining the rate of trans-esterification reaction; either it is homogeneous or heterogeneous. In this study, the catalyst effect on the yield was analysed by using 0.25–1.0 wt.% catalyst. Oil to methanol ratio used for optimisation reactions were 1:3, 1:6, 1:9, 1:12. Reaction temperature was optimised by changing the temperature in the range 60–90 °C and the reaction time was optimised by varying time in the range 60–160 min.

3. Results and Discussion

3.1. Characterisation of Catalysts

The surface morphology of potassium hydroxide (KOH)-activated *Ailanthus* cake (KAC) was analysed via scanning electron microscopy (SEM), as shown in the Figure 2. The visible SEM images taken at different resolutions depict the morphology of the KAC, which appears to be irregular in shape, having hollow small cavities that, along with macropores, correspond to making the surface porous. The micrographs have a spongelike, fluffy appearance may aid in the increase in catalytic activity. Additionally, the micrographs of CdS were also investigated: fine particles were found in a regular pattern, as shown in Figure 3.

The important values of 2θ observed in the case of KAC are 29°, 30°, 31°, 32°, 33°, 34°, 36° and 39°. The peaks at 29°, 30°, 31°, 32°, 34°, 36° and 39° correspond to the presence of potassium in the form of potassium hydrogen carbonate (JCPDS Card No. 00-020-0886), whereas the strong peaks at 32° and 33° show the presence of potassium in the hydroxide form. The XRD clearly shows the incorporation of potassium in the calcined *Ailanthus* cake (Figure 4a). The average particle (crystallite) size was calculated by using the Debye–Scherrer equation ($D = k\lambda/\beta \cos \theta$) where β stands for full width half maximum, θ is the diffraction peak, k is a constant value that is 0.9 for the factor shape and λ is the wavelength of the X-ray. The calculated particle size is 34 nm. The diffraction pattern of CdS nanoparticles is shown in Figure 4b. The observed values of strong diffraction peaks of 2θ and (hkl) are 25 (100), 27 (002), 28 (101), 37 (102), 44 (110), 48 (103) and 52 (112). The broad peaks indicate the presence of nanosized CdS particles. The diffraction pattern matches well with the (JCPDS Card No. 00-001-0783) for CdS. The average particle size calculated by using the Debye–Scherrer equation is 14 nm.

