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Activated Carbon from Residues of the Wild Mustard Biodiesel Production Process

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ABSTRACT

Vegetable oils and animal fats consist of saturated and unsaturated fatty acids. The proportions of these fatty acids can be increased or decreased by mixing the oils in equal amounts to obtain a blend containing different proportions of the fatty acids present in the original oils or fats. This blend was reacted with alcohol in the presence of a basic catalyst to produce biodiesel. A comparison was made between the physical and chemical properties of the oils and the biodiesel prepared from the vegetable oil blend to achieve standard specifications close to those of conventional diesel. A blend of mustard and castor oils was used as the feedstock for fatty acid methyl ester (FAME) production via alkali-catalyzed transesterification with methanol under the optimum reaction conditions of a 1:6 oil-to-methanol molar ratio, a reaction temperature of 60°C, a reaction time of 60 min, and 0.75 wt.% KOH as the catalyst. The solid residue from the mustard seed pressing process was used as a raw material for the production of activated carbon through thermal pyrolysis. It was mixed with mustard plant waste to obtain a raw material for activated carbon preparation by chemical activation using zinc chloride and phosphoric acid as activating agents. Fourier Transform Infrared Spectroscopy (FTIR) and Thin Layer Chromatography (TLC) techniques were employed to identify the functional groups of the lipid components and to verify the formation of biodiesel.

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الكربون المنشط من مخلفات عملية إنتاج الديزل الحيوي من الخردل البري

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الملخص

تتكون الزيوت النباتية والدهون الحيوانية من أحماض دهنية مشبعة وغير مشبعة. ويمكن زيادة أو تقليل نسب هذه الأحماض الدهنية من خلال خلط الزيوت بكميات متساوية للحصول على مزيج يحتوي على نسب مختلفة من الأحماض الدهنية الموجودة في الزيوت أو الدهون الأصلية. وقد أُخضع هذا المزيج للتفاعل مع الكحول بوجود محفز قاعدي لإنتاج الديزل الحيوي. كما أُجريت مقارنة بين الخواص الفيزيائية والكيميائية للزيوت والديزل الحيوي المحضر من مزيج الزيوت النباتية بهدف الوصول إلى مواصفات قياسية قريبة من مواصفات الديزل التقليدي. استُخدم مزيج من زيت الخردل وزيت الخروع كمادة أولية لإنتاج إسترات ميثيل الأحماض الدهنية (FAME) بتفاعل الأسترة التبادلية المحفز قاعديًا باستخدام الميثانول، وذلك تحت ظروف التشغيل المثلى المتمثلة في نسبة مولية زيت إلى ميثانول مقدارها (1:6)، ودرجة حرارة 60°م، وزمن تفاعل قدره 60 دقيقة، مع استخدام 0.75% وزنيًا من هيدروكسيد البوتاسيوم (KOH) كمحفز. واستُخدمت المخلفات الصلبة الناتجة من عملية عصر بذور الخردل كمادة أولية لإنتاج الكربون المنشط عن طريق الانحلال الحراري. كما خُلِطت هذه المخلفات مع مخلفات نبات الخردل للحصول على مادة أولية لتحضير الكربون المنشط بطريقة التنشيط الكيميائي باستخدام كلوريد الزنك وحامض الفوسفوريك كعوامل تنشيط. واستُخدمت تقنيتا مطيافية الأشعة تحت الحمراء بتحويل فورييه (FTIR) والكروماتوغرافيا بالطبقة الرقيقة (TLC) للتعرف على المجاميع الوظيفية للمكونات الدهنية والتحقق من تكوّن الديزل الحيوي.

