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Production and Characterization of Biodiesel from Hybrid Feedstock of *Annona muricata* and *Ziziphus mauritiana* Seed Oils

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ABSTRACT

This research investigated the preparation and the fuel potential of a hybrid biodiesel blend derived from *Annona muricata* (Soursop) and *Ziziphus mauritiana* (Jujube) seed oils. The crushed seed biomass was characterized using Fourier Transform Infrared Spectroscopy (FTIR), Thermogravimetric Analysis and Differential Thermal Analysis (TGA/DTA), Scanning Electron Microscope coupled with Energy Dispersive X-ray Spectroscopy (SEM-EDS), X-ray Diffraction and Brunauer-Emmett-Teller (BET) analyser, whereas GC-MS was used for the extracted oils. Oil extraction was performed via the Soxhlet method using n-hexane, followed by a two-step acid-esterification (1.1 mL H_2SO_4, 7.5:1 methanol-to-oil ratio) and base transesterification (1 wt% KOH, 6:1 methanol-to-oil ratio at 60 ^oC) process. The lipid yields were 18.40% for *A. muricata* and 14.72% for *Z. mauritiana*, while the results demonstrated a synergistic effect in hybrid blends, particularly in the A10/Z30 ratio (10% *Annona muricata*, 30% *Ziziphus mauritiana* seed oil), achieved an optimal biodiesel yield of 90.00%. Fuel property evaluations showed cetane numbers of 67.41 - 69.70 and flash points of 130 – 155 ^oC, though kinematic viscosity remained elevated at 32.10 - 77.65 mm^2s. This study shows that hybridizing *A. muricata* and *Z. mauritiana* provides a viable and sustainable framework for producing high-performance bio-energy while promoting circular bio-economy.

Keywords: *Annona muricata*, biodiesel, transesterification, waste valorization, *Ziziphus mauritiana*

INTRODUCTION

The global energy landscape is currently defined by the dual pressures of fossil fuel depletion and the environmental imperative to mitigate greenhouse gas (GHG) emissions. As global energy demands rise, the search for renewable, biodegradable, and non-toxic alternatives to

petroleum-based diesel has intensified. Biodiesel, derived from vegetable oils or animal fats, has emerged as a promising solution. First-generation biodiesels derived from edible oils provided the foundational proof-of-concept for renewable fuels; however, their commercial adoption is limited by feedstock cost volatility and the "food-versus-fuel" dilemma [1, 2].

Feedstocks high in saturated fatty acids (such as palm oil or tallow) possess high cetane numbers for favorable ignition but exhibit high melting points [3]. This leads to "waxing" or gelling at low ambient temperatures, causing fuel filter clogging and engine failure in cold climates [4]. Conversely, unsaturated fatty acids (such as sunflower or soybean oil) improve cold-weather performance; however, their double bonds make the fuel highly susceptible to oxidative degradation [5]. Because no single natural oil satisfies both low-temperature fluidity and long-term storage stability [6], hybridizing distinct feedstocks offers a viable strategy to optimize the Fatty Acid Methyl Ester (FAME) profile [7].

Two promising candidates for hybrid blending are *Annona muricata* and *Ziziphus mauritiana*. *Annona muricata*, a tropical Annonaceae species, produces seeds with an oil content of 18–29.6% that are dominated by unsaturated fatty acids—specifically oleic (43.6%) and linoleic (32.4%) acids [8]. While this unsaturated profile provides excellent cold-flow properties, the raw oil presents a high free fatty acid (FFA) content (acid value ~54.4 mg KOH/g), requiring a mandatory two-step synthesis process to achieve biodiesel yields up to 97.02% with a Cetane number of 53 [9]. On the other hand, *Ziziphus mauritiana*, a drought-resistant Rhamnaceae species, yields seeds containing 25–33% oil rich in tocopherols (Vitamin E) [10]. These natural antioxidants enhance oxidative stability and extend shelf-life, though single-source conversions typically yield lower than hybrid formulations (82–85%). By formulating a hybrid blend of *A. muricata* and *Z. mauritiana*, this study addresses the binary performance trade-offs inherent to single-source biodiesels by balancing cold-flow properties with oxidative stability.

The fundamental novelty of this research is the formulation and characterization of an unstudied hybrid bio-energy system derived from underutilized *Annona muricata* and *Ziziphus mauritiana* seed oils. By engineering a dual-feedstock blend, this work addresses the long-standing binary limitations of single-source biodiesels reconciling the cold-flow advantages of highly unsaturated oils with the high cetane and storage stability of saturated, antioxidant-dense fats. This synergistic approach provides a sustainable framework for high-performance biofuel production while advancing waste valorization.

The specific objectives are:

1. To characterize the potential of the raw *Annona muricata* and *Ziziphus mauritiana* seeds using FTIR, TGA, XRD, BET, and SEM-EDS analyses.
2. To characterize the crude extracts of *Annona muricata* and *Ziziphus mauritiana* using GC-MS analysis.
3. To produce bio-oil via acid-catalyzed esterification using sulfuric acid (H_2SO_4) with methanol.
4. To produce biodiesel via base-catalyzed transesterification of the esterified extract using potassium hydroxide (KOH) and methanol.
5. To evaluate the fuel properties (such as flash point, pour point, cetane number, density, and calorific value) of the produced biodiesel against ASTM D6751 standards.