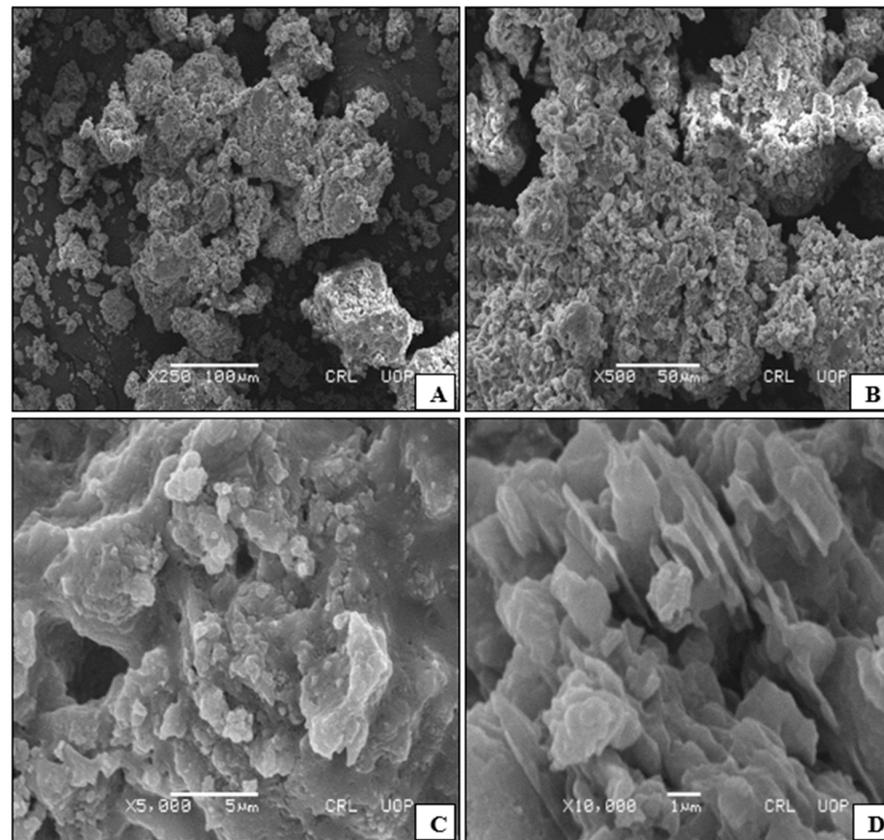


Figure 2. SEM images of KAC at different magnifications (A–D).

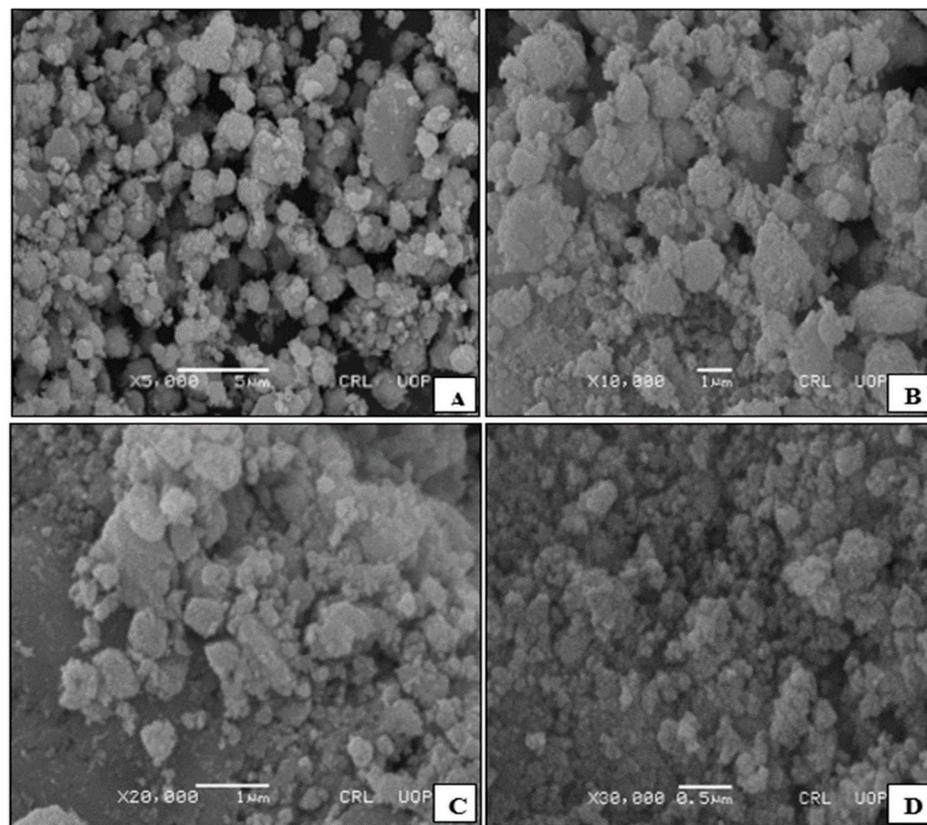


Figure 3. SEM images of CdS at different magnifications (A–D).