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Introduction

Biodiesel has attracted considerable attention as a sustainable alternative fuel owing to its renewable nature and environmental benefits. This study focuses on the production of biodiesel from non-edible vegetable oils through the transesterification reaction as a sustainable fuel for future energy applications. Biodiesel has been widely applied as a substitute for petroleum diesel, particularly in agricultural machinery, heavy-duty trucks, and irrigation pumping systems. The continuous increase in global energy demand has accelerated the depletion of conventional energy resources and increased dependence on fossil fuels (Alabim et al., 2025). Consequently, renewable resources with industrial potential have emerged as promising alternatives (Singh et al., 2020). Furthermore, the use of biodiesel contributes to reducing greenhouse gas emissions, making it an environmentally friendly alternative to conventional fossil diesel (Folayan et al., 2019).

Transesterification is the most common process for biodiesel production, in which triglycerides react with a short-chain alcohol in the presence of either a basic or acidic catalyst to produce fatty acid methyl esters (biodiesel) (Osman et al., 2021). In addition to biodiesel, the reaction generates glycerol as a valuable by-product, which has extensive applications in the pharmaceutical, cosmetic, and medical industries (Mishra and Goswami, 2018).

Glycerol is widely used as a sweetening agent in beverages, an ingredient in toothpaste, a moisturizing additive in shampoos and conditioners, and as an antifreeze component in several industrial applications (Hanif et al., 2018). Biodiesel can be produced from edible oils, such as olive and corn oils, used cooking oils, and non-edible oils such as wild mustard (Brassica juncea) (Lee et al., 2020). However, large-scale biodiesel production from edible oils requires extensive agricultural land and irrigation resources, increasing production costs and competing with food supplies. Therefore, the utilization of non-edible oils and waste cooking oils represents a more sustainable approach for biofuel production while simultaneously reducing environmental pollution.

The transesterification reaction requires efficient contact between the reactants and the catalyst to achieve high conversion. Catalysts used for biodiesel production are generally classified as either homogeneous or heterogeneous. In homogeneous catalysis, the catalyst and reactants exist in the same phase, whereas in heterogeneous catalysis, they are present in different phases. Homogeneous catalysts are widely employed because of their high reaction rates, while heterogeneous catalysts, typically solid materials with high surface areas, offer advantages in catalyst recovery, reusability, and simplified product purification. Enzymes have also been investigated as catalysts for biodiesel production, although they represent a separate catalytic system rather than an intermediate category. Regardless of catalyst type, the catalyst reduces the activation energy, shortens the reaction time, and improves biodiesel yield (Faruque et al., 2020).

Thermal pyrolysis of residues generated after oilseed processing produces gaseous, liquid, and solid products (Singh and Shadangi, 2011; Ucar and Ozkan, 2008). The resulting solid residue (char) can be converted into activated carbon through thermal and chemical activation, providing an environmentally sustainable route for the valorization of agricultural waste. Previous studies have demonstrated that castor seed pressing residues can be successfully pyrolyzed to produce char, bio-oil, and condensable moisture, with the solid fraction serving as an effective precursor for activated carbon production (Fadhil et al., 2011).

Accordingly, the present study aims to optimize the utilization of renewable energy resources by producing biodiesel with physicochemical properties comparable to those of conventional diesel through blending vegetable oils followed by transesterification. In addition, the oil extraction residues were thermally pyrolyzed to produce solid carbonaceous materials, which were subsequently converted into activated carbon suitable for adsorption applications, thereby enhancing the overall utilization of biomass resources.

Material Used and Experimental Procedures

1. Feed stock preparation:

Oil was extracted from the ground seeds using a Soxhlet extractor with petroleum ether as the extraction solvent. The extracted oil met the relevant ASTM specifications. The particle size of the ground seed material ranged from 45 to 65 mesh. The physicochemical properties of wild mustard oil and castor oil are presented in Tables 1 and 2.

Table 1. Physicochemical properties of wild mustard oil.

Physical and chemical properties	Values
Density (gm/cm ^{3}) 15.6 ˚c	0.9118
Viscosity (mm^2/s) 40˚c	23.2
Flash point (˚c)	145
Acid number (mg KOH/gm	2.70
Saponification (mg KOH/gm)	190
Iodine number (100mg/I_2) /gm	106.20
Cloud point (C˚)	-3
Pour point (PP) (C˚)	-15>
Refractive index @ 20˚c	1.478
Distillation carve (˚C)	215/355
Carbon residue %	0.13
Cetane number	51.13
High heat value (HHV) (Mj/kg)	38.72
Molecular weight (gm/mole)	898.50

Table 2. Physicochemical properties of castor oil.

