Unique seed oils of Terminalia phellocarpa, Khaya nyasica and Baccaurea courtallensis as potent feed stocks for liquid fuel Production: Modelling and Evaluation

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***Abstract*—In the pursuit of sustainable alternatives to fossil-derived fuels, this study investigates the feasibility of using non-edible seed oils from *Khaya nyasica*, *Terminalia phellocarpa*, and *Baccaurea courtallensis* for the production of biodiesel. These plant species, native to tropical regions, yield 72%, 38%, and 23% seed oil respectively. Their oils vary significantly in saturated and unsaturated fatty acid content, making them ideal candidates for compositional blending. In the present investigative approach, the biodiesel properties are optimized by mixing these trio seed oils through the Bio-mix strategy for the synthesis of biodiesel. The data like Saponification value (SV), Iodine value (IV) of seed oil and the various parameters of biodiesel viz., Cetane number (CN), Higher heating value (HHV), Flash point(FP), Cloud point(CP), Viscosity, Pour point(PP) of fatty acid esters of KNSO, TPSO, BCSO and Bio-mix (blend) of three seed oils are assessed empirically. The fatty acid methyl esters (FAMEs) of optimized Bio-mix oil meets the ASTM and EN meets standards. This work reports that of selected species and their blend are ideal for synthesis of liquid fuel. This strategy nullifies the dependency on one set of traditional feedstocks. Bio-mix:II and Bio-mix:III reported optimized feed stock property for liquid fuel production**

Keywords*— *Terminalia phellocarpa, Khaya nyasica, Baccaurea courtallensis, Bio-mix, liquid fuel, biodiesel.

I. INTRODUCTION

The advancement in overall development has led to rising energy demands across various sectors, resulting in unforeseen environmental consequences and societal concerns. One of the critical challenges today involves the growing dependency on fossil fuels, leading to issues such as global warming, diminishing hydrocarbon fuel reserves and fluctuating fuel prices. The combustion of hydrocarbon fuels releases pollutants like CO_2, NO_x, SO_x, and particulate matter, which exacerbate climate change and cause severe ecological impacts. [1]To mitigate the aforesaid issues related to alternative energy and their modeling evaluation, forecasting is the hot topic for the researchers in the energy domain presently. This has motivated to initiate research activities to develop renewable and sustainable energy sources. Currently one of these researches is on the utilization of mixtures of fatty acid esters popularly known as biodiesel. The biomass resources like vegetable oils, animal fat etc., are used as feedstocks. This strategy still has challenges and issues entangled with feedstock availability and fuel properties [2]. According to global energy outlooks, the share of renewable energy, including biofuels, is expected to grow from 9% to 12% by 2040. The International Energy Agency (IEA) predicts a gradual decline in the dominance of fossil fuels, from 82% in 2012 to around 80% in 2040 [3].

In this context, researchers have turned to a broad spectrum of renewable energy options such as solar, wind, hydropower, tidal and geothermal energy, which are both sustainable and less harmful to the environment. Additionally, the use of biomass residues, agroforestry practices and silviculture techniques has gained attention as a means of enhancing the availability of renewable feedstocks particularly non-edible vegetable oils. These biomass sources can be converted into solid, liquid, or gaseous fuels using various technological pathways[4]. Among these, biodiesel production from oil-yielding crops has emerged as a promising route. The seed oils with sufficient carbon content and suitable fatty acid profiles offer good calorific values, making them competent energy carriers. Transesterification remains the most commonly used method for converting oils to biodiesel, effectively reducing viscosity and enhancing fuel compatibility. Compared to petro-diesel, biodiesel contains more oxygen and exhibits superior environmental

performance. As a result, blending biodiesel with petro-diesel in different proportions is becoming standard practice [5-6]. Feedstocks for biodiesel production are broadly categorized into first-generation (e.g., edible oils), second-generation (non-edible oils, waste), third-generation (algal biomass), and emerging fourth-generation options, which include genetically modified algae and electrofuels [7].

Currently, non-edible seed oils that do not compete with food supply are being identified as promising biodiesel feedstocks. The Bio-mix approach, where the blend of seed oils with differing levels of saturated and unsaturated fatty acids has proven effective in addressing key limitations such as high viscosity or poor cold flow properties [8]. The challenge lies in obtaining sufficient quantities of a single seed oil from a specific location. Each oil has unique advantages and limitations. The seed oils with high % of saturated fatty acids improve oxidation stability, while unsaturated fatty acids enhance cold flow performance [9]. Blending oils helps balance these properties. Studies show that mixing oils with complementary fatty acid profiles can lower density, viscosity, acid value, and flash point, while improving cetane number and oxidative stability [7,9]. Various mathematical models for the evaluation of fuel characteristics such as viscosity, cold filter plugging point (CFPP), density, cetane number (CN), iodine value (IV), and oxidative stability (OS) were used [10]. Optimizing biodiesel production and tribological related analysis using biodiesel needs the conduct of experiments and development of mathematical /computational models that relate the responses to the process inputs [11]. In order to overcome the expenditure incurred for experimentations, researchers and technologists developed models for easy forecasting, evaluation and modeling with reference to the available primary data like seed oil parameters and fatty acid details [12].