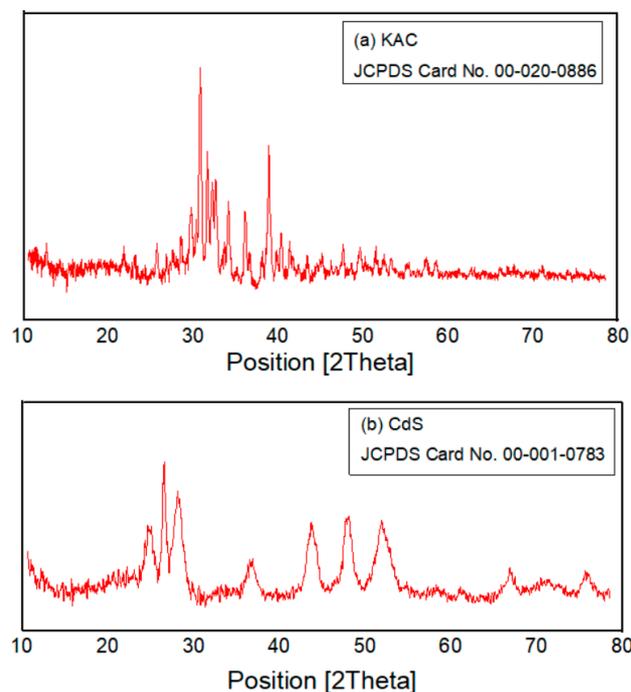


Figure 4. XRD pattern of KAC (a) and CdS (b).

The energy dispersive X-ray (EDX) results show the elemental composition in the prepared catalysts (KAC and CdS) (Figure 5a,b). As the catalyst is activated by potassium, the high percentage of 32.18% (wt.%) was observed along with carbon (27.7 wt.%) and oxygen (34.7 wt.%) as major elements. The EDX spectrum of CdS revealed the presence of only two elements in the compound: i.e., cadmium and sulphur with 72.34 and 27.30 wt.%, respectively. The EDX results depicted that the nanoparticles consisted entirely of cadmium and sulphur, thus establishing the purity of the particles.

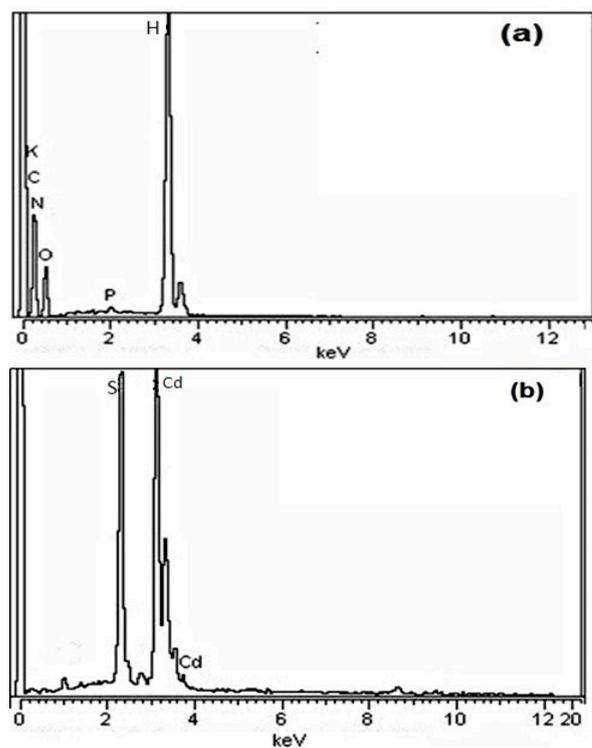


Figure 5. EDX of KAC (a) and CdS (b).

3.2. Biodiesel Synthesis Using *Ailanthus altissima* Seed Oil

Before the conversion of *Ailanthus altissima* seed oil (AAO) to biodiesel (AAOBD), the oil content and the free fatty acid (FFAs) contents of the seed oil were determined. The FFA content determined was 0.7%. The oil content of the *Ailanthus altissima* 5 g seeds was determined by using the Soxhlet apparatus and was recorded as 40%, which is substantially high as compared to many other edible or non-edible seed oils based on dry biomass. The reported FFA in the seed oil was determined by simple titration in two steps; the trans-esterification reaction rate and the yield of the biodiesel directly relates to the quality of the feedstock provided. As stated in the literature, FFA below 3% is the doorstep to the conversion of the oil to biodiesel. If the limit of the FFA exceeds this, the rate of conversion of triglycerides to esters directly affects and reduces the efficiency of the reaction. The excess value of FFA limits the efficiency of the process and finally leads to the process of saponification, i.e., formation of soaps as an extra product, which is the wastage of the feedstock and time, too, resulting in difficulty separating the layers of the products formed.