Physical and chemical properties	Values
Density (gm/cm ^{3}) 15.6 ˚c	0.9630
Viscosity (mm^2/s) 40˚c	210.0
Flash point (˚c)	205
Acid number (mg KOH/gm	0.85
Saponification (mg KOH/gm)	0.85
Iodine number (100mg/I_2) /gm	83
Cloud point (C˚)	-3
Pour point (PP) (C˚)	-10>
Refractive index @ 20˚c	1.479
Distillation carve (˚C)	235/310
Carbon residue %	0.27
Cetane number	57.73
High heat value (HHV) (Mj/kg)	44.71
Molecular weight (gm/mole)	889.24

2. Thermal Pyrolysis of Mustard Residues

The residue (oil cake) remaining after seed grinding was subjected to thermal pyrolysis at 400–600°C in a closed reactor. Approximately 20 g of the raw material was placed in the reactor and thermally decomposed in an electric furnace. The temperature was monitored and controlled using a Ni–Cr–Ni thermocouple positioned inside the reactor. Heating was performed at a rate of 11°C min^{-1} until the desired temperature was reached. The target temperature was maintained for 1 h, or until the evolution of volatile matter ceased. The released vapors were condensed through ice-cooled traps to collect the bio-oil. The solid residue remaining inside the reactor was weighed and designated as pyrolytic char, which was subsequently used for thermal and chemical activation, as summarized in Table 3.

Table 3. Physicochemical properties of wild mustard de-oiled cake used for pyrolysis (Kumar et al., 2013).

Raw materials	Moisture content (%) Per Kg	Volatile matter	Ash content	Carbon (%)
Mustard de-oiled cake	0.3	74.49	3.08	22.13

3. Preparation of Activated Carbon

The char produced by pyrolysis at 500°C was used as the precursor for activated carbon preparation. The char was impregnated with 50% (w/v) H_3PO_4 or $ZnCl_2$ solutions and subsequently heat-treated at 600–700°C for 2 h. Phosphoric acid and zinc chloride served as chemical activating agents to develop a porous carbon structure suitable for adsorption applications.

4. Determination of the Adsorption Efficiency of Activated Carbon

The adsorption performance of the prepared activated carbon was evaluated using methylene blue (MB, $C_{16}H_{18}ClN_3S$) and p-nitrophenol (PNP, $NO_2C_6H_5OH$) as model adsorbates. Adsorption experiments were carried out by adding 1 g of activated carbon to 25 mL of either MB solution (250 mg L^{-1}) or PNP solution (500 mg L^{-1}) in a closed glass vessel. After equilibrium was reached, the residual concentrations of MB and PNP were measured using a Shimadzu UV–Vis 1260 PC spectrophotometer at wavelengths of 665 nm and 315 nm, respectively. The adsorption capacity was then calculated according to the method reported by Al-Qaessi et al. (2010).

5. Evaluation and Analysis of Fatty Acid Methyl Esters

The fatty acid composition of oils and their derivatives strongly influences the physicochemical properties of biodiesel (Bindhu, 2012; YOGA and SUNART, 2025). The major functional groups of fatty acid methyl esters (FAMEs) were identified using Fourier Transform Infrared Spectroscopy (FTIR) (Biotechnology, UK). Spectra were recorded over the 400–4000 cm^{-1} range with a resolution of 4 cm^{-1}. The physicochemical properties of the produced FAMEs, together with their blends with petroleum diesel, were evaluated according to the standard methods of the American Society for Testing and Materials (ASTM).

Results and Discussion

Physicochemical Properties of Castor Oil, Wild Mustard Oil, and Their Blend

The physicochemical properties of castor oil, wild mustard oil, and their 50:50 blend were evaluated to determine their suitability as feedstocks for biodiesel production. The measured properties, including density, viscosity, flash point, and acid value, are presented in Table 4.