MATERIALS AND METHODS

The primary feedstocks for this study were seeds of Soursop and Jujube. Chemical reagents utilized included n-hexane (99.0% purity) for Soxhlet oil extraction, concentrated sulfuric acid (95.0% H_2SO_4) as an acidic catalyst for esterification pretreatment, and potassium hydroxide pellets (85.0% KOH) as the alkaline transesterification catalyst. Anhydrous methanol (99.5% purity) was employed across both reaction stages. All chemical reagents were of analytical grade and used without further purification.

Biomass Preparation and Characterization

Fresh seeds of soursop and jujube were manually cleaned, washed with distilled water, and dried in a hot-air oven at 60 ^oC for 24 hours to a constant weight. The dried seeds were pulverized using a laboratory mechanical mill and passed through a 1.0 mm standard mesh screen. The prepared seed biomass precursors (and subsequently extracted oils/esters) were subjected to the following analytical characterization techniques:

Fourier Transform Infrared Spectroscopy

Surface functional groups of the raw seed biomass and extracted oils were identified using an Agilent Cary 630 FTIR Spectrophotometer (Agilent Technologies, USA). Samples were analyzed using an Attenuated Total Reflectance (ATR) module across a spectral range of 4000 cm^{-1} to 650 cm^{-1} at a spectral resolution of 4 cm^{-1} over 32 co-added scans.

Thermogravimetric and Differential Thermal Analysis

Thermal degradation profiles and mass loss behavior of the crushed seed biomass were measured using a Shimadzu DTG-60H Simultaneous TGA/DTA Analyzer (Shimadzu Corporation, Japan) controlled via TA-60WS software. Approximately 10 mg of biomass was heated from ambient temperature up to 900 ^{o}C at a constant heating rate of 10 ^{o}C/min under a continuous nitrogen flow (50 mL/min).

Scanning Electron Microscopy and Energy-Dispersive X-ray Spectroscopy

Surface morphology and elemental composition of the seed biomass were evaluated using a Carl Zeiss EVO MA10 Scanning Electron Microscope (Carl Zeiss Microscopy GmbH, Germany) equipped with an EDAX Element-C2B Energy Dispersive Spectroscopy detector. Micrographs were acquired at an accelerating voltage of 25 kV under high vacuum following gold-sputter coating.

X-ray Diffraction

Crystalline phase identification and relative crystallinity ratios of the raw biomass were determined using a PANalytical Philips X'Pert PRO X-ray Diffractometer (PANalytical B.V., Netherlands). Data collection was performed using Cu-Kα radiation (λ= 1.5406 Å) operated at 40 kV and 40 mA, scanning across a 2Θ angular range of 10^{o} to 80^{o} at a step size of 0.02^{o}.

Brunauer-Emmett-Teller Surface Area Analysis

Textural properties, specific surface area, and pore size distributions of the biomass were measured via N_2 gas adsorption-desorption isotherms at 77 K using an ASAP 2460 Surface Area and Porosity Analyzer (Micromeritics Instrument Corporation, USA). Prior to analysis, samples were degassed under vacuum at 105 ^{o}C for 12 h. Surface area and pore metrics were calculated using the BET, Dubinin-Astakhov (D-A), and Barrett-Joyner-Halenda (BJH) models.

Gas Chromatography-Mass Spectrometry (GC-MS)

The fatty acid profiles of the crude extracted oils and the fatty acid methyl ester (FAME) composition of synthesized biodiesels were determined using an Agilent 7890B GC system coupled with an Agilent 5977B Mass Selective Detector (MSD) (Agilent Technologies, USA) fitted with an HP-5MS capillary column (30 m × 0.25 mm × 0.25 μm). Helium was used as the

carrier gas at a flow rate of 1.0 mL/min. Compound identification was executed by matching electron ionization spectrum profiles against the NIST17 mass spectral library.

Oil Extraction and Yield Determination

Oil extraction was performed using the Soxhlet extraction method. Approximately 150 mL of n-hexane was used as the solvent for each 50 g batch. The extraction proceeded for 6 hours at 60 °C. Following the extraction, the solvent was removed using a R300 Buchi Rotary Evaporator (Büchi Labortechnik, Flawil, Switzerland), and the soursop and jujube seed crude oil was obtained. The percentage oil yield was calculated as shown in Equation 1:

$$\boldsymbol{Oil\ yield} = \frac{\boldsymbol{Weight\ of\ extracted\ oil}}{\boldsymbol{Total\ weight\ of\ raw\ material}} \times \mathbf{100} \quad (1)$$

Feedstock Hybridization

The *in-situ* hybridization protocol involved preparing three binary feedstock formulations A_{10}/Z_{30}, A_{20}/Z_{20}, and A_{30}/Z_{10} where "A" represents Soursop (*Annona muricata*) seed oil and "Z" represents *Ziziphus mauritiana* seed oil, with the subscripts denoting their respective percentage proportions in the composite blend. To ensure a uniform lipid matrix prior to chemical conversion, each crude oil mixture underwent mechanical homogenization at 500 rpm and 60 °C for 2 hours. This pre-treatment step reduces oil viscosity, eliminates phase separation between the distinct lipid sources, and creates a thermally balanced, molecularly homogenous feedstock that optimizes transesterification reaction kinetics and yields a balanced FAME profile combining the cold-flow performance of Soursop with the oxidative stability of Jujube.