In addition to these parameters, calcination temperature and time greatly influence the catalytic activity. As in the current study, the as-synthesized catalyst (KAC) was calcined at different temperatures (200–500 °C) and time (1–5 h). The highest yield of biodiesel, however, was achieved using the catalyst that was calcined at 450 °C for 3 h. Our results are in line with earlier work (Munir et al., 2019a).

3.2.1. Optimisation of Biodiesel Yield

The trans-esterification process can be affected by different parameters. By regulating these parameters, one can obtain the maximum yield of biodiesel without the wastage of reactants. These parameters mainly include the oil-to-methanol ratio, type and concentration of catalysts, temperature ranges of the reaction, time set for the conversion of reactant to the desired product and the agitation intensity, but all the parameters basically depend on the nature of oil used for the synthesis of biodiesel.

Effect of Catalyst Concentration on Biodiesel Yield

Catalyst concentration is the key factor in determining the rate of trans-esterification reaction, either it is homogeneous or heterogeneous. In this study, the catalyst effect on the yield was analysed by using 0.25–1.0 wt.% catalyst (Figure 6a). The results clearly showed that biodiesel yield increased directly with the increase in catalyst amount, maximum yield was attained at 0.5 wt.%, after which a slight decline appeared referring to the decrease in biodiesel yield that may be due to the adsorption of liquid on the solid catalytic surface. Rozina et al. (2018) obtained a high yield of 99% at catalyst concentration 0.18 wt.% using ethanol obtained from the simultaneous saccharification and fermentation (SSF) process for the synthesis of *Saussurea heteromalla* (D.Don) seed oil biodiesel. Results of our study are compatible to their findings. The lowest catalyst concentration was insufficient to precede methyl ester formation efficiently.

The important values of 2θ observed in the case of KAC are 29° , 30° , 31° , 32° , 33° , 34° , 36° and 39° . The peaks at 29° , 30° , 31° , 32° , 34° , 36° and 39° correspond to the presence of potassium in the form of potassium hydrogen carbonate (JCPDS Card No. 00-020-0886), whereas the strong peaks at 32° and 33° show the presence of potassium in the hydroxide form. The XRD clearly shows the incorporation of potassium in the calcined *Ailanthus* cake (Figure 4a). The average particle (crystallite) size was calculated by using the Debye–Scherrer equation ($D = k\lambda/\beta \cos \theta$) where β stands for full width half maximum, θ is the diffraction peak, k is a constant value that is 0.9 for the factor shape and λ is the wavelength of the X-ray. The calculated particle size is 34 nm. The diffraction pattern of CdS nanoparticles is shown in Figure 4b. The observed values of strong diffraction peaks of 2θ and (hkl) are 25 (100), 27 (002), 28 (101), 37 (102), 44 (110), 48 (103) and 52 (112). The broad peaks indicate the presence of nanosized CdS particles. The diffraction pattern matches well with the (JCPDS Card No. 00-001-0783) for CdS. The average particle size calculated by using the Debye–Scherrer equation is 14 nm.