Table 4. Physicochemical properties of castor oil, wild mustard oil, and their 50:50 blend.

Physical and chemical properties	Castor oil	Mustard oil	blend oil (50:50)
Density 15.6 (g/cm^3)	0.9630	0.9118	0.9308
Viscosity 40 (mm^2/s)	210.0	23.2	52.64
Flash point c°	205	145	168
acid number	0.85	2.70	2.14

As shown in Table 4, castor oil exhibited the highest density, viscosity, and flash point among the investigated oils because of its unique fatty acid composition, particularly its high ricinoleic acid content. In contrast, wild mustard oil showed considerably lower viscosity and flash point values. Blending castor oil with wild mustard oil produced intermediate physicochemical properties, indicating that the blending process effectively modified the fuel characteristics. Such improvements make the blended oil a more suitable feedstock for biodiesel production while maintaining acceptable physicochemical properties.

Properties of the Produced Biodiesel

The biodiesel produced under the optimized transesterification conditions was characterized by measuring its major physicochemical properties. The results are summarized in Table 5.

Table 5. Physicochemical properties of the produced biodiesel.

Density 15.6 m◦ (g/cm^3)	Yield	**Acid value**	**Viscosity**	**Flash point**	**H.H.V**	**Refractive index**
0.8990	94.2	0.14	4.40	83	41.25	1.458

The produced biodiesel exhibited a density of 0.8990 g/cm^3, viscosity of 4.40 mm^2/s, flash point of 83°C, acid value of 0.14 mg KOH/g, refractive index of 1.458, and biodiesel yield of 94.2%. These results indicate that the selected transesterification conditions successfully converted the blended oil into biodiesel with properties suitable for fuel applications.

Properties of the Produced Activated Carbon

Activated carbon was prepared from the solid residue remaining after mustard seed processing, and its adsorption-related properties were evaluated. The measured characteristics are listed in Table 6.

Table 6. Properties of the prepared activated carbon.

Temperature degree	**Yield %**	**Iodine number mg/g**	**MB Number mg/g**	**PNP Number mg/g**
AC thermal	42	230	29	56
AC H_3PO_4	33	320	30	70
AC Zncl$_2$	35	650	40	97

As presented in Table 6, the prepared activated carbon achieved a yield of 42%, an iodine number of 230 mg/g, a methylene blue adsorption capacity of 29 mg/g, and a p-nitrophenol adsorption capacity of 56 mg/g. These results demonstrate that the biomass residue can be successfully converted into activated carbon with measurable adsorption performance, providing an additional value-added product from the biodiesel production process.

Properties and Analysis of Castor and Wild Mustard Oils

Castor oil and wild mustard oil were selected because of their potential as non-edible feedstocks for biodiesel production. Their fatty acid compositions strongly influence the physicochemical properties of both the oils and the resulting biodiesel. The fatty acid compositions reported in the literature are summarized in Table 7.

Table 7. Fatty acid composition of various oils used in the present study (Hanif et al., 2022)