The Bio-mix is a method to improve the saturation level of seed oil by blending the oil of high saturated fatty acid content with unsaturated fatty acid oil content. Literature reveals that carbon chains, especially long chains suited on par with petro diesel. % Saturation content and % unsaturation content of fatty acids in the entire mixture influence the biodiesel properties. The objective of the present research work is to improve the saturation content of the fatty acid alkyl esters by bringing down the unsaturated fatty acids concentrations with a strategic Bio-mix approach [9,13].The different seed oil species, namely *Khaya nyasica*, *Terminalia phellocarpa* and *Baccaurea courtallensis* were selected and mixed to obtain a Bio-mix oil (BMO) sample. Thereby, the optimization of fuel properties is possibly achieved. The biodiesel/liquid fuel derived using the raw bio-mix oil is called Bio-mix Alkyl Ester (BMAE) or Mixed Oil Methyl Ester (MOME). The properties of Bio-mix alkyl esters were evaluated and compared with the International standard methods, like ASTM standards and EN standards.

II. MATERIALS AND METHODS

2.1. Mechanism of Transesterification

Transesterification process involve conversion of triglycerides into fatty acid alkyl esters along with glycerol. This mechanism initiated by transformation of triglycerides to diglycerides followed by diglycerides into monoglycerides followed by separation glycerol yielding fatty acid alkyl ester. This process is catalysed by acid or base[14].

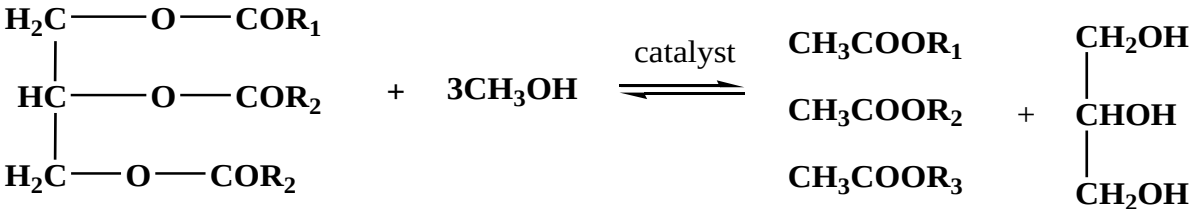


Figure 1: Chemical reaction of Transesterification

2.2 General procedure for liquid fuel synthesis

As shown in Figure 2, during the biodiesel synthesis, seed oil and the alcohol are taken in the ratio of 1:6 and refluxed for 60 minutes in the presence of homogenous or heterogenous catalyst. At the end of the reaction, the mixture is taken into a separating funnel and kept for overnight leading to two phases. The lower phase contains unreacted methanol, glycerol and catalyst. The upper phase consists of fatty acid esters admixed with traces of alcohol and

the catalyst. Thus, the obtained liquid fuel is washed using warm de-ionized water. The residual alcohol is removed by rotary evaporator at 70 °C. Thus, the obtained liquid material containing fatty acid ester is biodiesel [15]. Biodiesel synthesis by Bio-mix Strategy involves logical selection of feedstocks based on % SFA and %USFA in order to improve fuel properties.

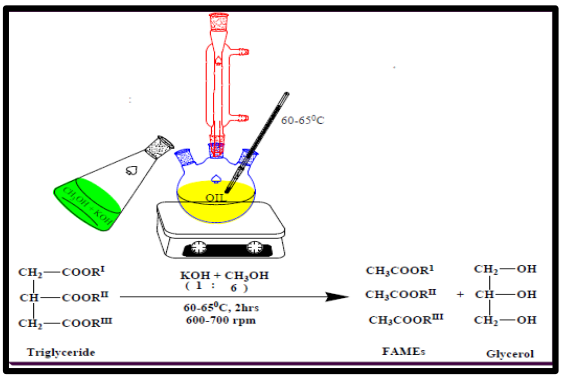


Figure 2. Schematic representation of transesterification

i)Khaya nyasica

Khaya nyasica belongs to the Meliaceae family. It is a tall tree. It grows in Tanzania south to Mozambique in evergreen forest and riverine fringe forest. It is a semi-evergreen large tree. The bark is grey to brown, mainly smooth but flaking in characteristic rounded scales. Fruit is a dry capsule 5cm across, breaks into 4-5 sections, scattering 30-60 pale flat winged seeds. Seeds of *Khaya nyasica* yields 72% of seed oil. [16]

Figure 3: (a)*Khaya nyasica* plant (b)*Khaya nyasica* seeds

ii)Terminalia phellocarpa

Terminalia phellocarpa belongs to Combretaceae family. This genus name is derived from Latin word *terminus*, refers to the leaves emerging at the very tips of the shoots. It is found in Malaya to Sumatera. It is a tree grows in the wet tropical biome. Seeds of *Terminalia phellocarpa* contain 38% of oil. [16]