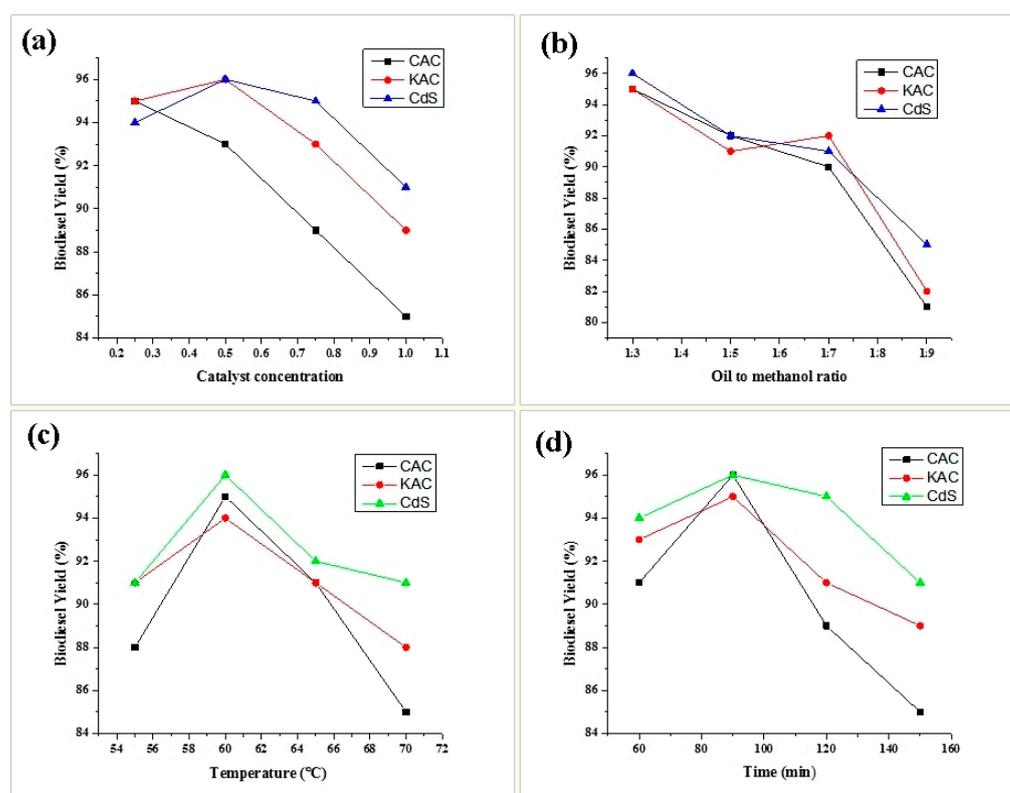


Figure 6. Effect of catalyst concentration (a), oil-to-methanol ratio (b), temperature (c) and time (d) on biodiesel yield.

Effect of Reaction Temperature on Biodiesel Yield

Reaction temperature plays a key role in determination of total percent yield of methyl ester. The temperature effect on the reaction was studied by a series of reactions performed by keeping all the other conditions constant except the temperature. In optimisation with KAC, a maximum of biodiesel obtained at 60 °C with all the other conditions constant, i.e., oil-to-methanol ratio 1:6, catalyst concentration 0.50 wt.%, agitation 600 rpm and time 1 h. In the other optimisation, with CdS, the temperature was 60 °C for the maximum yield of biodiesel with the same constant conditions (Figure 6c). The same positive effect of increase in temperature was confirmed by [16] during methyl ester production from *Heavea brasiliensis* seed oil. During this whole process, a constant increase in reaction rate was observed to a certain level, but after that the reaction rate stopped since methanol has a 64.7 boiling point, after which its reaction stops [17].

Effect of Reaction Time on Biodiesel Yield

As high yield of methyl ester with efficient conversion of oil to biodiesel was observed at adequate time in the course of the trans-esterification reaction, therefore, an appropriate reaction time is required to ensure efficient mixing with proper stirring at constant rate for suitable chemical interaction of oil and alcohol during the trans-esterification reaction. With both catalyst KAC and CdS, the maximum yield of biodiesel was achieved at a reaction time of 90 min with all the other variables constant. A slight difference of biodiesel yield was observed with an increase in time; however, 90 min was selected to give sufficient time for reaction completion (Figure 6d). During the trans-esterification reaction for each type of catalyst, the minimum time required for the conversion is usually 25–30 min. Hence, the biodiesel yield increases directly with the increase in time [18].