Sr. No	Fatty acid	Molecular formula	Fatty acid amount (%)				
			Karanja oil	Wild Mustard oil	Wild Saflower oil	Castor oil	Bitter apple oil
1	Capric acid	$C_{10}H_{20}O_2$	0.11	0.15	0.13	0.12	0.07
2	Lauric acid	$C_{12}H_{24}O_2$	0.22	0.12	0.09	0.08	0.06
3	Myristic acid	$C_{14}H_{28}O_2$	0.93	0.18	0.16	0.11	0.13
4	Palmitic acid	$C_{16}H_{32}O_2$	10.33	0.63	0.73	0.30	0.35
5	Margaric acid	$C_{17}H_{34}O_2$	0.09	0.05	0.06	0.07	0.01
6	Linolenic acid	$C_{18}H_{30}O_2$	3.15	0.09	0.32	1.57	0.17
7	Linoleic acid	$C_{18}H_{32}O_2$	11.03	15.03	75.17	7.65	70.71
8	Oleic acid	$C_{18}H_{34}O_2$	51.92	23.11	12.98	5.83	9.96
9	Ricinoleic acid	$C_{18}H_{34}O_3$	-	-	-	80.54	0
10	Stearic acid	$C_{18}H_{36}O_2$	4.66	1.15	0.89	1.43	8.29
11	Eicosanoic acid	$C_{20}H_{40}O_2$	9.76	12.83	0.11	0.18	0.03
12	Arachidic acid	$C_{20}H_{40}O_2$	0.96	0.07	0.76	0.21	0.11
13	Erucic acid	$C_{22}H_{42}O_2$	-	41.43	-	-	0.17
14	Behenic acid	$C_{22}H_{44}O_2$	4.36	0.09	0.43	0.17	0.07
15	Lignoceric acid	$C_{24}H_{48}O_2$	2,12	1.12	0.32	0.15	1.13

Castor oil contains a high proportion of ricinoleic acid, whereas wild mustard oil is characterized by a relatively high erucic acid content. These differences explain the variations observed in density, viscosity, and flash point between the two oils. Because both oils are non-edible, they represent promising renewable feedstocks for biodiesel production without competing with food resources. The oil yield obtained from castor seeds was 51.76 wt.%, whereas wild mustard seeds produced 74.33 wt.%. Although the oil yield of castor seeds is lower, it remains considerably higher than that of several other oilseed crops, supporting its potential as a biodiesel feedstock. Furthermore, castor oil exhibits higher density, viscosity, and flash point than many conventional vegetable oils, including safflower and palm oils (Alagha et al., 2024). Consequently, blending castor oil with wild mustard oil provides an effective approach to improving the overall fuel properties while maintaining characteristics suitable for biodiesel production. Therefore, in the present study, biodiesel production was investigated by blending castor oil with wild mustard oil at an equal volume ratio (50:50) to obtain a feedstock with physicochemical properties more suitable for biodiesel production. The physicochemical properties of the resulting oil blend were evaluated prior to transesterification, and the results are presented in Table 8.

Table 8. Physicochemical properties of the 50:50 castor oil–wild mustard oil blend.

Physical and chemical properties	Values
Density (gm/cm ^{3}) 15.6 ˚c	0.9308
Viscosity (mm^2/s) 40˚c	52.64
Flash point (˚c)	168
Acid number (mg KOH/gm	2.14
Refractive index @ 20˚c	1.477
High heat value (HHV) (Mj/kg)	39.56

As shown in Table 8, the blended oil exhibited intermediate physicochemical properties compared with the individual oils. The density was 0.9308 g/cm³, the viscosity was 52.64 mm²/s, and the flash point reached 168°C, while the acid value was 2.14 mg KOH/g. The blend also showed a refractive index of 1.477 and a higher heating value (HHV) of 39.56 MJ/kg. These results indicate that blending successfully modified the fuel properties and provided a suitable feedstock for the subsequent biodiesel production process.

The blended oil was then subjected to alkali-catalyzed transesterification under the optimized reaction conditions. The physicochemical properties of the produced biodiesel are summarized in Table 9.

Table 9. Physicochemical properties of biodiesel produced from the blend.

Physical and chemical properties	Values
Density (gm/cm^3) 15.6 ˚c	0.8990
Viscosity (mm^2/s) 40˚c	4.40
Flash point (˚c)	83
Acid number (mg KOH/gm	0.18
Refractive index @ 20˚c	1.458
High heat value (HHV) (Mj/kg)	41.25

It is observed from the table that the density, viscosity, flash point, and acid number values were relatively high for the oil mixture. However, for the biodiesel produced from this mixture, these values decreased under the optimal reaction conditions: 1–6 molar concentration, temperature of 60 °C, reaction time of 60 minutes, and potassium hydroxide catalyst 0.75% (Fadhil, 2012).