Biodiesel Synthesis

Esterification

An acidic homogeneous catalyst, H_2SO_4-catalyzed pretreatment was employed to reduce the oil's acidity and convert its FFAs into biodiesel. To study the influence of reaction factors on esterification, 1.1 ml of sulphuric acid was mixed with 7.5 ml of methanol to reduce oil acidity. The molar ratios of methanol to oil (7.5:1), temperatures (60-85 °C), catalyst amounts (0.44%), and reaction time (120 min). After each reaction, the samples were withdrawn to evaluate the FFA conversion according to the method used by Chia-Hung [8].

Transesterification

An alkaline homogeneous catalyst was used to convert substrate obtained from esterification process. Transesterification of the hybrid oils was carried out using methanol. The process was carried out according to ASTM standard procedure using methanol to hybrid oil mole ratio of 6:1. The reaction time was 1 hour, reaction temperature of 60 ^{o}C and 1 % (w/w) KOH as a catalyst. Upon reaction completion, the mixture was allowed to cool at room temperature without agitation leading to a two-phase separation. The upper phase of the mixture was the hybrid oil methyl ester (HOME) i.e., the biodiesel and the lower phase consists of glycerol, excess methanol and catalyst formed during the reaction, some entrained HOME and traces of glycerides. The two phases were separated by decantation. The HOME was washed with warm distilled water and dried at 100 ^{o}C to remove any traces of water.

Fuel Property Testing

The physical and chemical fuel properties of the purified hybrid oil methyl esters were evaluated against ASTM D6751 [11] standards using established testing methodologies. Kinematic viscosity at 40 °C was measured with a calibrated Cannon-Fenske glass capillary viscometer following ASTM D445 [12], while flash point determination was conducted using a Pensky-Martens closed-cup tester per ASTM D93 [13]. Cold-flow performance was assessed by measuring the pour point according to ASTM D97 [14], and fuel density at 15 °C was recorded using a calibrated hydrometer pursuant to ASTM D1298 [15].

The energy content and combustion profiles were characterized through higher heating value (calorific value) measurements using a Parr oxygen bomb calorimeter in accordance with ASTM D240 [16]. Additionally, the ignition quality was quantified by calculating the Cetane index using the Krisnangkura empirical relation based on saponification and iodine values aligned with ASTM D613 [17] estimation protocols. Together, these standardized procedures ensured a precise comparison of the synthesized hybrid biodiesel blends against international industrial fuel metrics.

RESULT AND DISCUSSION

Characterization of *Annona muricata* and *Ziziphus mauritiana* seeds and seed oils

Figures 1 and 2 show the FTIR spectroscopy result of the crushed seeds of *Annona muricata* and *Ziziphus mauritiana* respectively.

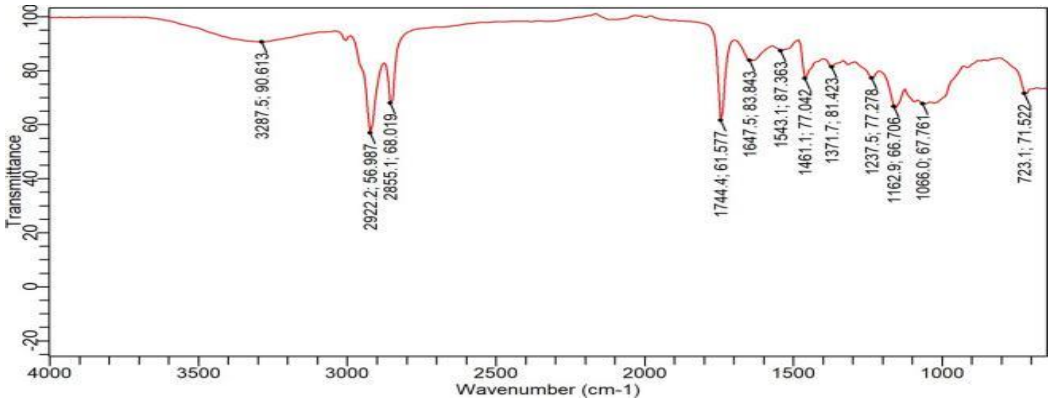


Figure 1: FTIR spectroscopy of *Annona muricata* and

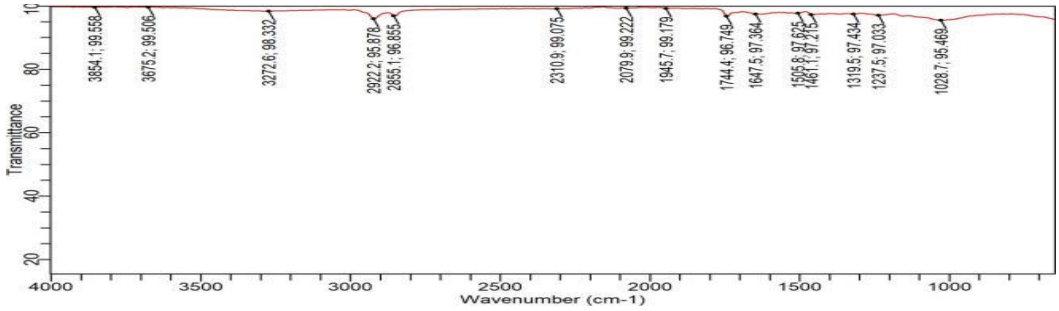


Figure 2: FTIR spectroscopy of *Ziziphus mauritiana*

The Fourier Transform Infrared Spectroscopy spectra of *Annona muricata* and *Ziziphus mauritiana* both identify long-chain aliphatic esters (triacylglycerols) via methylene stretching at 2922.2 cm^{-1} and 2855.1 cm^{-1}, and ester carbonyl (C=O) bands at 1744.4 cm^{-1}. While *A. muricata* shows high-purity lipidic peaks including C-O stretching (1162.9–1237.5 cm^{-1}) and CH rocking (723.1 cm^{-1}). *Z. mauritiana* displays identical positions with suppressed intensities and a higher signal-to-noise ratio. These findings, aligning with Manigandan and Ganguide [18, 19], and confirm that both species contain characteristic lipid markers, though the functional group density is markedly higher in *A. muricata*.