Thus, optimal conditions of the trans-esterification reaction of *Ailanthus altissima* oil (AAO) were found to be the 3:1 methanol-to-oil molar ratio, 90 min reaction time, 60 °C temperature and 600 rpm stirring speed, at which maximum yield up to 94% was obtained.

3.3. Fuel Properties of Biodiesel

Fuel properties of *Ailanthus altissima* seed oil biodiesel were determined and compared with international biodiesel standards: American Society for Testing and Materials (ASTM), European Union (EN-14214) and China (GB/T 20828-2007), are presented in Table 1. These fuel properties included specific gravity at 60/60 °F, flash point °C, pour point °C, kinematic viscosity at 40 °C, density, total acid number and sulphur content. Fuel properties help to determine the quality of fuel and its impact on diesel engines.

Table 1. Fuel properties of the synthesised biodiesel.

S. No.	Tests	Method	<i>Ailanthus altissima</i> Biodiesel (Current Study)	American (ASTM D-6751)	European EN-14214	China GB/T 20828-2007
1.	Color	Visual	2	–	–	–
2.	Flash Point °C (PMCC)	ASTM D-93	72.6	≤0.5	≤0.5	≤0.5
3.	Density at 15 °C Kg/L	ASTM D-1298	0.800	–	0.86–0.89 g/m ³	–
4.	Kinematic Viscosity at 40 °C cSt	ASTM D-445	4.12	1.9–6.0	3.4–5.0	–
5.	Pour Point °C	ASTM D-97	–8	≥93	≥120	≥120
6.	Cloud Point °C	ASTM D-2500	–11.33	–	–	–
7.	Sulphur wt. %	ASTM D-4294	0.0002	–	–	–
8.	Total Acid No. mg KOH/gm	ASTM D-974	0.162	≤0.05	0.020	0.020

Density plays a vital and significant role in the determination of biodiesel quality. Fuel density gives us an idea of the fuel's purity and free fatty acid amount, which is closely linked to the number of carbon atoms (Adepoju 2020). Higher density oil contains more energy. The density of the *Ailanthus* oil biodiesel was compared to ASTM D-1298 and was found to be in the range 0.752–0.83@ 15 °C kg/L, while high speed diesel has a density of 0.834. Compared to ethanol, biodiesel synthesised in the presence of methanol has low density and the density is also sensitive to the temperature [19]. The determined result revealed that synthesised biodiesel is less dense than petro-diesel.

The temperature at which a fuel can be ignited is called its flash point, affinity of a substance to form combustible mixture in the presence of oxygen. The safety of handling and transportation is directly affected by the flash point. It is strongly affected by methanol levels in synthesised biodiesel. During storage and transportation, handling fuel with high value of flash point is considerably safe. The flash point for high speed diesel falls in the range 60–80 °C. The flash point of the *Ailanthus altissima* ranges from 71 to 73 °C, just according to the HSD values, marked as safe for use as biodiesel according to a previous study [20].

Some additional free fatty acids are present in the fuel sample, recognising the acid value. It is generally denoted by mg KOH/gm. High acid value is not favourable for engine efficiency. Acid-rich mixtures can corrode engines and affect their performance [14]. The maximum acid value standard set by ASTM D-664 is 0.5 mg KOH/gm and that of *Ailanthus altissima* oil biodiesel recorded a range from 0.144 to 0.175, which lies within the standard and is perfect for use as diesel, as discussed in the previous study [21].

Cloud point is the specific temperature at which crystallization of paraffin occurs, causing separation from the solution in the ice-cold fuel. The cloud point value of the *Ailanthus altissima* oil biodiesel ranges from –11 to –6 °C, which in accord with the ASTM standards [22].

The lowest temperature at which the fuel can flow in cold conditions is the pour point. The pour point of *Ailanthus altissima* oil biodiesel ranges from –6 to –9 °C, which meets the standards of the ASTM [22].