Properties and Analysis of the Castor Oil–Wild Mustard Oil Blend

A 50:50 mixture of wild mustard and castor oil was used as a sample, and the sample was measured using gas chromatography as shown in the Table10:

Table 10. Fatty acid composition of the 50:50 castor oil–wild mustard oil blend determined by gas chromatography.

Fatty acid	blend oil %	Mustard oil %	Castor oil %
Palmitic acid	4.42	5.54	1.88
Palmoleic acid	0.14	0.21	-
Stearic acid	1.86	1.51	2.48
Oleic acid	6.97	7.53	5.5
Linoleic acid	10.35	10.79	8.74
Linolenic acid	14.74	20.95	0.64
Erucic acid	24.09	45.39	-
Ricinoleic acid	25.17	-	78.03

The fatty acids produced in mixtures differ in their percentage proportions from the fatty acids in individual oils. For example, the concentration of percent fatty acids like ricinoleic acid, found in castor oil, decreases in the mixture, thus reducing the effect of the hydrogen bonds present in this oil. Similarly, the concentration of Erucic acid, found in mustard oil, decreases in the mixture, thereby reducing the toxicity associated with this acid. Furthermore, the chemical and physical properties of biodiesel blends have improved and are close in specifications to conventional diesel (Bastawissi et al., 2024).

Properties and Analysis of Activated Carbon

The adsorption performance of the prepared activated carbon was evaluated using iodine number, methylene blue (MB), and p-nitrophenol (PNP) adsorption tests. These parameters are widely used to assess the surface area, pore structure, and adsorption capacity of activated carbon.

The activated carbon prepared using $ZnCl_2$ exhibited higher adsorption performance than that prepared using H_3PO_4, indicating the development of a more porous structure with a greater number of accessible adsorption sites. In contrast, phosphoric acid activation resulted in a lower carbon yield because of the greater removal of volatile components during activation. Similar observations have been reported in previous studies on activated carbon prepared from agricultural biomass. Methylene blue (MB) adsorption is commonly used to evaluate the mesoporous structure of activated carbon and its ability to adsorb relatively large organic molecules from aqueous solutions (Ahmed, 2016; El Ouadrhiri et al., 2021). p-Nitrophenol (PNP) adsorption is commonly used to evaluate the adsorption capacity of activated carbon toward small aromatic organic compounds(Bestani, 2008; Salvestrini et al., 2023). Table 11 shows that the iodine number and adsorption capacities depend strongly on the activating agent. Activated carbon prepared using $ZnCl_2$ exhibited the highest iodine number and adsorption capacities for both methylene blue and p-nitrophenol, indicating a well-developed pore structure and enhanced adsorption performance.

Table11. Adsorption properties of activated carbon prepared from castor oil residues using different activating agents. (Al dobouni et al., 2015)

Temperature degree	Yield %	Iodine number mg/g	MB Number mg/g	PNP Number mg/g
AC thermal	41	234	23	118
AC H_3PO_4	34	325	50	119
AC $Zncl_2$	37	691	65	121

Analysis of Oils and Biodiesel

Thin layer chromatography

Thin-layer chromatography (TLC) is a rapid and simple analytical technique commonly used to monitor the progress of transesterification reactions during biodiesel production. Although gas chromatography (GC) provides more detailed quantitative information, TLC offers a convenient qualitative method for distinguishing triglycerides, intermediates, and the fatty acid methyl esters (FAMEs) formed during the reaction. In the present study, TLC was employed to compare the chromatographic behavior of the original oils and the corresponding biodiesel products. Wild mustard oil exhibited three distinct spots with different Rf values, indicating the presence of several lipid components. In contrast, the biodiesel sample produced only a single spot with a higher Rf value, demonstrating the successful conversion of triglycerides into fatty acid methyl esters (FAMEs) (Makay et al., 2024). The absence of additional spots suggests that the produced biodiesel contained minimal residual oil or reaction impurities, confirming an efficient transesterification process.

Table12. TLC results for wild mustard oil and the corresponding biodiesel.