Figure 4: (a)*Terminalia phellocarpa* plant (b)*Terminalia phellocarpa* seeds

iii)Baccaurea courtallensis

The *Baccaurea courtallensis* is a moderately sized evergreen tree belonging to Euphorbiaceae family. It is distributed from South Konkan to South Kerala and western parts of Tamil Nadu, India. The fruits are crimson coloured and acidic. This species has local name Kolikukku, Mootipazham in Karnataka and Kerala, respectively. It is edible but has with sour taste. The seed oil content is 23%, with 63.47% of saturated fatty matter and 36.53% unsaturated content. [17]

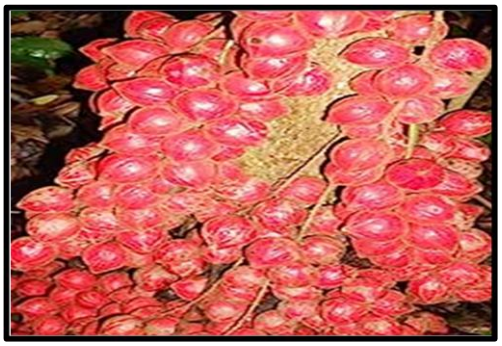
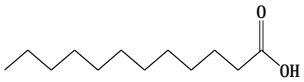
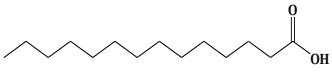
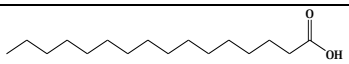
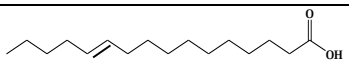
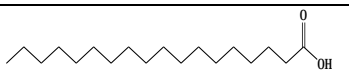
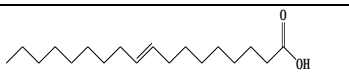
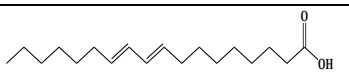
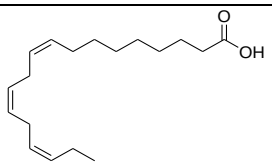


Table 1. Component fatty acids in *Khaya nyasica* seed oil (KNSO), *Terminalia phellocarpa king*

Component fatty acids	N_C:N_{db}*	Molecular formula	Structure of Fatty acids	% Fatty acid		
				KNSO	TPSO	BCSO
Lauric acid	12:0	$C_{12}H_{24}O_2$		-	-	0.40
Myristic acid	14:0	$C_{14}H_{28}O_2$		-	-	4.28

Palmitic acid	16:0	$C_{16}H_{32}O_2$		11.0	-	42.59
Palmitoleic acid	16:1	$C_{16}H_{30}O_2$			28.0	-
Stearic acid	18:0	$C_{18}H_{36}O_2$		12.0	5.0	16.20
Oleic acid	18:1	$C_{18}H_{14}O_2$		63.0	20.0	36.15
Linoleic acid	18:2	$C_{18}H_{32}O_2$		14.0	47.0	0.38
Linolenic acid	18:3	$C_{18}H_{32}O_2$		-	-	-
%TSFA	-	-	-	23.0	5.0	63.47
%TUSFA	-	-	-	77.0	95.0	36.53

III. EXPERIMENTAL METHOD

3.1. Computational analysis

The screening of biodiesel properties is on par with standards like ASTM, DIN D 6751 and EN 14214 methods. Mathematical models from the literature are applied for evaluation of the fuel properties of seed oils under investigation [18,19]. The biodiesel properties viz. iodine value (IV), Ceatne number (CN), Higher heating value (HHV), Lower heating value (LHV), Cloud point (CP), Pour point (PP), Cold filter plugging point (CFPP), Degree of unsaturation (DU), Kinematic viscosity (KV) and Flashpoint (FP) of the processed seed oils have been computed and compared with standards.

Table 2. Computational analysis using mathematical models for screening of seed oils for fuel properties

Eq No.	Equation	Denominations	Ref.
i.	Molecular weight of oil: $MW_{oil} = 3\ (MW_i) + 3\ (MW_{glycerol}) - 3\ (MW_{alcohol})$	where M_{wi} = molecular weight of each fatty acid	[20]
ii.	Saponification value: $SV = \sum \frac{56.03 \times Ai}{Mwi}$	where, Ai is the % of component fatty acids, Mwi is the molecular mass of each component	
iii.	Iodine value: $IV = \sum \frac{253.81 \times Ndb \times Ai}{Mwi}$	where, Ai is the % of component fatty acids, Ndb is the number of double bonds, Mwi is the molecular mass of each component	
iv.	Cetane Number: $CN_{mix} = \sum A_C \times CN_C$	where, A_C is the percentage composition of individual fatty acid ester, CN_C is cetane number of respective fatty acid ester	[21]
v.	Higher heating value: HHV = 49.43 – (0.015 x IV) – (0.041 x SV)	where, IV is iodine value and SV is saponification value	