Figure 3 shows the TGA/DTA result of *Annona muricata* and *Ziziphus mauritiana* crushed seed.

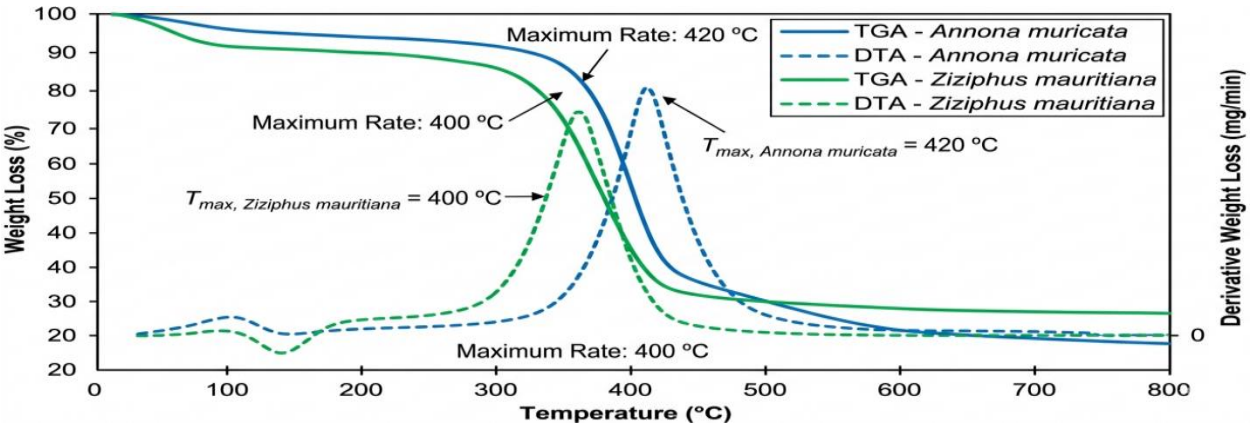


Figure 3: TGA/DTA of *Annona muricata* and *Ziziphus mauritiana*

Figure 3 presents the DTA/DTG profiles for *Annona muricata* (blue lines) and *Ziziphus mauritiana* (green lines) across a temperature range of 0 °C to 800 °C, illustrating their thermal decomposition behavior. The TGA curves measure the remaining weight percentage on the left axis, while the dashed DTA curves depict the rate of weight loss on the right axis. Both biomass samples undergo an initial minor weight loss below 100 °C to 200 °C due to moisture evaporation, followed by a major degradation phase between 300 °C and 500 °C corresponding to the decomposition of hemicellulose, cellulose, and lignin. *Ziziphus mauritiana* reaches its maximum degradation rate (T_{max}) at 400 °C and leaves a solid char residue of approximately 27% at 800 °C, whereas *Annona muricata* demonstrates higher thermal stability with its peak decomposition rate occurring at 420 °C and a lower final residue around 18–20%, confirming that both species possess robust structural integrity and high-temperature stability suitable for thermochemical conversion [20].

Figures 4 and 5 show the SEM result of *Annona muricata* and *Ziziphus mauritiana* crushed seeds respectively.