Kinematic viscosity shows the stickiness of fuel. The lubrication properties of engines are obstructed by reduced kinematic viscosity. Operational difficulties such as engine deposits and incomplete combustion can be produced by high viscosity of fuel. Kinematic viscosity depends inversely on the temperature; it decreases with the increase in temper-

ature. The kinematic viscosity of the *Ailanthus altissima* oil biodiesel ranges from 3.91 to 4.34 and was compared with the ASTM D-445 standards; it lies within the range of ASTM standards [23].

Sulphur content of a biodiesel can be found by burning the biodiesel and then treating it with Kaemari acid. Generally low sulphur-containing fuel is preferred as it is the major cause of pollution. The sulphur content of *Ailanthus altissima* oil biodiesel was recorded as 0.0002–0.0005, which lies in the limits of ASTM D-4294. The reported sulphur content in the current study for AAO biodiesel indicates it is superior to petro-diesel, as it has a significantly lower amount of sulphur.

3.4. Characterisation of Synthesised Biodiesel

3.4.1. FTIR of Biodiesel

FTIR is a promising technique that is used to analyse the changes in vibrational bands in synthesised biodiesel. The characteristic peaks in the FTIR spectrum of *Ailanthus altissima* oil (AAO) are 2921.76 cm^{-1} (sp^2 C-H stretching), 2852.44 cm^{-1} (sp^3 C-H stretching), 1743.72 cm^{-1} (C=O stretching) and $1462.76, 721.14$ (C-H bending vibrations). Similar peaks (stretching and bending vibrations) were observed in the synthesised biodiesel with both catalysts due to similar functional groups with minor difference (Munir et al. 2021). However, the formation of the methyl ester group has strong impact on the fingerprint region of $1500\text{--}500\text{ cm}^{-1}$. The vibrational band at 1435 cm^{-1} (corresponds to methyl ester group deformation) is the one of the significant differences between AAO (oil) and AAOBD (biodiesel), which is present in both biodiesel spectra that have been synthesized using different catalysts (Figure 7) and absent in the oil spectrum. The broad and strong signal at 1158.44 cm^{-1} in AAO was observed to split into two peaks at 1169 and 1195 cm^{-1} in biodiesel. Therefore, the peaks discussed above confirm the occurrence of fatty acid methyl esters (biodiesel) as a transformation product of the AAO.

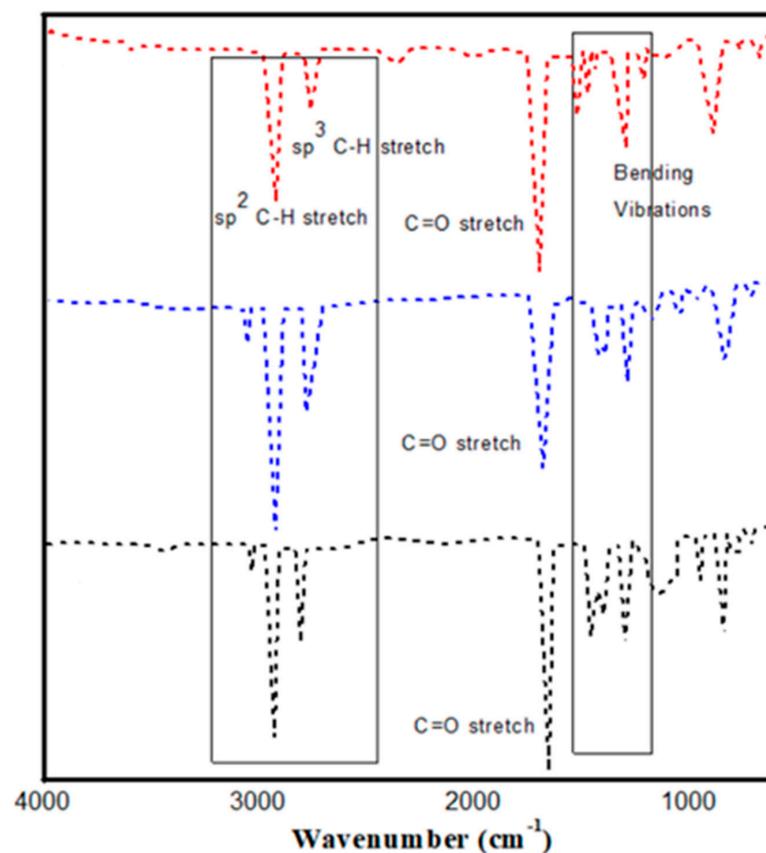


Figure 7. FTIR spectrum of synthesised biodiesel with different catalysts.