vi.	Lower heating value: $LHV = 0.0011\left(\frac{H}{O}\right)^3 - 0.0785\left(\frac{H}{O}\right)^2 + 2.0409\left(\frac{H}{O}\right) + 20.992 - 0.100\,Ndb$ $LHV = 0.0901\left(\frac{C}{O}\right)^3 - 0.3515\left(\frac{C}{O}\right)^2 + 4.200\left(\frac{C}{O}\right) + 21.066 - 0.100Ndb$	where, C is the number of carbon atoms, H is the number of hydrogen atoms, O is the number of oxygen atoms and Ndbis the number of double bonds	[22]
vii.	Kinematic viscosity: KV =0.235 x N_C – 0.468 x N_{dbw}	where N_C is the weighted average number of carbon atoms and N_{dbw} is the weighted average number of double bonds.	[23]
viii.	Flash point: FP= (23.362 x N_C) + (4.854 x N_{dbw})	where, N_C is the weighted average number of carbon atoms and N_{dbw} is the weighted average number of double bonds.	
ix.	Cloud Point CP = – 0.576 x UFAME + 48.3	where, UFAME is % unsaturation of FAMEs	
x.	Pour point: PP= – 0.626 x UFAME + 45.694	where, UFAME is % unsaturation of FAMEs	
xi	CFPP CFPP = -0.561×UFAME + 43.967	where, UFAME is % unsaturation of FAMEs	[23]
xii	LCSF LCSF=(0.1×C16) +(0.5×C18)+(1×C20)+(1.5×22)+(2×C24)	where, C16, C18, C20, C22 & C24 refer to the percentage composition of respective fatty acid component.	

IV. RESULTS AND DISCUSSIONS

The procedures used to experimentally determine the fuel properties are lengthy and cost effective. In this context evaluation based on relevant data the theoretical approach is deployed. This is supported with the prior experimental support is a useful strategy. In the literature it is cited that the mathematical models are developed and applied for the evaluation of fuel properties is a proficient technique.

4.1. Saponification Value (SV) and Iodine Value (IV):

Saponification Value and Iodine Value are the important analytical parameters of seed oils. These parameters augment in signifying seed oil suitability for synthesis of biodiesel. The molecular weight (MW) and saponification value (SV) are inversely proportional and the data obtained are depicted in Table 3. The MW of seed oils is calculated using equation (i). The Saponification Value depends on the molecular weight (MW) of oil and is evaluated using equation number (ii). The seed oil of *Baccaurea courtallensis* with low molecular weight has relatively higher SV compared to *Terminalia phellocarpa* and *Khaya nyasica.* The degree of unsaturation (DU) in seed oil is measured based on Iodine Value. It is dependent on fatty acid profile. The IV of seed oils are calculated from the equation(iii). The limitation recommended by European standard organization (EN 14214) for biodiesel is not to exceed the value of 120 mg of I_2 g^{-1} oil. The calculated values for KNSO, TPSO, BCSO are 81.95, 130.98, and 33.17 mg I_2/100 g of oil respectively. Increased IV in case of TPSO is high due to % of USFAs. Which does not satisfy EN 14214. This issue can be nullified and feedstock is optimized by blending seed oil which is having higher % SFAs.

Table 3. Physico-chemical properties of *Khaya nyasica* seed oil (KNSO) seed oil, *Terminalia phellocarpa king* seed oil (TPSO) and *Baccaurea courtallensis Muell. Arg* seed oil (BCSO)

Physicochemical properties	KNSO	TPSO	BCSO	Bio-mix: I	Bio-mix: II	Bio-mix: III
% Yield of Oil	72	38	23	NA	NA	NA
Density of oil (g/cm^3)	0.8926	0.8990	0.8869	0.8958	0.8929	0.8895

Molecular weight of oil	834.64	815.56	803.11	825.52	809.33	817.77
SV (mg KOH/g of oil)	200.88	205.85	209.34	203.23	207.59	205.35
IV (g of I_2/100 g of oil)	81.95	130.98	33.17	106.46	82.07	82.03
%TSFA	23	5	63.47	13.5	34.23	30.49
%TUSFA	77	95	36.53	86.5	65.76	69.51

Where, Bio-mix I = (KNSO+TPSO), Bio-mix II = (TPSO+BCSO), Bio-Mix III = (KNSO+TPSO+BCSO) and NA = Not Applicable

Table 4. Comparison of properties of biodiesels empirically computed for KNFAMES, TPFAMES, BCFAMES and Bio-mix: I, Bio-mix: II, Bio-mix: III with existing biodiesels and petro-diesel (PD)