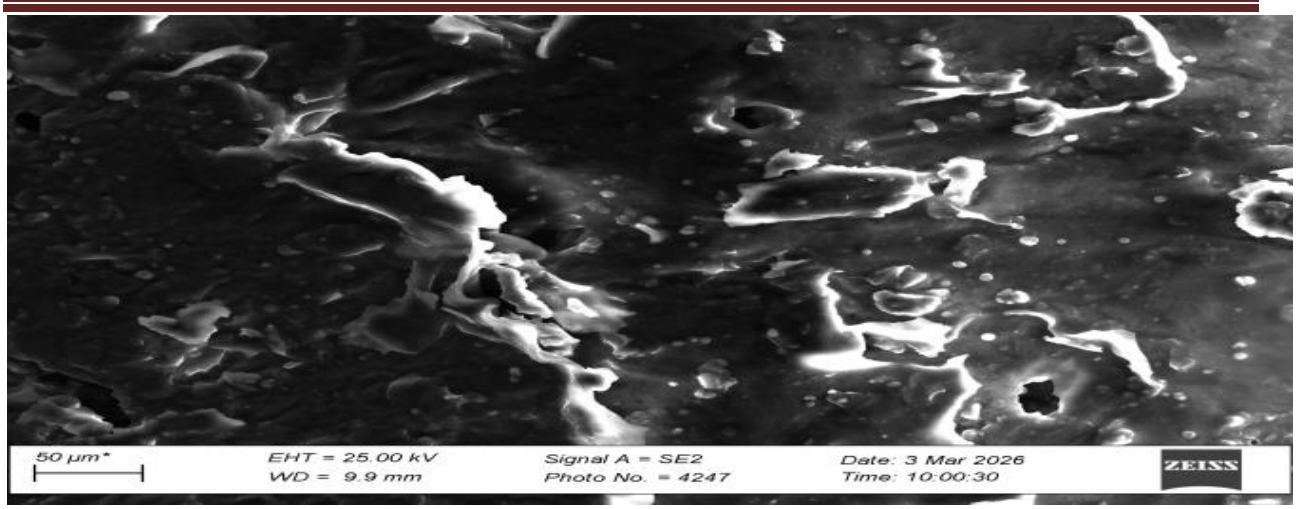


Figure 4: SEM of *Annona muricata* crushed seed

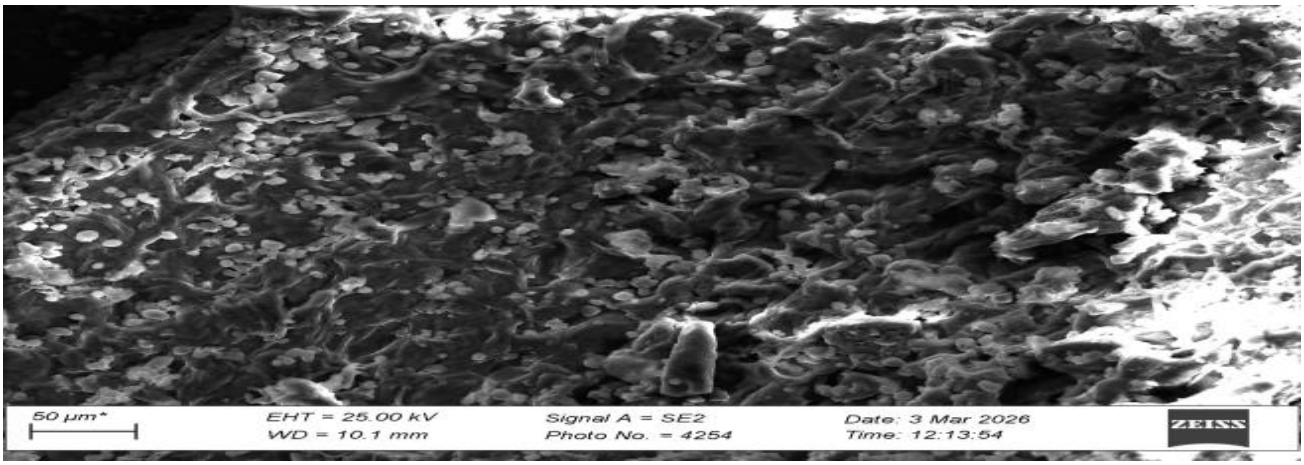


Figure 5: SEM of *Ziziphus mauritiana* crushed seed

The Scanning Electron Microscopy (SEM) analysis results of *A. muricata* and *Z. mauritiana* reveal complex, porous morphologies characterized by irregular bulk shapes and internal networks of macropores derived from collapsed cellular structures. At high resolutions (10–50 µm), both species exhibit rough surfaces with micro-granules and oil-like droplets, consistent with findings by Ugwuodo [21].

This combination of high surface area and significant pore volume enhances thermal degradation efficiency by facilitating rapid heat transfer and gas diffusion, making these biomass precursors ideal for high-yield bio-oil and biodiesel production.

Figure 6 is the X-Ray Diffraction result of *Annona muricata* and *Ziziphus mauritiana* crushed seed biomass

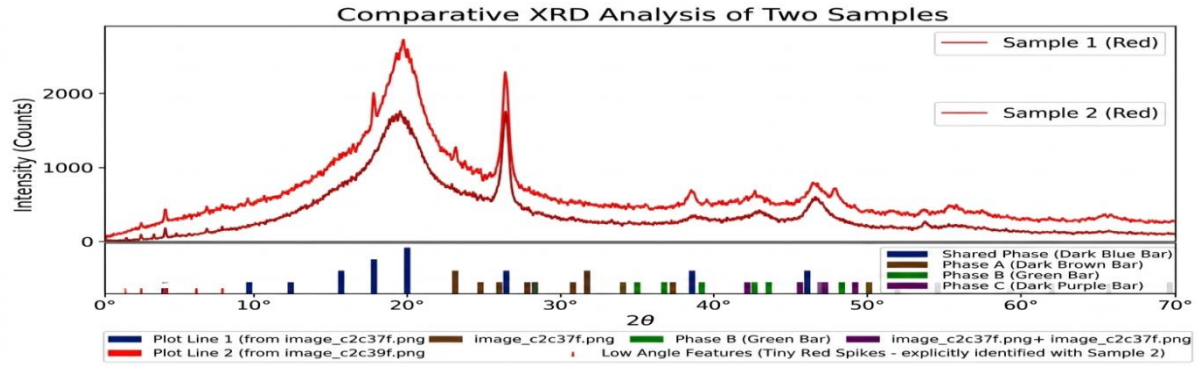
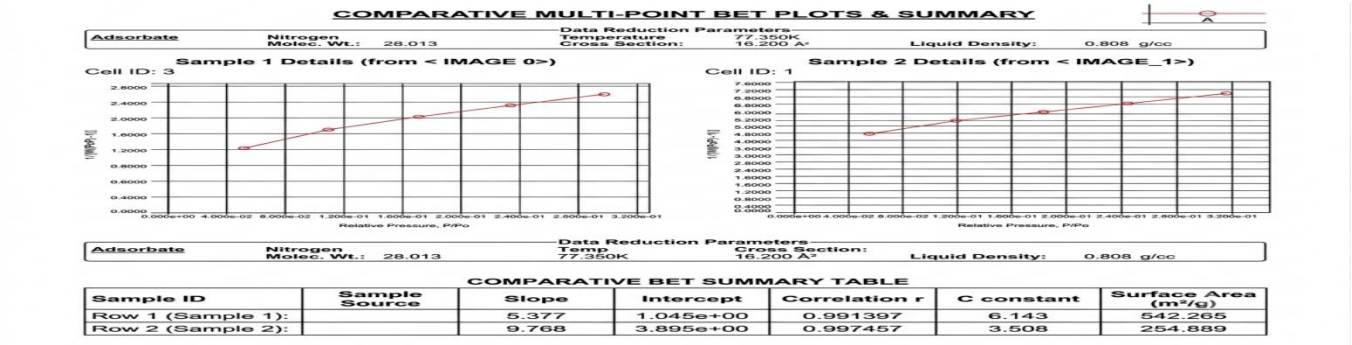