3.4.2. GCMS Analysis of *Ailanthus altissima* Oil Biodiesel

Gas chromatography is an advanced analytical technique used to investigate the chemical composition of the synthesised biodiesel (AAOBD) by using a capillary column DB-5MS (30 m, 80.32 μm and 0.25 micron film thickness), helium (He) as carrier gas at 1.5 mL/min flow rate, column temperature 120–300 °C at 10 °C/min and 0.1 μL sample, which was injected in split mode (1:10). The characteristic four peaks were found along with retention time, as shown in Figure 8, which corresponds to the formation of fatty acid methyl esters (FAMES). The most frequent esters in synthesised biodiesel are octadecenoic acid, hexadecanoic acid and 2,4-decadienal methyl ester.

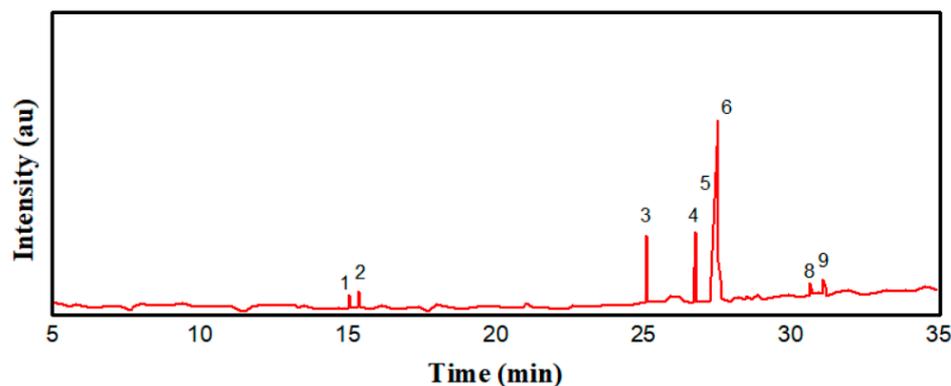


Figure 8. Representative GCMS spectrum of synthesised biodiesel.

4. Conclusions

- The biodiesel (AAOBD) synthesis from highly efficient, novel non-edible seed oil of *Ailanthus altissima* (AAO) via a trans-esterification process is strongly recommended as a suitable source of biofuel on industrial scale due to its low cost, high productivity and eco-friendly nature.
- In the present study, promising yields of biodiesel with KAC and CdS (94.3 and 93.5%, respectively) were achieved.
- The optimum operating conditions for trans-esterification of *Ailanthus altissima* seed oil (AAO) are 3:1 methanol-to-oil molar ratio, 90 min reaction time, 60 °C temperature and 600 rpm. Therefore, it can be concluded that heterogeneous green catalysts are ideal to use due to their limited preparation time and cost-effective nature.
- This study is also optimistic towards efficient and reusable heterogeneous catalyst along with a sustainable oil source that establishes a way to reduce overall biodiesel production cost.
- Fuel properties of *Ailanthus altissima* biodiesel, such as specific gravity, flash point, pour point, kinematic viscosity, density, total acid number and sulphur content, were thoroughly investigated and met the requirements of international fuel standards. Low sulphur content of 0.0002 wt.% indicates a high value and pollution-free quality of the synthesised biodiesel.
- However, further investigation is suggested concerning the economic feasibility of AAO methyl ester in the fuel market. Furthermore, in the light of this investigation, kinetic and thermodynamic study on methyl ester formation from *Ailanthus altissima* seed oil and combustion characteristics, which are very sensitive to fuel quality, will be explored in future research.

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