Fuel property	Seed oil species under investigation			Optimization by mixed oils			Existing biodiesel / petro-diesel			
	KNME (A)	TPME (B)	BCME (C)	Bio-mix: I (A+B)	Bio-mix: II (B+C)	Bio-mix: III (A+B+C)	PPME[24]	SBME [25]	RSME [26,27]	PD
CN	55.03	43.34	64.91	49.20	54.12	54.42	63.1	45.0	59.0	42.0
HHV (MJ kg^{-1})	39.96	39.03	40.35	39.50	39.49	39.78	40.5	39.8	37.0	46.0
LHV (MJ kg^{-1})	38.18	38.01	37.98	38.10	38.09	38.05	34.3	33.5	32.8	43.1
Viscosity mm^2/s	3.69	3.43	3.81	3.58	3.62	3.64	4.6	3.65	6	3.14
Flash point (K)	419.79	413.39	397.85	416.83	405.62	410.34	485	389.5	425	393
Cloud point (°C)	-0.78	-4.99	17.41	-1.84	12.42	11.64	6	0	-3.9	-8.1
CFPP (°C)	5.83	5.4	22.35	5.6	13.87	11.19	3	-6	-9.0	-15
LCSF	7.10	2.50	12.36	4.8	7.43	7.32	7.99	4.3	4.6	NA

where, PPME= Pongamia methyl ester, SBME = Soyabean methyl ester, RSME = Rape seed methyl ester, PD = Petrodiesel.

Table 5. Specifications of diesel and biodiesel fuels

Fuel property of Diesel	Diesel	Bio Diesel
Fuel standard	ASTM D975	ASTM PS 121
Fuel composition	C_{10}–C_{21} HC	C_{12}–C_{22} FAME
Lower heating value (MJ/m^3)	36.6×10^3	32.6×10^3
Kinematic viscosity at 40°C (mm^2/s)	1.3–4.1	1.9–6.0
Specific gravity at 15.5°C	0.85	0.88
Density at 15°C (kg/m^3)	848	878
Carbon (wt%)	87	77
Hydrogen (wt %)	13	12
Oxygen (by diff.) (wt %)	0	12
Sulphur (wt %)	0.05	max 0.0–0.0024
Boiling point (°C)	188–343	182–338
Flash point (°C)	60–80	100–170
Cloud point (°C)	−15 to 5	−3 to 12
Pour point (°C)	−35 to −15	−15 to 10
Cetane number	40–55	48–65

4.2. Fuel properties

4.2.1. Cetane number (CN):

The cetane number is an important quality metric that determines the ignition delay of biodiesel in diesel

engines. It is influenced primarily by the carbon chain length and the degree of saturation or unsaturation in fatty acids [21]. In this work, the CN values of FAMEs from *Terminalia phellocarpa*, *Khaya nyasica*, and *Baccaurea courtallensis* were 43.34, 55.01, and 64.91, respectively. Blended formulations—Bio-mix: I, II, and III has CNs of 49.20, 54.12, and 54.42, respectively, aligning well with ASTM D6751 and EN 14214 standards. As shown in figure 6(a) and (b), a strong inverse correlation ($R^2 = 0.9258$) was observed between CN and unsaturated fatty acid (USFA) content, while a positive correlation ($R^2 = 0.9245$) was evident with saturated fatty acids (SFAs), indicating the ignition quality improves with increased saturation [28].

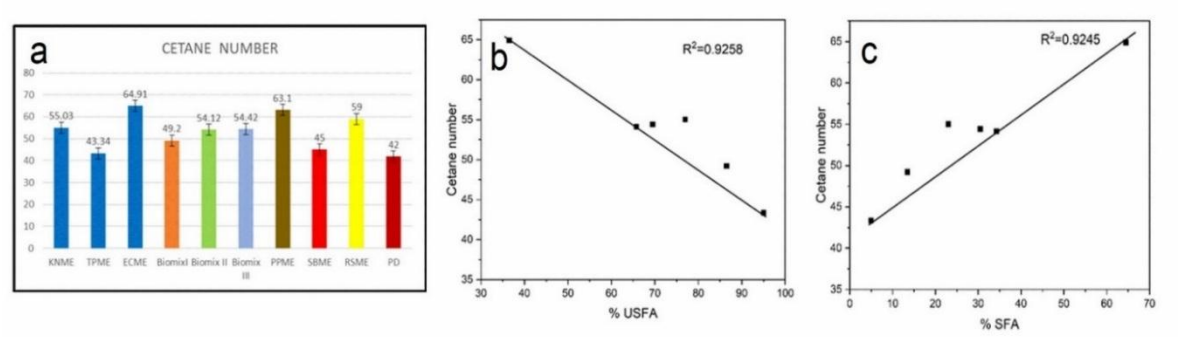


Figure 6. (a)Cetane number of biodiesels compared with existing biodiesels and Petro diesel. (b) Correlation graph between CN and USFA (c) Correlation graph between CN and SFA

4.2.2. Higher heating value (HHV):

The HHV reflects the energy output of the fuel and depends on the molecular structure and elemental composition, particularly carbon, hydrogen, and oxygen [28]. The HHVs of KNFAMEs, TPFAMEs, and BCFAMEs were 39.96, 39.03, and 40.35 MJ/kg, respectively. Bio-mix variants showed values ranging between 39.49 and 39.78 MJ/kg. Although slightly lower than that of petro-diesel (43 MJ/kg), these values are notably higher than those for coal (32–37 MJ/kg). As illustrated in Figure 7 (a) and (b),correlation graphs revealed that HHV tends to increase with higher saturated fatty acid content due to their higher hydrogen-to-carbon ratio and the absence of double bonds, which promotes efficient combustion and HHV decreases with increase in unsaturated fatty acids [30].