Figure 6: X-Ray Diffraction *of Annona muricata* and *Ziziphus mauritiana, where* Sample 1 *signifies Annona muricata and* Sample 2 *represents Ziziphus mauritiana*

X-Ray Diffraction analyses of *A. muricata* and *Z. mauritiana* depicted in Figure 6 reveal a predominantly amorphous structure, with *Annona muricata* consisting of 38.5% crystalline phase and 61.5% amorphous phase, while *Ziziphus mauritiana* shows a slightly higher degree of structural order with 42.2% crystalline phase and 57.8% amorphous phase. This higher crystallinity in *Ziziphus mauritiana* suggests a more organized cellulose framework compared to the more disordered, lignin-rich composition of *Annona muricata,* noted by Anosike-francis *et al*. [22]. Also, Cellulose I frameworks with prominent crystalline peaks at 2Θ approximately 21.8^{o} and 22.1^{o}, respectively, resulting in broader peaks that indicate high accessibility for chemical conversion and oil extraction [22].

The higher crystallinity in *Ziziphus mauritiana* suggests a more organized cellulose framework compared to the more disordered, lignin-rich composition of *Annona muricata*. These values are typical for raw agricultural seed biomass, where the amorphous components such as hemicellulose and lignin surpass the crystalline cellulose content, influencing the material's overall thermal stability and mechanical properties as described by Brunauer et al. [23].

Figure 7 is the Brunauer-Emmett-Teller analysis result of *Annona muricata* and *Ziziphus mauritiana* crushed seed biomass



Sample ID	Sample Source	Slope	Intercept	Correlation r	C constant	Surface Area (m^2/g)
Row 1 (Sample 1):		5.377	1.045e+00	0.991397	6.143	542.265
Row 2 (Sample 2):		9.768	3.895e+00	0.997457	3.508	254.889

Figure 7. Brunauer-Emmett-Teller analysis of *Annona muricata* and *Ziziphus mauritiana.* Sample 1 signifies *Annona muricata and* Sample 2 is *Ziziphus mauritiana*

The multi-point BET analysis performed using nitrogen gas at 77.350 K confirms excellent linear correlation (r = 0.991397 for Sample 1 and r = 0.997457 for Sample 2) across the relative pressure (P/P_0) range of 0.05 to 0.30 [24]. From the linear regression slopes and y-intercepts (5.377 and 1.045 for Sample 1; 9.768 and 3.895 for Sample 2), Sample 1 (*Annona muricata*) yields a significantly higher BET C constant of 6.143 compared to 3.508 for Sample 2 (*Ziziphus mauritiana*), indicating stronger adsorbent-adsorbate binding affinity. Crucially, *A. muricata* exhibits a specific surface area (*S*BET) of 542.265 m^2g more than double the 254.889 m^2g recorded for *Z. mauritiana*—confirming that *A. muricata* possesses a far more porous, amorphous matrix with superior active surface area to facilitate solvent contact during oil extraction [25].

Figures 8 and 9 show the GCMS profiles result of *Annona muricata* and *Ziziphus mauritiana* crushed seed respectively.