Sample	Flow **Coefficient** (R_f)
Oil	0.47, 0.27, 0.18
Bio diesel	0.69

Castor oil also exhibited three chromatographic spots with relatively low and closely spaced Rf values. This behavior can be attributed to the high ricinoleic acid content of castor oil, whose hydroxyl functional groups influence chromatographic migration. Following transesterification, the biodiesel sample exhibited two spots with higher Rf values than the original oil, indicating the formation of methyl esters and confirming the progress of the transesterification reaction.

Table13. TLC results for castor oil and the corresponding biodiesel.

Sample	**Flow** Coefficient **(R_f)**
Oil	0.19, 0.05, 0.01
Bio diesel	0.76 , 0.196

The blended oil exhibited three chromatographic spots with Rf values that were more widely separated than those observed for castor oil. After transesterification, the corresponding biodiesel produced a single spot with the highest Rf value among the analyzed samples. The appearance of a single chromatographic spot indicates effective conversion of the blended oil into fatty acid methyl esters and suggests the absence of significant quantities of unreacted oil or intermediate products. These findings demonstrate that blending castor oil with wild mustard oil improved the transesterification performance and produced a biodiesel of higher purity.

Table14. TLC results for the blended oil and the corresponding biodiesel.

Sample	**Flow Coefficient (R_f)**
Oil	0.18, 0.27, 0.47
Bio diesel	0.78

Spectroscopic Measurement

Fourier Transform Infrared (FTIR) spectroscopy was employed to characterize the functional groups present in the vegetable oils and the corresponding biodiesel samples. FTIR analysis was performed for two main purposes: (i) to identify the characteristic functional groups associated with the oils and the produced fatty acid methyl esters (FAMEs), and (ii) to compare the integrated areas of the major absorption bands before and after transesterification. The calculated peak areas for the oil samples and the corresponding biodiesel products are presented in Tables 15 and 16, respectively.

Table 15. Integrated FTIR peak areas of blend, castor, and wild mustard oils.

Functional Group	**Area under the peak (mm²)**		
	Blend oil	**Castor oil**	**Wild Mustard oil**
C–H stretching vibration, presence of esters (-COOCH $_3$)	13.1736	11.7084	15.6425
C–H bending vibration, presence of alkane group	30.142	28.30	24.97
C=O (carbonyl) aldehydes, ketones and esters	6.701	5.641	5.581

Table 16. Integrated FTIR peak areas of biodiesel produced from the blend, castor, and wild mustard oils.

Functional Group	**Area under the peak** (mm²)		
	Blend bio diesel	**Castor bio diesel**	**Mustard bio diesel**
C–H stretching vibration, presence of esters (-COOCH $_3$)	10.488	8.662	11.796
C–H bending vibration, presence of alkane group	15.94	23.46	13.02
C=O (carbonyl) aldehydes, ketones and esters	4.21	5.18	4.1

Comparison of the integrated FTIR peak areas before and after transesterification demonstrates noticeable changes in the characteristic absorption bands of the oil and biodiesel samples. These differences indicate changes in the relative abundance of the corresponding functional groups during the conversion of triglycerides into fatty acid methyl esters (FAMEs). Therefore, the FTIR results provide additional evidence supporting the successful transesterification reaction and the formation of biodiesel.

Conclusion

This study demonstrated the feasibility of producing biodiesel from a blend of wild mustard and castor oils and utilizing the solid residues as a precursor for activated carbon production. Blending the two oils improved the fuel properties compared with the individual oils, yielding biodiesel with physicochemical characteristics closer to those of conventional diesel. FTIR and TLC analyses confirmed the successful transesterification reaction and the formation of fatty acid methyl esters (FAMEs). In addition, the activated carbon prepared from mustard processing residues exhibited favorable adsorption properties, indicating its potential as an effective adsorbent. These findings demonstrate that the integrated utilization of wild mustard biomass can simultaneously produce renewable biodiesel and value-added activated carbon, thereby improving resource utilization and reducing agricultural waste.

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