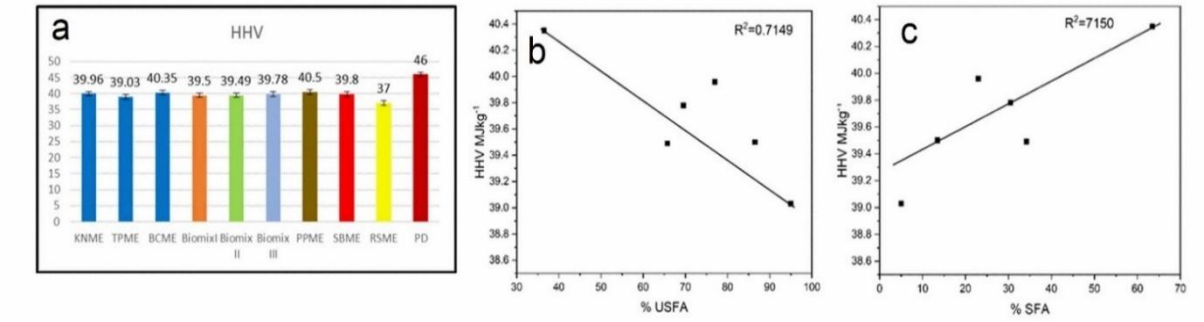


Figure 7: (a) HHV of biodiesels compared with existing biodiesels and Petro diesel (b) Correlation graph between HHV and USFA (c) Correlation graph between HHV and SFA

4.2.3. Viscosity:

Fuel viscosity directly impacts atomization, spray pattern and combustion efficiency. The kinematic viscosity of biodiesel depends on both the chain length and degree of saturation of the fatty acid methyl esters [22]. The viscosities recorded were 3.69 mm²/s (KNFAMEs), 3.43 mm²/s (TPFAMEs), and 3.81 mm²/s (BCFAMEs), all falling within the limits prescribed by ASTM D6751 (1.9–6.0 mm²/s) and EN 14214 (3.5–5.0 mm²/s). Figure 8 (a) and (b) shows that blending these oils further stabilized the viscosity values. As shown in figure 8(a) and (b), a clear inverse relationship ($R^2 = 0.7955$) was observed between viscosity and USFA content, while a direct correlation ($R^2 = 0.7956$) was noted with SFA content. These relationships are attributed to the structural geometry of unsaturated and saturated fatty acid chains [31].

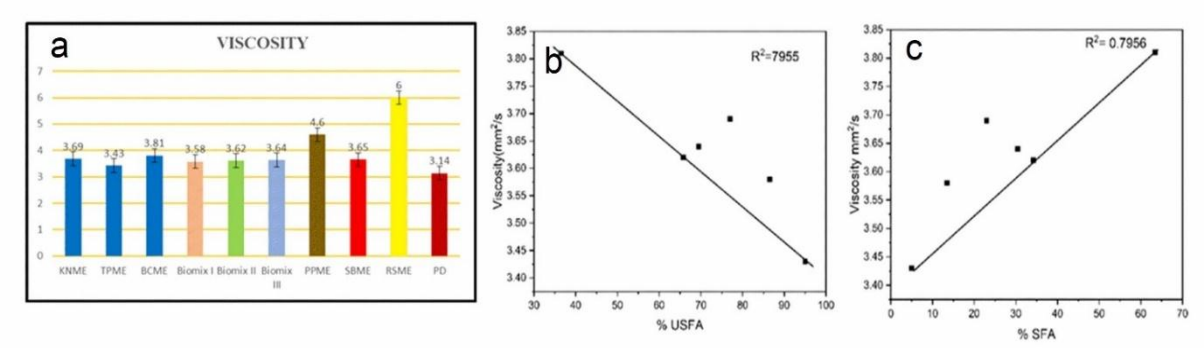


Figure 8: (a)Viscosity of biodiesels compared with existing biodiesel and Petro diesel (b) Correlation graph between viscosity and USFA (c) Correlation graph between viscosity and SFA

4.2.4. Flash Point:

The flash point represents the lowest temperature at which a fuel can vaporize to form an ignitable mixture in air. This parameter is crucial for safe storage and transport. Biodiesels generally have higher flash points than petro-diesel, enhancing their handling safety [32]. The flash points of KNFAMEs TPFAMEs, and BCFAMEs were 419.79 °C, 413.39 °C, and 397.85 °C, respectively. Bio-mix formulations showed slightly lower values but still exceeded those of conventional diesel. As shown in Figure 9 (a)and (b) Correlation data show a direct relationship ($R^2 = 0.7236$) between USFA content and flash point and an inverse relationship ($R^2 = 0.7235$) with SFA content.