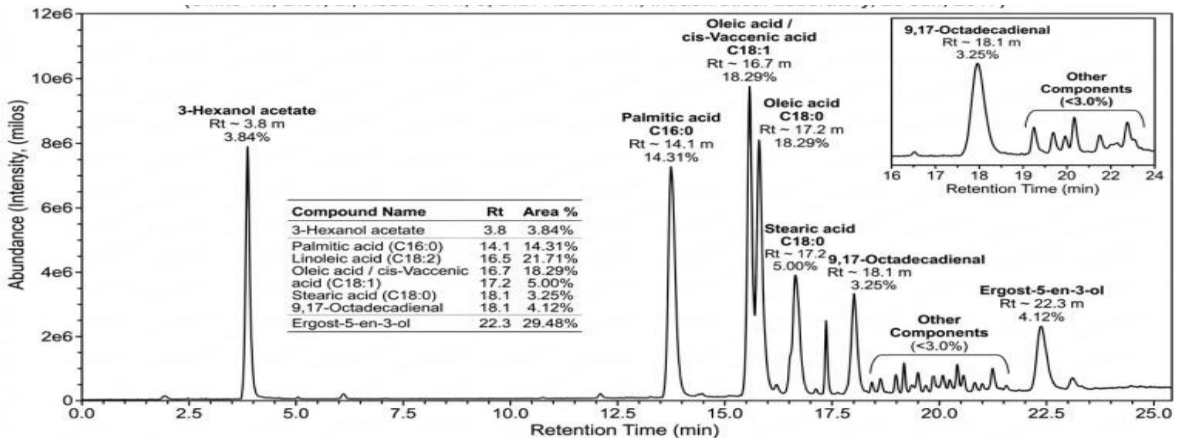


Figure 8: GCMS analysis of *Annona muricata*

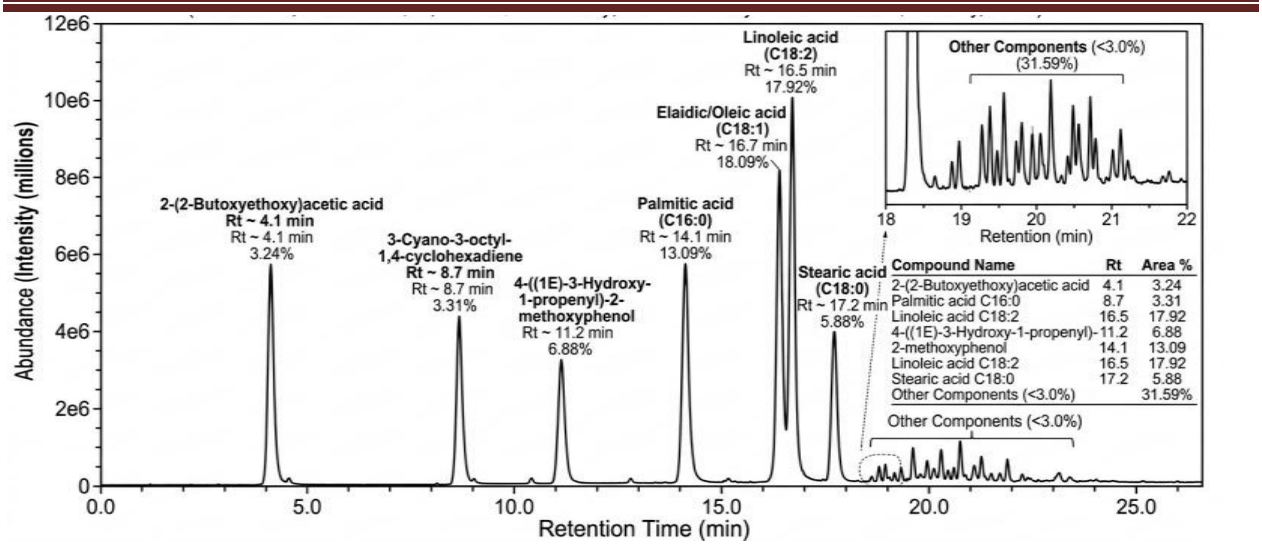


Figure 9: GCMS analysis of *Ziziphus mauritiana*

The Gas chromatography-mass spectrometry (GC-MS) analysis demonstrate that both *Annona muricata* (soursop) and *Ziziphus mauritiana* (jujube) seed oils possess complementary fatty acid profiles highly suitable for biodiesel production. The chemical fingerprint of *A. muricata* is dominated by linoleic acid (21.71%), oleic acid (18.29%), and palmitic acid (14.31%), which together account for 54.31% of the total relative area, consistent with the findings of Dalmis [26].

This high unsaturation level enhances low-temperature fluidity and cold-flow properties, though prominent acid peaks indicating elevated Free Fatty Acids (FFA) necessitate a two-step process H_2SO_4 catalyzed esterification followed by KOH catalyzed transesterification to prevent saponification, as validated by Chia-Hung [8]. In contrast, *Z. mauritiana* seed oil exhibits a 36.01% unsaturation baseline driven by oleic acid (18.09%) and linoleic acid (17.92%), alongside saturated fractions of palmitic acid (13.09%) and stearic acid (5.88%), a balance that Adebayo and Masoko [10] report enhances combustion efficiency, cetane number, and energy density.

Furthermore, because *Z. mauritiana* exhibits a significantly lower inherent FFA content, it does not strictly require a prior acid pretreatment step. Consequently, combining both feedstocks leverages a strategic hybridization that merges the oxidative stability and ignition quality of *Z. mauritiana* with the superior cold-flow performance of *A. muricata*, resulting in a synergistic, high-performance hybrid biodiesel.

Percentage yield from *Annona muricata* and *Ziziphus Mauritania* the crushed seed biomass was obtained using the Soxhlet method, as shown in Table 1.

Table 1: Percentage yield of oil extracted from *Annona muricata* and *Ziziphus Mauritania* seeds biomass

Seed material	Weight of extracted oil (g)	Total weight of raw material (g)	Oil yield (%)
Soursop	73.6	400	18.4
Jujube	73.6	500	14.72

The following table illustrates the impact of varying feedstock blend ratios on the total biodiesel yield.