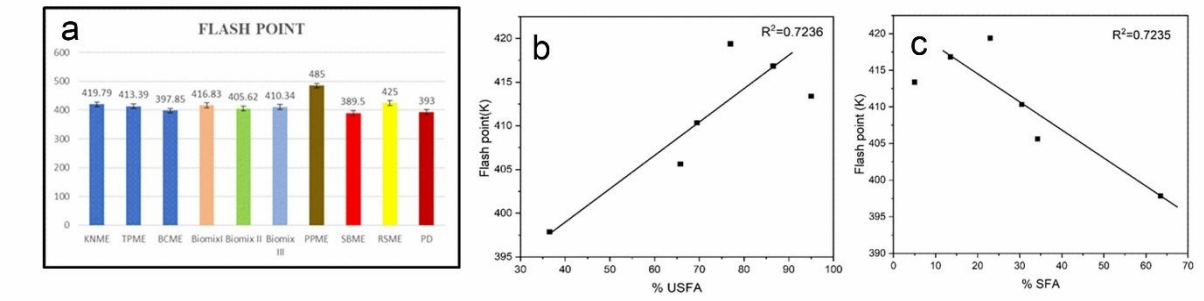


Figure 9: (a)Flash point of biodiesels compared with existing biodiesels and Petro diesel (b) Correlation graph between flash point and USFA (c) Correlation graph between point and SFA

4.2.5. Cloud Point:

Cloud point (CP) and pour point (PP) are critical for evaluating a biodiesel's performance in cold climates. CP is the temperature at which wax crystals begin to form, and PP is the lowest temperature at which the fuel remains flowable. Petro-diesel typically has a CP around -8.1 °C. The CPs of KNSO, TPSO, and BCSO were -0.78 °C, -4.99 °C, and 17.41 °C, respectively. The Bio-mix samples exhibited improved cold flow characteristics, with Bio-mix: I recording the lowest CP at -1.81 °C. A strong inverse relationship was identified between USFA and CP ($R^2 = 0.83039$), and a direct relationship was noted with SFA ($R^2 = 0.8303$) [33]. Equation (ix) helps in calculating the cloud point of biodiesel. Petro diesel has CP values of around -8.1°C whereas, biodiesels derived from KNSO, TPSO and BCSO have CP values -0.78°C, -4.99°C, and 17.41°C respectively and cloud point value of Bio-mix:I, Bio-mix:II, Bio-mix:III are -1.81 °C, 12.42 °C, 11.64 °C respectively are presented in Table 4 and shown in Fig.10. The values obtained are comparable with the existing biodiesels and tend to have moderate cold flow properties, but still they can be used as liquid fuels in the countries under moderate climatic conditions. Figure 10 (b) and (c) shows that inverse correlation was observed between USFA and cloud point with correlation coefficient $R^2 = 0.83039$, meanwhile CP increases with increase in SFA with a correlation coefficient $R^2 = 0.8303$.

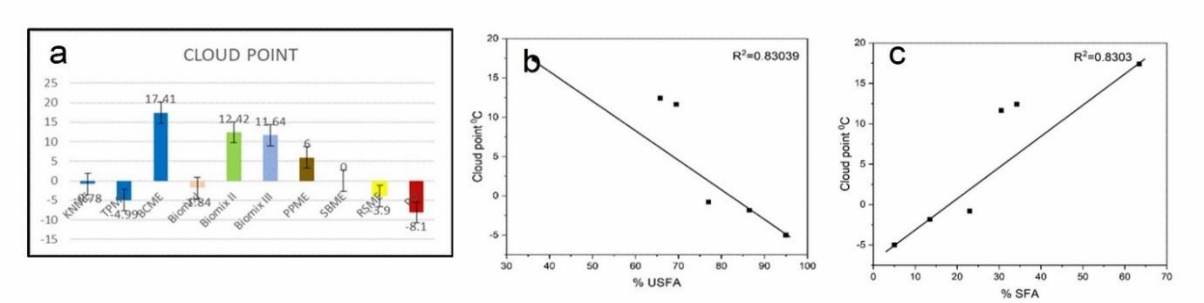


Figure 10: (a)Cloud point of biodiesels compared with existing biodiesels and Petro diesel (b) Correlation graph between cloud point and USFA (c) Correlation graph between cloud point and SFA

4.2.6. Cold filter plugging point (CFPP)

The Cold Filter Plugging Point (CFPP) is defined as the lowest temperature at which 20 mL of a sample can pass through a filter within a specified time of 60 seconds. In colder regions, fuels with a high CFPP are more prone to clogging engines, potentially leading to operational issues. The CFPP values of KNSO, TPSO are 5.83 ^{0}C and 5.4^{0}C respectively. These are lower than BCSO and other Bio-mix derived biodiesel. This test gives an idea on the lowest temperature at which fuel flow easily. CFPP value can be calculated from equation (xi) from Table 1. Figure. 11 (b) and (c) shows that with increase in USFA with correlation coefficient R^2 = 0.9256 CFPP decreases, meanwhile CFPP increases with an increase in SFA with a correlation coefficient R^2= 0.9256.