Table 2: Biodiesel yield from blend feedstock ratios

Feedstock ratio	Weight of pure biodiesel (g)	Weight of Initial oil (g)	Biodiesel yield (%)
A10/Z30	33.44	36.8	90
A20/Z20	31.68	36.8	86
A30/Z10	31.68	36.8	86

Physicochemical parameters of a biodiesel blend ratio

Table 3 illustrates the physicochemical parameters of a biodiesel blend and the specific property values resulting from the mixture ratio used to ensure engine compatibility and performance.

Table 3: Physicochemical parameters of a biodiesel blend ratio

I.D	A.V (MgKoH/g)	S.P (Mg KoH/g)	I.V (g/100 g)	F.P.T (C^0)	P.P.T (^0C)	S.G	B.D (Kg/ M^3)	Density (g/Cm^3)	F.F.A (Mg/KoH/g)	C.V (mj/Kg)	Viscosity (mm^2/Sec.) in 40 ^oC
A10/Z30	0.28	175.66	34.11	155	-8	0.72	641.10	0.81	0.31	28.69	32.10
A20/Z20	0.34	192.60	30.65	134	-10	0.74	782.41	0.85	0.28	31.40	77.65
A30/Z10	0.46	198.41	28.43	130	-13	0.81	830.22	0.89	0.25	37.88	41.35

ABREVATIONS

(I.D =Identity, A.V= Acid Value, S.P=Saponification Value, I.V =Iodine Value, F.P.T=Flash Point Test, P.P.T= Pour Point Test, S.G=Specific Gravity, B.D=Bulk Density, F.F.A = Free Fatty Acid, C.V = Calorific Value).

Table 4 compares biodiesel parameters against ASTM D6751 standards ensuring that the fuel's physical and chemical properties meet the rigorous safety and performance required for use in diesel engines.

Table 4: Comparison of some biodiesel parameters obtained against ASTM D6751 standard

Fuel properties	ASTM D 6751 standard	A10/Z30	A20/Z20	A30/Z10
Acid Value (Mg/KoH/g)	0.50 Max	0.28	0.34	0.46
Flash Point Test (C^0)	130min	155	1.34	130
Viscosity (mm^2/Sec.) in 40^{o}C	1.9-6.0	32.10	77.65	41.35
Cetane number	47min	69.70	67.73	67.41

The initial phase of this research focused on the solvent extraction of lipids from Soursop and Jujube seeds, revealing a higher lipid content in Soursop (18.4%) compared to Jujube (14.72%) as shown in (Table 1). These results align with the findings of Avendano et al. [25], who reported an 18.92% yield for Soursop, and Memo et al. [27], who noted that regional Jujube varieties typically exhibit moderate fat content between 12% and 18%. The variations in yield are primarily attributed to geographical origin and seed moisture content, while the moderate recovery in Jujube may also be influenced by mechanical crushing factors that limit solvent access to internal oil-bearing globoids. The subsequent transesterification process yielded high

conversion efficiencies, with pure Soursop oil reaching yields of 90% to 97% [9], significantly outperforming the 82% to 85% recorded for Jujube reported by Memo et al., [27]. This disparity is linked to the fatty acid profiles, where the higher concentration of unsaturated acids in Soursop facilitates a more complete reaction. Interestingly, a synergistic effect was observed in the hybrid blends; the A10/Z30 ratio achieved a 90% yield, outperforming pure Jujube oil despite being dominated by it. This demonstrates that even minor additions of Soursop oil can significantly improve reaction kinetics and solubility, offering an effective strategy to enhance the fuel potential of lower-yielding feedstocks.

Physicochemical evaluation as illustrated in (Table 2), showed that the biodiesel blends largely align with ASTM D6751 standards, with acid values (0.28–0.46 mg KOH/g) and flash points (130°C–155°C) meeting safety and non-corrosive requirements. Using the Krisnangkura [28] formula, the cetane numbers were calculated between 67.41 and 69.70, far surpassing the ASTM minimum of 47 and indicating superior ignition quality. However, the kinematic viscosity (32.10–77.65 mm^2/sec) was notably higher than the standard range of 1.9–6.0 mm^2/sec. This suggests that while the chemical conversion was successful, the high-density molecular structure of these non-traditional oils may require further optimization, such as pre-heating or further blending, to ensure optimal performance in modern fuel systems.

CONCLUSION

This study demonstrates a viable pathway for converting agricultural bio-waste into clean energy by producing a hybrid biodiesel from soursop and jujube seed oils. GC-MS profiling confirmed a powerful chemical synergy: soursop oil's unsaturated fatty acids supply superior cold-flow properties, while jujube oil's saturated lipids deliver thermal and oxidative stability. Using a two-step process acid esterification (H_2SO_4) to drop free fatty acids below 1.0%, followed by alkali transesterification (KOH) the optimal A10/Z30 blend (10% soursop, 30% jujube) achieved a 90% conversion yield. The resulting fuel meets ASTM D6751 standards for high Cetane Number (67.41–69.70), strong energy content (up to 37.88 MJ/kg), safe Flash Points (130–155°C), and low Pour Points (down to -13°C). However, elevated kinematic viscosity (32.10–77.65 mm^2s) remains the primary technical bottleneck. To enable commercial deployment, future research must prioritize B20 petro-diesel blending, vacuum distillation, engine emission testing (NOx, CO, PM), and comprehensive Techno-Economic and Life Cycle Assessments (TEA/LCA).

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