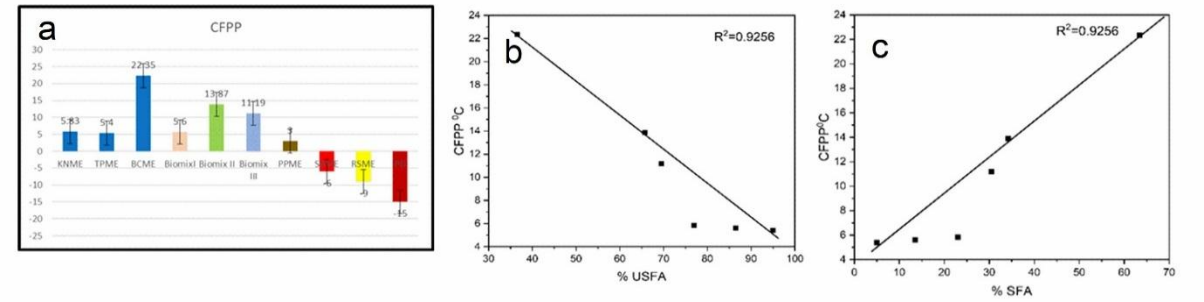


Figure 11: (a)Cold filter plugging point of biodiesels compared with existing biodiesels and Petro diesel (b) Correlation graph between CFPP and USFA (c) Correlation graph between CFPP and SFA

4.2.7. Long chain saturation factor (LCSF)

The most important reasons that affect the fuel properties is saturated and unsaturated fatty acid. The LCSF value of BCFAMEs is 12.36 is higher than KNFAMEs, TPFAMEs due to the presence of higher saturated fatty acid content. By Bio-mix Strategy LCSF value can be reduced by blending highly saturated seed oil with seed oil with higher unsaturated content. The LCSF value can be calculated from equation (xii) from Table 1 and graphically represented as follows. Figure 12. (b) and (c) illustrates that with increase in USFA with correlation coefficient R^2 = 0.962 LCSF decreases, meanwhile LCSF increases with an increase in SFA with a correlation coefficient R^2= 0.9662.

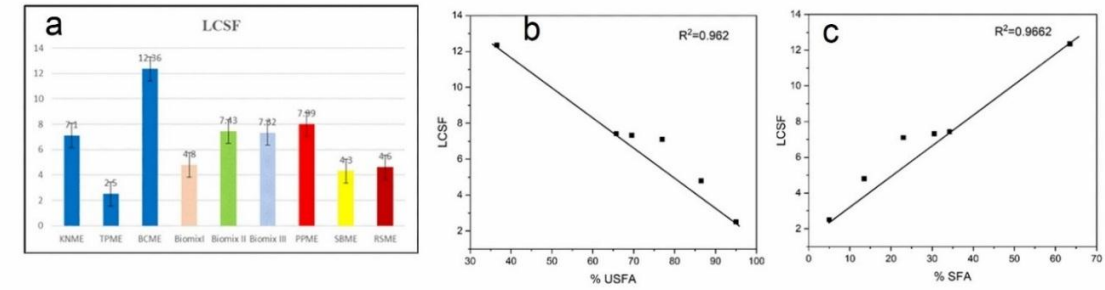


Figure 12: (a)Long chain saturation factor of biodiesels compared with existing biodiesel and Petro diesel (b) Correlation graph between LCSF and USFA (c) Correlation graph between LCSF and SFA

V. CONCLUSIONS

This investigation affirms the potential of non-edible seed oils derived from *Khaya nyasica*, *Terminalia phellocarpa*, and *Baccaurea courtallensis* as promising feedstocks for biodiesel production. Through the strategic Bio-mix approach, these oils were blended in specific proportions to harness their complementary properties particularly in terms of fatty acid composition. The resulting biodiesel formulations demonstrated improved cetane numbers, favorable viscosity, enhanced thermal stability, and acceptable cold flow properties. Among the combinations tested, Bio-mix: II and Bio-mix: III exhibited the most balanced and superior fuel characteristics, aligning well with global biodiesel quality standards. In addition, the use of computational models to predict fuel parameters based on fatty acid profiles proved to be an efficient alternative to conventional experimental procedures. This not only reduced time and cost but also allowed for rapid screening of multiple feedstock combinations. Overall, the study supports the use of mixed non-edible oils as a sustainable and flexible route to high-quality biodiesel. Future work should focus on engine-level testing and long-term performance assessments to validate these findings under practical operating conditions.

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